Novel Gas-Liquid Contactor Concepts for PCC Capital and Operating Cost Reduction

ANLEC R&D Project 3-1110-0069 – Final Technical Report

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EP146140
25 August 2014
ANLEC R&D
CSIRO Energy Flagship

Citation

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Acknowledgements
The authors wish to acknowledge financial assistance provided through Australian National Low Emissions Coal Research and Development (ANLEC R&D). ANLEC R&D is supported by Australian Coal Association Low Emissions Technology Limited and the Australian Government through the Clean Energy Initiative.

Preliminary work leading to this project was funded by the CSIRO Advanced Coal Technology Portfolio. The authors wish to express their thanks to Don Chase and Ed Garland for their contribution to the preliminary experimental work and making the concept a reality. Russell Reynolds provided the initial engineering drawings for the 3-d printer version of the slotted tube and production of the 3-d printed slotted tubes was carried out by Chris Knight and Steven Percy.
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Executive summary

This final technical report for the ANLEC R&D funded project 3-1110-0069 describes the development of a novel gas-liquid contactor aimed at reducing the capital and operating costs of Post Combustion Capture (PCC) commercial scale plants. The novel contactor in this study is one in which liquid is ejected from an axially located rotating slotted tube as a continuous sheet that acts in a similar fashion to the helices of an auger or the blades of a compressor. This device therefore combines the functionality of gas-liquid mass transfer with flue gas pumping in a single column without packing. Experimental measurements and Computational Fluid Dynamics (CFD) modelling have collaborated to improve the design of the slotted tube internals to increase pumping efficiency and to understand the technical parameters that would be important in determining pilot scale and commercial scale design and cost. This 24 month project commenced on 25 May 2012 and was resourced at a total of 1.5 FTE (full-time equivalent) staff per year.

The overall objective was to develop a contactor that can operate at higher gas velocities than conventional packed beds. Velocity sets the contactor column diameter and is a significant factor in contactor column costs which in turn make up 50% of the cost of the major equipment items of a PCC plant. Performance of the Rotating Liquid Sheet (RLS) contactor has been shown to match or exceed that of conventional packed beds. Target gas velocities of twice that of conventional packed beds can be achieved at modest rotation rates without external pumping. The stretch target of five times conventional packed bed gas velocity may be possible at higher rotation rates with forced draft assist (more energy) or, more appropriately, with further refinement in the design of the slotted tube leading to even further improvements in pumping efficiency.

The key technical challenge remaining is the scale-up beyond the pilot scale involving parallel operation of the RLS contactors. A design is proposed (to be tested at a larger scale) that, if successful, could apply the concept to any scale of operation.

Cost reduction occurs as a result of eliminating the packing, reducing or eliminating the need for external flue gas pumping and in contactor column size reduction. Overall capital cost savings are estimated to be approximately 30% based on the elimination of packing and reduction in column diameter (2x target). Elimination of the flue gas blower provides further capital cost savings (approx. 3%) and provides a net reduction in electrical power consumption of 25%.

Results and estimated cost savings are sufficiently encouraging to justify the further development at pilot plant scale. A conceptual design of a test module at the pilot plant scale and a proposed design at the commercial scale are presented in this report. Further support is actively being sought to progress the next stage of development.

Overall achievements of this project can be summarized as follows:

- A continuous unbroken liquid sheet can be established experimentally to 500mm in the larger flow visualization column and up to 1m diameter in unconfined (open air) tests. The experimental work at 500mm diameter matches the actual pilot plant columns allowing performance evaluation to be carried out at direct (1:1) scale.
- Induced gas velocities (no external gas pumping) have been experimentally measured that match those typical of conventional randomly packed beds. These experiments were done on simple slot designs that were not yet optimized. Therefore it is possible that at least the initial target (2x velocity) will be matched with higher rotation rates or more efficient designs.
- The internal design of the slotted tube is critical to controlling the shape and stability of the continuous liquid sheet and hence pumping efficiency. CFD analysis has been applied to understand the effect of the liquid flow field at the slot exit point and has provided further improvements to design.
• CFD modelling has provided insight into the nature of the flow patterns in the gas and liquid phases thus explaining experimental anomalies, such as poor blade shape definition and has reduced the need for trial and error in the experimentation by arriving at an optimized design more quickly.
• The cyclonic action of the device and the deliberate avoidance of the formation of droplets significantly reduces entrainment allowing higher forced draught fan rates (5x velocity target).
• Significantly lower total pressure drops (removal of packing) allows lower cost fans to be utilized as required for higher gas velocities (5x velocity target).
• Modelling shows that the RLS contactor can be readily designed to match the interfacial surface area of conventional random or structured packing materials.
• Fluids with viscosity up to 50 mPas have been successfully run showing similar behaviour to low viscosity fluids and improved liquid sheet stability. This creates the potential to utilize a wider range of capture solvent viscosities due to the ability to control the liquid sheet thickness.
• The shorter residence time and the cyclonic nature of the gas flow may be particularly advantageous in dealing with flue gas streams with high ash, high SO\textsubscript{x} and high NO\textsubscript{x} levels as are typical of flue gas streams in Australian conditions.
• The main challenge remains the definition of the maximum commercial scale to which this device can be effectively built and operated, that is, the maximum diameter to which the continuous liquid sheet will extend. A proposed device is presented that will allow RLS contactor modules to act in parallel in an hexagonal array. If successful, there would be no technical limit to the column diameter.
## Summary of Milestones

<table>
<thead>
<tr>
<th>Date Due</th>
<th>Description</th>
<th>ANLEC Funding ($)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>25/05/2012</td>
<td>Signing of contract</td>
<td>$109,457</td>
<td>Complete</td>
</tr>
<tr>
<td>25/05/2013</td>
<td>Completion of experiments/CFD model to assess whether the liquid sheet contactor has the technical potential to compete favourably with conventional packed bed contactors for the capture of CO₂ from flue gases from coal fired power stations using a liquid solvent. Draft First Technical Report that addresses outcome 1 of section 1.3: State of the art and setting benchmark performance required of contactor processes for CCS applications, including an assessment of the proposed benchmarks and whether the Novel Design can meet benchmark performance.</td>
<td>-</td>
<td>Complete</td>
</tr>
<tr>
<td>25/07/2013</td>
<td>Final First Technical Report submitted to ANLEC R&amp;D incorporating any feedback provided by ANLEC R&amp;D and reviewers on the draft First Technical Report provided in milestone 2a.</td>
<td>$109,457</td>
<td>Completed</td>
</tr>
<tr>
<td>25/05/2014</td>
<td>Submission of a short progress to ANLEC describing completion of the PDU scale experiments and evaluation/costing of the contactor at full commercial scale.</td>
<td>$87,566</td>
<td>Completed</td>
</tr>
<tr>
<td>25/07/2014</td>
<td>Draft of Final Technical Report that addresses outcome 2 of cl 1.3 submitted for ANLEC R&amp;D review which demonstrates the full-scale potential of the concept to show whether the stretch target (5-fold increase in gas velocity) leading to a reduction in the capital costs of Post-Combustion Capture plants as applied to coal fired power stations by approx 35% is possible</td>
<td>-</td>
<td>Completed</td>
</tr>
<tr>
<td>25/08/2014</td>
<td>Final Technical Report that addresses outcome 2 of cl. 1.3 and includes ANLEC R&amp;D feedback submitted to ANLEC R&amp;D which demonstrates the full-scale potential of the concept to show whether the stretch target (5-fold increase in gas velocity) leading to a reduction in the capital costs of Post-Combustion Capture plants as applied to coal fired power stations by approx 35% is possible</td>
<td>$131,348</td>
<td>Completed</td>
</tr>
</tbody>
</table>
1 Introduction

1.1 Background

Carbon Capture, Utilization and Storage (CCUS) technologies seek to eliminate more than 90% of the emissions of carbon dioxide (CO$_2$) to the atmosphere from the combustion of fossil fuels in large stationary facilities such as coal or gas fired power stations, cement kilns or furnaces. In each CCUS technology CO$_2$ is separated at some point in the combustion process as an essentially pure component suitable for sequestration or conversion to a useful product.

There are 3 main carbon capture processes being developed at various centres around the world:

1. **Pre-Combustion** capture in which fossil fuels are converted to a mixture predominantly of CO$_2$ and H$_2$, from which CO$_2$ is separated by membrane and/or solid adsorption processes while the H$_2$ is combusted in a turbine to generate power.

2. **Oxy-Fuel** in which oxygen is separated from air via membrane and/or cryogenic distillation processes prior to combustion with the O$_2$ fed to the furnace generating a high concentration CO$_2$ flue gas stream. The furnace must be modified to some extent to allow the recycling of flue gas for temperature control.

3. **Post-Combustion Capture** (PCC) technologies in which a liquid solvent contacts the flue gas after combustion capturing the CO$_2$ via a reversible liquid absorption process. This technology can be retrofitted to the exhaust of existing stationary fossil fuel burning facilities with minimal disruption to the existing facilities (the main disruption being provision of heat from the power station steam cycle). PCC technology has been developed from gas ‘sweetening’ technology used commercially in the gas processing industry, though, in the case of PCC, the presence of O$_2$ in the flue gas stream, the much lower CO$_2$ partial pressures (much lower driving force for capture) and the huge scale have presented unique technology challenges.

As discussed in Section 1.4, the significant reliance on existing fossil fuel power generation in many countries including Australia and China was the driver for the specific focus by CSIRO on PCC technology for CO$_2$ capture. The cost for this emission reduction is in the form of the capital and operating cost of the PCC plant itself and in the parasitic energy demand required by the PCC plant (up to 30% of the steam raised in the power station).

The vast majority of PCC research effort has been aimed at reducing the energy demand of the PCC process through improved solvents (Puxty, Rowland et al. 2009) and improved process configurations (Cousins, Wardhaugh et al. 2011), however it is important to note that the repayment of the capital can be in excess of half the total annual costs of a commercial scale CO$_2$ recovery project (Black, Haslbeck et al. 2013). The starting point for this study was a consideration of the engineering parameters that lead to capital and operating cost contributions of PCC as discussed in Section 1.5.

The main premise of this study has been that substantial cost reductions can only come from a radical re-think of the nature of gas-liquid contacting and the development of novel devices to achieve this. The overarching objective has been to develop a technology that will break through the barrier imposed by the gas velocity limits of conventional contator technologies (flooding, entrainment limits, etc.). This led to the development of a novel gas-liquid contactor referred to as the Rotating Liquid Sheet (RLS) contactor as described below. This work is part of extensive research that CSIRO has been carrying out in all areas of Post Combustion Capture (CSIRO 2012) including the implementation of Pilot Scale operations at three Australian power stations (Cottrell, McGregor et al. 2009).

The basic concept of the RLS contactor technology development is that a continuous sheet of liquid can be formed in the shape of a rotating helical auger or rotating angled blades similar to the blades in a compressor. The axial rotation of these liquid sheets is capable of pumping gas through a column,
contacting closely with the liquid and transferring gaseous components to the liquid, as would be required by the capture of CO$_2$ from a flue gas stream. The basic principle was proven experimentally in 2010 and patented (Wardhaugh, Chase et al.).

The purpose of this ANLEC R&D funded project (3-1110-0069) was to further investigate the concept to determine whether it could favourably compete with conventional packed bed contactors, operate at sufficient scale and to provide sufficient experimental data to estimate the cost savings at the commercial scale thus warranting further development at the pilot plant stage.

1.2 Outline of this report

Section 1 sets out the underlying reasons for the research, the limitations of existing technologies, the purpose and targets of this specific project, explains why this work has been necessary and places this work in an Australian context. The basic concept of the RLS contactor as envisioned at the start of the project is described.

Section 2 describes the experimental apparatus and methods and in particular the fabrication of the slotted tube as the key technology development.

Section 3 provides the main experimental outcomes with more details provided in Appendix C

Section 4 gives an outline and key results of the Computational Fluid Dynamics (CFD) modelling, with details provided in Appendix D.

Section 5 is a discussion of the implications of the research for scale-up and commercial design with an estimate of the cost savings that could be expected to be achieved with the full scale implementation of this technology.

Section 6 outlines the business development carried out to date and plans for future work included proposed designs for a Pilot scale test RLS contactor test module and proposed commercial scale flowsheet.

Section 7 is the conclusion to the report.

The appendices set out a baseline cost analysis; the details of the theoretical development; an example calculation that feeds directly into the cost analysis discussion of Section 5.3; and further details of methods and results.

1.3 The need for PCC cost reduction

Recent studies (Black, Haslbeck et al. 2013), (Raksajati, Ho et al. 2013), (Dahowski, Davidson et al. 2012) place the cost of the addition of a Carbon Capture facility to a coal fired power station at between 30 $/t CO$_2$ avoided and 80$\$/t CO$_2$ avoided (USD 2013) depending on location, scale, the degree of flue gas pre-treatment, the cost of capital and costing assumptions (Rubin 2012).

A study of low CO$_2$ emission technologies for power generation in the Australian context (EPRI 2010) placed the addition of a Carbon Capture and Storage (CCS) facility to a new coal fired power station at between 90$\$/t CO$_2$ captured and 180$\$/t CO$_2$ captured (AUD 2015 levelised costs).

The range of penalties for CO$_2$ emissions that have been implemented or proposed around the world do not match the costs of the implementation of the technological measures to reduce these emissions (Andersson and Karpestam 2013) and have an impact on electricity generation costs (Zhou, James et al. 2010). This difference between the cost of capture and the possible net penalties associated with emission of CO$_2$ must be met with technical developments that substantially reduce the capital and operating cost of PCC plants if this technology is to be implemented.
1.4 Relevance to Australia

In Australia, over 70% of the electricity generation is fuelled by black and brown coal with most of the generating plant still having a useful life measured in decades. Australia is the second largest coal exporter in the world (recently overtaken by Indonesia)\(^1\). The value of coal exports from Australia has risen nearly 300% in the decade from 2001 to 2011 when it was valued at $46.8 billion\(^2\).

Unlike most nations in the OECD, Australia does not have any form of de-sulphurization (de-SO\(_x\)) and de-nitrification (de-NO\(_x\)) of the flue gases emitted from power stations. The historical reasons for this relate to the very low sulphur contents of Australian thermal coals, especially the brown coal reserves that contribute over 90% of Victoria’s power supply, and the relative isolation of the power stations from major population centres. PCC technologies developed overseas rely on solvents that are particularly susceptible to even low levels of SO\(_x\) and NO\(_x\), requiring that Australian power producers must remove these flue gas contaminants before even considering the removal of CO\(_2\), thus adding further to the capital cost of PCC in Australia.

PCC technologies that require chilling of the flue gases, e.g. Alstom’s chilled ammonia process, would be at a further disadvantage in the Australian climate and the severe restrictions on cooling water usage in most Australian locations. Capital cost repayment in Australia is a much higher percentage of total cost than is the case overseas, especially in China (Dave, Do et al. 2011) and in Europe where the reduction of the energy cost of PCC is the primary focus of research.

In the event that enforceable global agreements are put in place to limit CO\(_2\) emissions, Australia would need to make greater adjustments than most other OECD nations to meet such requirements. It would be advantageous to have a range of technology options available. PCC offers a viable option being to a greater extent able to be retrofitted to our existing power generation facilities and at a further stage towards commercialization compared to most other alternatives.

Because of the impact of SO\(_x\) and NO\(_x\) on the solvent and the limitations imposed by Australian conditions, it is not clear that overseas technology can simply be imported to meet Australia’s possible future CO\(_2\) emission reduction obligations. Given that such obligations are imposed globally, overseas expertise may simply not be available putting Australia at a disadvantage if locally developed technologies are not available. Such locally developed technologies may also have a potential export value.

1.5 Capital and Operating Cost Components

It is necessary to understand why PCC plants are so expensive and to determine what components of the plant contribute the most to this cost. Detailed engineering and costing studies have been carried out on proposed PCC plants as a retrofit (Ramezan, Skone et al. 2007) or as new facilities (Black, Haslbeck et al. 2013). The study by Ramezan et.al. (Ramezan, Skone et al. 2007), in particular, provides an understanding of the components of the plant that contribute to these unit operation costs, providing an understanding of the engineering parameters that must be changed and the limitations that must be overcome to reduce the costs. The details of this parametric cost study are provided in Appendix A. The main conclusions from this analysis are:

(i) Approximately half of the capital cost of the capture plant is in the gas-liquid contacting columns.

(ii) The flue gas train (pre-treatment; absorption and post-treatment columns) account for some 40% of the total capital cost.

(iii) The flue gas fan is a greater capital cost than all the other pumping equipment combined.

---


Pumping the flue gas through the packing in the contactor columns consumes approximately 50% of the total electrical load of the capture plant.

It is clear that any attempt to make a significant reduction in the capital costs of a PCC plant must address the costs associated with the unit operations of gas-liquid contacting and flue gas pumping.

1.6 Parameters that determine the cost of PCC

Having identified the equipment components that contribute the highest proportion of the cost of a PCC plant, it is necessary to understand the design process parameters that impact the capital and operating cost of these equipment items and to devise means to address those impacts in the most effective manner.

The cost of the contactor column can be directly related to the cost of steel in the column, the internals and the supporting structure. The column diameter is determined by gas throughput and the entrainment constraints of the contactor type (limiting gas velocity). Column height is determined by the physical (diffusivity) and chemical (reaction kinetics) properties of the solvent package which is assumed here to be optimized. The direct contact cooler (integral to the absorber in the DOE/NREL design) adds 10% to the capital cost but may, in alternate designs, be incorporated at the base of the absorber or in the Flue Gas Desulphurization (FGD) plant (an additional cost in Australia where, unlike the Conesville plant and elsewhere in North America and Europe, no pre-existing FGD facilities exist).

Another significant cost item as noted above, is the flue gas blower which alone represents a greater capital cost than all of the liquid pumps combined for a modest pressure rise (typically 10 kPa). Note that there is an order of magnitude step change in cost in gas pumping equipment when the discharge pressure exceeds approximately 3.5 kPa (Peters, Timmerhaus et al. 2003). Gas-liquid contactor designs that increase the required flue gas inlet pressure, no matter how efficient, may not reduce the overall capital cost and may add significantly to the operating cost as discussed in the next section.

The choice of solvent (assumed here to be optimized) also affects the design of the overall system and hence the cost. It is worth noting that a conventional design utilizes low molecular weight and low viscosity solvents with high reaction rates but with high energy costs to strip the CO$_2$ from the solvent. There are a number of promising solvents (high reactivity and low energy cost) which are also of higher concentration, higher molecular weight and therefore of higher viscosity. These solvents are pushing the limits of conventional packed bed contactors as discussed below. Further development of these types of solvents will require alternate contactors less constrained by viscosity or other properties.

This project has targeted a reduction in the capital and operating costs of PCC plants by endeavouring to reduce the size and cost of the most expensive capital item – the gas liquid contactors including the absorber and desorber (stripper) column, direct contact cooling (pre-treatment) column and flue gas wash (post-treatment) column without addition to the flue gas pumping pressure. To further understand why a radical re-think of gas-liquid contactor design is necessary, the limitations of existing contactor types are summarized briefly in the next section (with details provided in Appendix B).

1.7 Limitations of existing contactors

To understand why a new gas-liquid contacting method is required it is first necessary to understand the fundamental limitations of existing devices and to use this information to make a step change improvement, leading to the proposed contactor design discussed in Section 1.8. The details of this analysis are provided in Appendix B and can be summarized as follows:

(i) **Packed columns** are mature technology and are fundamentally limited by the flooding and entrainment points. Also, the fact that liquid surface is generated by gravity alone limits application to low viscosity capture solvents.
(ii) Significant reduction in contactor size requires the elimination of the solid packing material and the avoidance of liquid droplets so that gas velocities can be increased.

(iii) Conventional spray columns are inherently inefficient in terms of interfacial surface area/unit total volume and gas back-mixing which reduces efficiency, increasing column height.

(iv) The generation of very fine droplets in a spray column is counterproductive as this leads to higher entrainment, necessitating lower gas velocities and larger column diameters. An optimum droplet size exists that minimizes spray column cost, but prevents further improvement.

(v) Devices which require that energy be added to the gas phase e.g. vortex contactors; venturi contactors will add significantly to capital and operating costs through increased flue gas pumping requirements.

(vi) The generation of adequate interfacial surface area requires that energy should be added to the liquid phase, for example as pressure or as centrifugal force, especially for more viscous solvents.

(vii) Complete control of the gas and liquid flow patterns must be achieved to maximize the space utilization and avoid back-mixing.

(viii) If momentum can be transferred from the liquid to the gas stream, then mass transfer may be enhanced, entrainment is diminished and the need for external gas pumping is reduced.

(ix) Maintaining the liquid as a sheet (delaying break-up) is advantageous as this maximizes the interfacial area.

Consideration of the above points together with technical knowledge of the system fluid dynamics led to the development of a novel contactor device that is the subject of this project. The concept is described in the next section.

1.8 Rotating Liquid Sheet (RLS) contactor concept

The Rotating Liquid Sheet (RLS) contactor (Wardhaugh, Chase et al. 2012) proposed here attempts to avoid the limitations of the conventional gravity driven contactors, by providing free surfaces for gas-liquid mass transfer in a more efficient manner, and to use the momentum of these free liquid surfaces to drive the gas through the contactor. The RLS contactor is based on a continuous sheet of liquid (the capture solvent) being ejected into the column through slots in a rotating tube that is aligned along the axial centre of an empty column (i.e. no column internals other than the rotating tube) as illustrated in Figure 1.

![Figure 1 Concept of the Rotating Liquid Sheet contactor](image)
The liquid travels in a parabolic arc as unbroken but continually thinning sheets from the slot exit to the column wall. The liquid then travels down the column wall and is collected in a suitable reservoir. The liquid is pumped into the rotating tube at the top or bottom of the rotating tube through appropriate seals. The gas is allowed to enter the bottom of the column without restriction and to exit through the top of the column via a liquid disengagement device. The design of the tube slots is key to the ultimate success of this design. Two kinds of slots have been investigated:

- Helical slots which form the rotating liquid sheet into an auger shape (Figure 2a). In this figure the rotation of the tube in an anti-clockwise direction pumps gas upward through the column.
- Blade slots which form individual sheets of liquid similar in appearance to the blades of an axial compressor (Figure 2b). In this figure the rotation of the tube in a clockwise direction pumps gas upward through the column.

The basic equations governing fluid flow in the RLS contactor are developed in detail in Appendix E and are summarized here.

(i) The chemistry, gas and liquid compositions and performance criteria determine the range of gas to liquid ratios (G/L) for the operation of each of the contactors.
(ii) Geometric considerations based on the number and the configuration of the slots determines the surface area per unit volume of the column gas space which can be compared to conventional random or structured packing.
(iii) Liquid surface tension, film thickness and radial velocity determine the throw of the liquid across the column and the ultimate breakup of the sheet into droplets due to the amplification of natural instabilities.
(iv) Achievable gas flowrates, induced by the rotation of the liquid sheet are determined by the rate of rotation of the tube, the angle of the sheet relative to the gas flow direction and the efficiency of pumping.

The parameters outlined above are the subject of the experimental work presented here.

The shape and rotational motion of the angled liquid sheet imparts momentum to the gas stream thus pumping the gas through the device in an efficient manner. A key aspect of the design of the slotted tube is that the slot exit, the point of discharge of the liquid into the gas column, must form the liquid sheet in such a way that it is continuous across the column or, at least, preventing the breakup of the sheet into droplets for as great a radius as possible. The liquid sheets provide a two sided surface and a high relative
velocity between gas and liquid phases which may promote mass transfer of chemical components between the gas and liquid streams. The sheet actually provides a greater surface area than the droplets that would result from the breakup of the sheet (an explanation of this phenomenon is provided in Appendix E). The pumping action imparted by the liquid stream to the gas stream encourages the gas stream to travel in a matching helical motion between adjacent leaves of the liquid stream rather than the gas stream forcing its way through the liquid sheets, so that the device also has a cyclonic action potentially capturing droplets that, if formed, would tend to be thrown to the wall.

The axially located liquid discharge tube itself represents a minimal obstruction to the flow of the gas and should require only a small amount of energy to rotate (although there will be a reaction effect). In the case of the more mechanically flexible helix slot design, an adjustable central rod controls the gap spacing potentially allowing control over a wider range of liquid turn-down ratios. The blade design offers the possibility of a more compact design through overlapping rows of blades, however has the disadvantages of more edges (the consequences of this are discussed in Section 3.7). The momentum imparted to the gas is derived from the liquid pump pressure in conjunction with the centrifugal force created by the rotating tube which itself acts on the liquid as a centrifugal pump. Since the necessary surface area in the liquid is provided by liquid pumping pressure which controls the formation of the liquid stream at the liquid discharge point (tube slot), the device allows a wider range of liquid viscosities to be utilized.

Such a device has the potential to overcome each of the limitations of conventional contactors to a significant extent by introducing a different mechanism of contact between the gas and the liquid. This is achieved by advantageously controlling the fluid dynamics between the phases without the need of metal packing surfaces and by adding energy more efficiently via the liquid phase which is then transferred to the gas phase.

The liquid discharge mechanism is quite different from conventional rotating spray nozzles occurring in spinning cup or spinning disc spray nozzles which have as their purpose the formation of a uniform spray at or near the edge of the cup or disc. Such devices do not impart any pumping action to the surrounding gas (refer to the discussion in Section 3.5).

The primary scientific challenge in the development of this concept is to optimize the design so that it can operate as a continuous liquid sheet over as wide a radius as possible. Of course, to achieve effective operation of the RLS contactor in a single column at the immense scale required by full-scale PCC is a massive challenge that is not unique to this technology. The approach taken in this project has been to develop this technology at progressively larger scales and to develop models calibrated using the experimental results which are then applied to the evaluation of the potential of the technology at the commercial scale.
2 Experimental Investigations

Experimentation has been carried out in 3 stages each supported by CFD modelling (described in section 4 and Appendix D)

(i) Initial flow visualization experiments using 150mm diameter column carried out prior to the start of this project are described here briefly for the sake of completeness.

(ii) Detailed parameter evaluation using the upgraded facility and using the 150mm diameter column on ambient air and water

(iii) Flow parameter and mass transfer measurements using the 500mm diameter column on air (ambient and lab supply compressed air) and concentrated triethylene glycol (TEG) solutions. Columns with internal diameter of 250mm and 400mm were also constructed, but given the success of the 500mm column were not required.

These experiments were supported by measurements of physical properties – density, viscosity, surface tension and measurements of fundamental flow relationships as described in Appendix C.

2.1 Flow Visualization facility

The flow visualization experimental facility used in this project is shown in Figure 3 and as a process flow diagram in Figure 4.

![Flow visualization experimental facility (front view)](image)

Figure 3  Flow visualization experimental facility (front view)
Originally constructed for the study of the flow patterns in various contactor types including packed and spray columns and various rotating contactor devices, the unit had been adapted to investigate the novel Rotating Liquid Sheet contactor under investigation in this study. The column test section was initially selected as 150 mm diameter transparent acrylic tube (Figure 5a) in order to match the amine capable PCC Process Development Unit, located in the Newcastle CSIRO Energy Centre, with a view to transferring the experiments to a custom built module in this facility.

Figure 4  Process flow diagram of the Flow Visualization Facility

Figure 5  Close-up of column test sections (a) 150mm diameter (b) 500mm diameter
As discussed below, the 150mm diameter scale proved to be too small to be practical and several larger diameter test columns were constructed. The largest (500mm diameter) is shown in Figure 5b.

A variable speed motor mounted above the column was used to drive the longitudinally mounted 25.4mm (1") diameter liquid feed tube through a rotating seal and supported by low friction bearings. Various slotted tube test sections were constructed (described in Section 2.2 with details in Appendix C1). For each experiment, a given slotted tube test section was mounted in the middle of the liquid feed tube at an appropriate height in the test column section.

Liquid (initially water with colouring agent, in later experiments concentrated triethylene glycol (TEG) solutions) was pumped through the rotating seal into the top of the tube, exited the tube via the slots in the test section, then travelled (ideally) as an unbroken liquid sheet to the column wall and finally drained down the wall to a reservoir to be recirculated with a liquid pump via a filter. Gas (ambient air in the early experiments or dry laboratory compressed air in the later experiments reported here) entered through a 110mm diameter gas inlet tube via a flow measurement device (anemometer or tumbler-type flowmeter), was drawn through the test section by the action of the rotating liquid sheet and exited through a reverse flow separator to collect and measure the quantity of any entrained liquids (usually negligible). A forced draft fan was also provided at the gas inlet but was used only in specific experiments as detailed below. Video recording facilities were also used to capture images of the rotating liquid sheet for later analysis.

Gas leaving the test section passed through a reverse flow separator to collect and measure the quantity of any entrained liquids.

Initial improvements in the facility included a weir to prevent the liquid as it left the test section being entrained by the gas entering the test section; a larger liquid reservoir to prevent air bubbles entering the water pump; a filter to remove possible solids from the liquid stream and improved bearings and motor controls. Incorporated into the 500mm design (as well as the other column sizes) was an entry cone for the gas to allow immediate separation of gas from the liquid to minimize the effect of the down-draught caused by the liquid draining down the column wall. Gas velocities quoted for the 500mm column are based on the gas inlet diameter as the gas flow would not have been fully developed in the column.

2.2 Development of the slotted tube

A device that would provide a stable continuous liquid sheet proved to be more challenging than first envisioned. The following section briefly describes the various construction methods that have been attempted in the initial development leading up to and during this project. The details of the development work are provided in Appendix C1.

The slotted tubes were manufactured by:

(i) Winding thin flat strip metal as a spring – unsuccessful due to distortion of the metal.

(ii) laser cutting thin wall stainless steel tubes – first successful device, however, unwinding (residual stress relaxation) of the cut stainless tube led to distortion of the slots adversely affecting the resultant liquid sheets.

(iii) by fabrication in a 3-d (plastic) printer – successful applications especially with the complex design of tube internals, though test sections were easily broken.

Each manufacturing technique presented a number of challenges to be overcome mainly due to the small scale of the tubes. Many of these challenges will disappear at larger scales. Figure 6 illustrates the various techniques for manufacturing the slotted tubes. All experimental work reported here was carried out with laser cut stainless steel tube or 3-d printed plastic devices fabricated directly from CFD design files.
Figure 6 Various techniques for manufacturing the slotted tubes
(from left to right) (a) spring wound from 22mm x 1.5mm stainless steel strip; (b) laser cut 1” diameter tube to match
geometry of tube ‘a’; (c) laser cut triple helix; (d) laser cut triple blade; (e) 3-d printer triple blade (Verowhite); (f) 3-d
printer triple blade (Veroclear); (g) printer triple blade (Titanium-raw product)

For the specific results reported in Section 3, the slotted tubes are listed in Table 1, while a full listing of the
devices made is provided in Appendix C1.

Table 1 Summary list of slotted tubes used in experiments

<table>
<thead>
<tr>
<th>Slotted tube code</th>
<th># Helices or blades</th>
<th>Angle to horiz [deg]</th>
<th>pitch [mm]</th>
<th># turns</th>
<th>slot length [mm]</th>
<th>Nom. slot width [mm]</th>
<th>Actual slot width-min [mm]</th>
<th>Actual slot width-max [mm]</th>
<th>Nom. slot area [mm^2]</th>
<th>Actual slot area [mm^2]</th>
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<td>112.8</td>
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<td>0.25</td>
<td>0.25</td>
<td>188.6</td>
<td>94.3</td>
</tr>
</tbody>
</table>

Legend: MxnTmvt – M = material (S=stainless; P=Verawhite plastic; C=Veraclear plastic); x=individual code (repeat
unit); n-number of starts/rows; T=type (H=helix; B=blade); m=number of turns (1 is default); v=internal vanes.
2.3 Slot configuration

For each design type (blade versus helix) there are design parameters that interact to affect the formation of the liquid sheet, the total surface area (hence mass transfer) and the gas pumping efficiency. Parameters include:

(i) Number of starts (helix design) or number of blades per row (blade design).
(ii) Number or turns (helix design) or number of rows (blade design). In the blade design, the rows could overlap increasing the total surface area in a given tube length.
(iii) Angle (to horizontal) of the blades or helix which determines, along with rotation rate, the theoretical gas pumping rate. Note that in more sophisticated designs (not investigated here), the angle could be varied along the length of the slotted section of the feed tube – a common strategy in pump or compressor design to improve pumping efficiency.
(iv) Slot width. This could also be variable (by design).
(v) Slot internal design (3-d printed plastic test sections) applied to improve the shape and stability of the liquid sheet.

Creating a multi-start helix or multiple interleaved layers of blade shaped slots creates the possibility of increasing the gas-liquid contact surface in a given total volume as discussed in Section 5.1. This may also improve the efficiency of pumping and improve the mass transfer coefficient (both nominally independent of total surface area) by creating tighter pathways for the gas flow. The challenge in a liquid system is that interactions or collisions between adjacent liquid sheet layers may impede gas flow and therefore reduce pumping efficiency and, in the worst case, stop gas flow altogether.

2.4 Experimental Procedures

Each slotted tube design was installed in turn into the flow visualization facility using 1” Swagelok union fittings with nylon ferrules. The upper union connected to the water inlet via a rotating seal while the lower union acted as a plug and sat in the lower bearing. Alignment of the rotating tube was achieved using alignment screws in the lower bearing housing.

A typical experiment proceeded by setting the liquid flow rate to establish a stable liquid sheet extending to the column wall. After checking visually the shape and continuity of the liquid sheet, a rotation rate was established using the variable speed motor and measurements were taken of:

- Gas flow using an American Meter Company (AL-425) displacement gas meter; a Dick Smith Q 1302 propeller anemometer, or a Kimo CV210 multi-directional thermal anemometer. Calibration was done in series using the AL-425 gas meter.
- Gas inlet pressure using a pair of Dwyer Differential Pressure transmitter Model 607-2, configured to read negative and positive pressures.
- Rotation rate using a hand-held tachometer.
- Humidity (in latter experiments) at gas inlet and outlet using Vaisala HMT337W warmed probe humidity meters.
- Temperature (probes in Kimo and Vaisala units).
- Entrainment (if any) as measured volume over a steady state time period.

Rotation rates up to 900 rpm were able to be applied stepwise, usually from high to low levels due to the hysteresis that occurred both in the process and in the gas flow meter. Anomalous behaviour was investigated further, e.g. by varying liquid flowrate at constant rotation rate.

In some experiments a gas flowrate was imposed using the fan upstream of the test section or laboratory compressed air supply (dried air). Most experiments, however, were carried out without the fan as the RLS contactor slotted tube being tested was, in most cases, able to create a measurable induced gas flow.

If warranted, more detailed investigations were carried out on specific slotted tube designs using the following procedures. In most such experiments, measurements were made with both stepwise increase
and decrease in the independent parameter (e.g. rotation rate; liquid flowrate) to determine if any hysteresis effect or external effect (e.g. instrument electronic drift) was effecting the results.

(i) A small constant flow of dry air (from the laboratory compressed air supply) was applied to the gas inlet. Rotation rate was varied and experimental parameters measured. Mass transfer occurs from the TEG solution to the dry air increasing the measured humidity (desorption).

(ii) With no rotation, the air flow was varied to determine the K factor (pressure vs flow) relationship for the experimental setup (determined by the flow path of the gas).

(iii) With the gas inlet sealed, the rotation rate was varied through the full range. The pumping effect of the rotating liquid sheet draws a partial vacuum which in turn can be used to measure the impact of suction head on each slotted tube design.

(iv) The inlet tube is opened to ambient (humid) air while a small rotation rate is applied to the slotted tube to maintain a measureable gas flow through the apparatus. The measurable mass transfer is now from the humid air to the TEG solution, so that the humidity of the pumped gas decreases as it passes through the RLS contactor (absorption). Rotation is varied through the full range or until the sheet has broken up into droplets (refer to the discussion in Section 3.10).

(v) A moderate rotation rate was chosen (for which there is a good gas pumping rate) and the liquid flowrate was reduced stepwise until the gas pumping rate drops to zero. The liquid rate was increased stepwise to find the flow that just initiates gas pumping.

(vi) In measurements focusing solely on mass transfer a liquid rate and rotation rate set to give a good shape to the liquid sheet; air flowrate varied over a practical range.

The effect of viscosity was determined using solutions of triethylene glycol (TEG) with high concentrations (up to nearly pure) of TEG in the solution. Viscosities up to 50mPas could be tested. This viscosity is an order of magnitude greater than would be practical as capture solvents in a packed bed. Alternating absorption and desorption experiments maintained a relatively constant water content in the solution. Measurements of density (Anton Paar DMA 38), viscosity (Anton Paar AMVn) and surface tension (Sigma 700/701) provided both the physical properties for modelling and, based on literature data (Sun and Teja 2003), a reliable estimate of water content is possible.
3 Experimental Results and Discussion

The following sections detail the investigation of the parameters affecting the gas pumping rate and mass transfer. The implications of these results are then discussed leading to further development of the design procedure and costing studies as described in Section 5.

3.1 Formation of the liquid sheet.

Initial success in obtaining a stable continuous liquid sheet from a slotted tube was obtained from manually honed laser cut tubes as described in Appendix C1. A typical image for the first laser cut tube (5 turn; 1-start; 22 mm pitch) is shown in Figure 7a together with a line diagram (Figure 7b) illustrating the main features. The acrylic column wall appears black in the photo, however, liquid impinging on and travelling down the wall is apparent and of course becomes a greater flow as more layers join the flow down the wall. In order to pump gas upwards through the column, tube rotation was clockwise when looking down from above. The trailing edge of the liquid helical sheet is apparent as a white line in the top left of the column. Gas would exit the helix between that trailing edge and the next liquid sheet layer and enter at the leading edge at the bottom of the helix (not visible in the photo but shown in Figure 7b).

![Figure 7](image-url) (a) Photo of liquid sheet contactor in operation showing well formed sheet as a rotating helix over 4-5 turns, (b) Schematic diagram showing the helical film structure and apparatus
The turbulence seen in Figure 7a (and in many of our experiments) at the point that the liquid sheet impacts the wall is unnecessary and a waste of energy. Ideally the sheet should fold over to a steeper angle at the point of contact producing no turbulence or spray at the wall. However this required a finer control over the slot design (as discussed below) than we were able to achieve experimentally at this small scale and was one of the reasons that we progressed to the larger diameter test columns.

The creation of a well-formed liquid sheet was of course critical to achieving high pumping efficiency. The sheet must break up eventually as it extends out from the slot, becoming thinner as it does (a linear relationship with radius) as seen in Figure 8. However breakup of a well formed sheet reduced the pumping efficiency only marginally if it occurred near the column wall (discussed further in Section 3.10). Of greater detrimental impact were the following:

(i) The breakup of the sheet at the slot due to imperfections in the slot edge (manufacturing imperfections), or blockage of the slot (pipe thread tape was the main culprit).

(ii) The twisting or distortion of the sheet away from a perfectly formed blade or helix due to the combined effects of surface tension and the liquid velocity field within the tube (Figure 9a).

(iii) Collapse of the top-most turns of the liquid sheet onto adjacent (lower) turns of the helix due to insufficient liquid supply flow or pressure. (Figure 9b - discussed in Section 3.4).
3.2 Evidence of the gas pumping effect and the role of rotation rate.

Confirmation of the gas pumping action induced by the rotation of the liquid sheet was achieved by sealing the gas inlet and outlet and measuring the pressure at the gas inlet. In this way, any possible effects of stray convective currents could be eliminated. At increasing clockwise rotation rate (pumping upwards) the pressure in the sealed gas inlet line decreased in steps corresponding to the rotation rate. Reversing the direction of rotation (anti-clockwise - pumping downwards) resulted in an increase in pressure at the gas inlet with each step increase in the rotation rate of the tube as shown in Figure 10a. For each step change in rotation rate, the change in the pressure signal was essentially instantaneous. The steady state results are replotted as pressure versus rotation rate in Figure 10b. The pressures so generated were quite small but do not need to be large as the pumping action is differential in nature and, while clearly monotonic, had complex features requiring further investigation.

Figure 9  Detrimental effects on sheet formation (a) Blade distortion due to liquid flow field (b) Sheet collapse due to insufficient liquid flowrate

Figure 10  Pressure at (closed) gas inlet line as a function of rotation rate in clockwise (negative rpm - pumping up) and counter-clockwise (positive rpm - pumping down) directions
(a) Raw result plotted versus time. (b) Steady state result (pressure versus rotation rate).
The appropriate response to both rotation directions confirmed that the pumping action was a real phenomenon and not an artefact of the experiment or equipment. Subsequent experiments for various gap spacings have confirmed this conclusion by showing that a measurable gas flow can be attained over a wide operating range of liquid and externally applied gas flow rates and tube rotation rates. This result would be entirely expected if the helical screw was a solid structure (as in an auger). The advantage of the use of liquid to form the surface of the screw is that now there is intimate contact between both sides of the liquid sheet and the gas. The gas itself is induced to travel in a helical path in the interstices between adjacent sheets of the liquid screw. A high surface area is attained without the need for a solid packing material (which adds cost and pressure drop) or the need for the formation of fine droplets (which limits the gas velocity and adds to entrainment). The cost implications are quantified in Section 5.3. The downflowing liquid at the column wall can create a down draught (refer to Section 3.4) which is a source of inefficiency however, unlike a solid auger (refer to CFD modelling in Section 4), the liquid at the wall provides a perfect seal between adjacent layers of the liquid sheet (provided the sheets are fully formed at the wall).

3.3 Effect of rotation rate

It is the rotation rate and angle of the continuous liquid sheet to horizontal\(^3\) that imparts momentum to the gas and creates the induced gas flow rate that is measured in most of the experiments. In the absence of secondary flows, the maximum theoretical induced gas flow rate is a linear function of the rotation rate and the tangent of the angle of the sheet. Any value of gas flow rate less than this theoretical maximum is due to secondary flows (eddies) in the gas and represents a loss of efficiency as with any pumping system. In the cases when the gas meter, used in the earlier experiments, offered too much resistance to flow, the negative pressure created by the pumping action of the rotating liquid sheet could be interpreted as velocity via imposed flow-pressure measurements. Results are therefore presented as actual gas velocity; efficiency; and/or as suction pressure. A typical result for the effect of tube rotation rate is shown in Figure 11.

![Figure 11 Effect of rotation rate - typical result](image)

[Helix design; 2 start; 1 turn; laser cut stainless steel]

\(^3\) Strictly speaking it is the angle of the blade or helix subtended to the direction of gas flow. Since in most gas-liquid contactor columns and in all our experiments, gas flow is vertically upwards through the column, it is convenient to refer to the angle of the blade to the horizontal.
At moderate to high rotation rates the expected linear effect is distinctly seen and would appear to continue to higher rotation rates. At lower rotation rates there appears to be a drop in efficiency and a minimum rotation rate is required to achieve any gas flow. In some runs, a drop of efficiency may also be seen at higher rotation rates. The reason for this is discussed in Section 3.5. A drop in efficiency could also occur due to increased turbulence at high rotation rates, while at the lower rotation rates slippage is thought to be the primary cause of the drop of efficiency to zero.

3.4 Effect of liquid flow rate

The liquid velocity at the slot exit is a function of the slot geometry, the liquid flow rate set by the pump and the tube rotation rate set by the motor speed. Provided that the liquid flowrate is sufficient to create a continuous liquid sheet that reaches the column wall (evident at zero rotation rate), the liquid flow rate has no further effect on the pumping performance of the rotating liquid sheet. This is shown in Figure 12 for the case of the stainless steel double helix slotted tube (Sa2H) where results at a range of liquid flow rates essentially overlap. In this case the slotted tube being tested is a 2-start, 1-turn helix design with 45° slot angle. At moderate to high rotation rates the expected linear effect is distinctly seen while at lower rotation rates there appears to be a drop in efficiency and a minimum rotation rate that is required to achieve an initial gas flow. Note that at high rotation rates the induced gas flow, even in these prototype slot designs, is equivalent to the load point of small size random packing. Higher gas velocities could be achieved in the RLS contactor by increasing the rotation rate (with a matching liquid flow as discussed below), however, it is of greater value to look for improved pumping efficiencies through optimized tube slot design at modest rotation rates.

The overlapping results of gas velocities for different liquid rates is an expected result as the (theoretical) induced gas velocity is primarily controlled by the rotation rate, not the liquid velocity at the slot exit. However, this is not the full picture as discussed in the next section.

![Figure 12 The effect of tube rotation rate and liquid flow rate on the induced gas flow rate](image-url)

Helix design; 2 start; 1 turn; laser cut stainless steel
3.5 The centrifugal effect of Rotation

An important result for a range of slot configurations has been that the imposed liquid flowrate (from the liquid pump) must always exceed the induced liquid flowrate (induced by the centrifugal force of the rotating liquid in the tube). The effect is determined by comparing the centrifugal velocity resulting from tube rotation with the liquid slot velocity due to the pumping rate. If the centrifugal velocity exceeds the pumping velocity, the pressure at the tube top falls to zero, the tube partially empties of liquid and the tube slot will act as a spinning spray device with liquid droplets clearly visible at the tube slot exit. At this point the induced gas flow reduces to zero with a small reduction in flowrate (at constant rotation rate). Two examples are shown below. Figure 13 is the case of a plastic triple blade slotted tube with internal vanes. The normal induced gas pumping is seen at high flowrates and rotation rates up to 800rpm. At 20Lpm liquid flow, the performance (and sheet continuity) begin to break down and there is no induced gas flow at liquid flowrates below 20Lpm. Unlike the result shown in Figure 12, there is a drop in performance at the highest rotation rate (above 900rpm). This may be due to the increased centrifugal velocity, or due to increased turbulence at these higher rates (higher slip).

![Figure 13](image)

**Figure 13** Variation in rotation and liquid flow rate showing effect of centrifugal velocity.
[Blade design; 3 rows of 4 blades; 3-d printed plastic with internal vanes]

A second example and a clear picture of the detrimental effect of an excessive rotation rate can be seen in Figure 14. For this slotted tube (stainless triple helix; angle =45°) the sheets were not well formed due to distortions in the manufacture of the slotted tube (as discussed above and in Appendix C1). Nevertheless, a small gas pumping rate could be attained at low rotation rate, the action of which tended to improve the shape of the liquid sheet. Breakup occurred at higher rotation rates, firstly at the column wall, then progressively closer to the tube as the rotation rate was increased. Equivalent results were seen for increasing rotation rates and decreasing rotation rates as shown in Figure 14.
Rotation of the tube imposes a centrifugal force on the liquid in the tube that is additional to the force imposed by the liquid pump. Rotation of the tube therefore reduces the pumping pressure required to achieve a given liquid velocity at the tube slot exit provided the liquid feed is to the centre line of the rotating liquid feed tube. A rotating nozzle is a popular form of spraying device. It is clear from the results shown in Figure 13 and Figure 14 that, if acting as a spray generator, the RLS contactor will not achieve the dual goals of creating high interfacial area and being capable of pumping the gas through the contactor. In contrast to these results, the break-up of the liquid sheet near the column wall does not appear to have a particularly adverse effect on the gas pumping efficiency.

3.6 Effect of imposed gas flow rate

Contrary to expectations, blowing a gas through the rotating liquid sheet using a small centrifugal fan (imposed gas flow) did not result in the break-up of the liquid sheet but rather lifted all the sheets slightly while the sheets themselves took on a roughened though still continuous appearance as seen in Figure 15. It can be anticipated that the higher momentum of the liquid, due to its mass and velocity, cannot readily be moved by the gas, while the gas will try to take the least resistant path through the spaces between adjacent liquid sheet layers. A number of measurements were made in which the flow of gas imposed by the fan was adjusted to try to balance the pressure at the contactor gas inlet. At the point at which the gauge pressure at the gas inlet equals zero, the gas flow imposed by the fan exactly matches that of the flow induced by the rotating liquid sheet. These measurements were instructive but difficult to carry out quantitatively due to small fluctuations that occurred in the fan speed and noise in the pressure signals arising from equipment vibration.
3.7 Blade versus helix design

An example of each type of slotted tube design in operation, but without rotation, has been illustrated in Figure 1a and Figure 1b. In all test work to date, the helix design out-performed the blade design in terms of measured induced gas flow rate and film stability, despite being of nominally equivalent slot areas in each set. The initial set of geometries was chosen to maintain the slot gap spacing and total slot area in a progression of designs of single, double and triple start helices; single, double and triple row blades each with equivalent slot areas as listed in Table 1 and shown in Figure 6. As discussed in Appendix C1, it proved very difficult to control the gap spacing of the laser cut slotted tubes in the manufacturing process with some of the helix tubes distorting due to the release of residual stresses created in the original tube manufacturing process. This distortion both changed the slot gap spacing and sent the tube out of alignment.

In general, the induced gas velocities produced by the helix designs were greater than those of the blade designs with equivalent slot areas, angles and rotations rates (an example shown in Figure 16). We attribute this to the possibility that the prototype blade designs are much further away from the optimum than the helix designs so far investigated. Tight, overlapping designs (as might be seen in compressor blades) have the potential to increase interfacial area (per unit volume) and improve pumping efficiency but have not yet been investigated. On the other hand, depending on the configuration, the helix design slotted tube has the attributes of a spring. In early experiments a central rod in the tube was used to adjust the slot spacing with good effect. Such a modification would give the helix design a high turn-down capability.
Despite the difficulties in manufacture, it was evident from the first operation that while the helix maintained a continuous liquid sheet over the full length with little distortion, in the case of the blade devices, surface tension pulled the edges of the liquid sheet into a vee or fan shape which was clearly affecting the shape of the liquid sheet and hence the performance of these devices. In some instances the distortion was sufficiently bad to twist the liquid blade in the opposite direction of what was desired thus having a negative effect on pumping efficiency. This was not entirely unexpected as it is known that surface tension will pull the liquid in on itself to form a cylindrical rod in its efforts to minimize the surface energy of the liquid. The solution to this problem lies in further development of the liquid feed tube internal design.

Of greater concern was the distorted angle of throw of the liquid sheet after exiting the slot and the considerable variation in the angle of throw along the length of the slot. Ideally the liquid should exit the slot at the angle determined by the slot wall (nominally 90˚ to the tube axis) but clearly this was not the case. The answer came from the CFD analysis of the liquid flow internal to the tube that showed a distinct downward direction to the liquid velocity profiles as discussed in Section 4. The inclusion of deflector plates in the slot inlets, developed from CFD analysis improved the flow pattern. As with the blade shape discussed above, it is anticipated that angle of throw can be significantly improved by further optimization of the design.

3.8 Effect of slot angle, pitch and number of turns

The angle that the blade or helix forms with the horizontal determines (along with rotation rate) the forward momentum imparted by the rotating liquid sheet to the gas. This also sets the pitch (the axial spacing of one full turn of the helix or blade (if continued) and, for a given total length, the number of turns (or rows of blades). For the blade design, overlap of adjacent rows must also be considered. The higher the angle, the greater the forward velocity of the liquid sheet but also the greater the slip of the gas as a fraction of the total theoretical flow. An optimum exists at approximately 45˚ which is intuitively correct and confirmed by CFD analysis for a single solid helical vane (Section 4).
Increasing the number of starts (Figure 17) at the same sheet angle improves the performance (as well as the interfacial area) and this must be due to improved pumping efficiency (since rotation rate and angle are the same). The improved gas pumping efficiency is attributed to the narrower gap limiting the formation of recirculation flows and slip.

There is no reason for the angle of the sheet to be constant along the length of the slotted tube. For example, a progressive decrease in both the slot angle and the slot pitch may provide a more efficient design as is commonly done in the design of pumping equipment.

![Figure 17: Performance of single vs triple helix](image)

### 3.9 Suction head

Preliminary gas flow measurements were carried out using a volumetric gas flow meter (American Meter Company AL-425) which provided a resistance so that a minimum gas flow was required to turn the tumblers. At lower gas flows, induced by the rotating liquid sheet, the gas meter acted as a seal and measurable negative pressures were developed at the gas inlet. Pressure and flow are synonymous and could be used interchangeably if the upstream and downstream resistances can be determined empirically. This was carried out by means of imposed flow/pressure measurements. Gas flow measurements using an anemometer (with essentially no upstream resistance) produced higher measured flows for a given experiment highlighting the known effect of suction head that exists for any axial fan system.

### 3.10 Sheet stability

As discussed above, the slotted tubes were initially operated in the open air using tap water running to drain to gain a first qualitative estimate of performance and the quality of the finish in the hand-honed slots. The oscillations (Raleigh instabilities) in the continuous sheet prior to ultimate breakup are apparent in the photo shown in Figure 18. Also clear from Figure 18 is that the sheet is stable over a much larger diameter (up to 1m commonly observed) than the current test facility column (diameter=0.15m). Flow
equivalence would dictate that a smaller slot gap would provide the correct breakup radius to match the test facility column, however, as discussed above, this has proved technically very difficult to accomplish and was a problem that did not need to be solved as our objective is to move to larger scales as soon as possible. This observation, more than anything, led to the decision to move to larger column diameters in the flow visualization test facility which matched directly the pilot plant columns.

![Figure 18 Outdoor testing of slotted tubes.](image)

### 3.11 Gap width – effect of tolerance and imperfections

In the first operation of the plastic triple blade it was evident that loose material (soft ‘fill’ plastic) had plugged small sections of some of the blade slots causing undesirable distortions or breaks in the liquid sheet. An important question is whether such distortions and breaks have a significant effect on the performance of the rotating liquid sheet to pump gas. The slotted tube (Pa3B) reported in Figure 13 was again thoroughly cleaned - a process that may have changed the characteristic of the slots and increased the slot diameter. The results at 25 Lpm liquid flow shown in Figure 19 indicate that at the higher flowrate, there is very little effect of the minor distortions and breaks on the induced gas flow. However, the cleaning process most likely resulted in a slight widening of the slot and this is most clearly seen in the minimum liquid flowrate that is required to induce a gas flow, as discussed in Section 3.4.
3.12 Entrainment of liquid droplets

For all experiments with the RLS contactor zero or negligible entrainment rates were detected. Operation with similar gas and liquid flows in an equivalent spray column generated measurable entrainment rates (experiments carried out in the early part of this work). On the other hand, operation of the fan to create a forced draft in the RLS contactor resulted in a more turbulent interface on the sheet but did not break up the sheet nor add to the entrainment rate as shown in Figure 20. This superior performance is attributed to the avoidance of spray generation in the RLS contactor and to the centrifugal nature of the flow of liquid and the induced flow of the gas creating an effect equivalent to a cyclone separator thus re-capturing the droplets that do form.
3.13 Mass Transfer

Direct mass transfer experiments of physical absorption and desorption on the RLS contactor were carried out by measuring humidity changes in various high concentration aqueous solutions of triethylene glycol (TEG) as described in Section 2. Surface area is estimated based on the projected annulus of the slot (equation 22 in Appendix E). In a typical result, shown in Figure 21, dry (approx. 5% humidity) compressed air from the laboratory supply is passed through a helix design RLS (5 turn single 22°helix) rotating at constant speed (440rpm and 530rpm). A power law fit (shown as the dotted line) gives a power law index of 0.31 and 0.45 respectively indicating a small but measureable effect of the gas flow. Given a constant driving force, the power law index values are slightly less than typical values for the gas side mass transfer coefficient applied to the gas velocity term (0.75 for Billet and Schultes (Billet and Schultes 1999).

Contrary to our expectations, changing the rotation rate did not significantly alter the mass transfer rate as seen by the typical result shown in Figure 22. The discrepancy between mass transfer measurements from different slotted tubes was mainly due to the uncertainty in the actual surface area. With a well defined mass transfer model, the mass transfer measurements could be turned around to determine actual (effective) surface areas.
The RLS contactor acts as a cross-flow contactor (similar to one stage of a tray column) but with residence times closer to that of a spray column. This feature may be more suited to fast reactions such as SO\textsubscript{2} scrubbing, pre-treatment of flue gases and solvent stripping, rather than for the slower amine absorption reactions. Control of the liquid sheet thickness is also seen as an advantage for CO\textsubscript{2} capture solvents that show advantageous kinetics and energy consumption but are too viscous to be used in conventional packed columns due to the fact that driving force for interfacial area formation in a packed bed is limited to that provided by gravity. For devices such as the RLS contactor (also rotating beds, etc.), the additional surface area per unit liquid volume that can be generated by the application of centrifugal energy can potentially overcome the disadvantage of lower diffusion in more viscous solvents as discussed in the next section.

### 3.14 Effect of Liquid Viscosity and Surface Tension

Measurements were carried out using water, and solutions of triethylene glycol (TEG) to provide a wide range of liquid test viscosities. Liquid test fluids with viscosities up to 50mPas and surface tension down to 44mNm were investigated. In all experiments the more viscous TEG solutions formed more stable sheets (due to the lower Reynolds Number). Mass transfer measurements at different viscosities indicated that the dominant effect was the surface area rather than the viscosity (and hence diffusivity). The ability to control the surface area per unit liquid volume in the formation of the liquid sheets, even for the more viscous solvents is overcoming the disadvantage of the higher viscosity.

### 3.15 Outcomes of experimental work and implications for scale-up

The key experimental results and the implications for scale-up are summarized below. The design concepts are outlined in Section 5.1 and described in detail in Appendix E.

(i) The rotating liquid sheet was able to achieve induced gas flow velocities matching that of conventional packed columns at modest rotation rates. Higher gas velocities are clearly possible from the results at higher rotation rates (additional operating cost) though it is of greater interest to increase the pumping efficiency through improved design. Note that the slotted
tubes used in experiments to date were designed for parameter evaluation rather than optimization.

(ii) The liquid velocity at the slot provided by the liquid pump must exceed the centrifugal velocity induced by slotted tube rotation. If this criterion is not met, the sheet breaks up at the slot exit and the induced gas flow falls rapidly to zero. At higher liquid flowrates, there is negligible effect of liquid flow on induced gas flowrate (as would be expected). When the liquid flowrate (slot velocity) falls below the centrifugal velocity, the tube begins to empty, the sheet breaks up at the slot exit (as in a rotary sprayer) and the induced gas flowrate falls to zero. This sets a design criterion for the slot width given that the L/G is fixed by the CO$_2$ capture process chemistry and performance demands.

(iii) The production of continuous unbroken liquid sheet of diameter exceeding 500mm (largest test section) has been proven experimentally and up to 1m in diameter may be possible as shown in unconfined (open air) experiments.

(iv) CFD modelling has shown that the liquid flow patterns within the slotted tube have a determining effect on the shape of the resultant liquid sheets and hence on the pumping efficiency. The CFD modelling provided optimized designs of the tube slots and internals to improve the shape of the liquid sheet developed.

(v) The multi-start helix design has proven to have the highest pumping efficiencies achieved experimentally. The multi-blade design was, however, considered to be further from an optimum design with higher rotation rates and overlapping blade rows seen as the way forward for this design type.

(vi) Turn-down is possible with the helix design using an adjustable central rod. Linking the rod positioner to a controller would provide constant slot velocity and match liquid flow to a variable CO$_2$ flow from the power station.

(vii) It is technically feasible to match the interfacial area of packed beds (with random or structured packing) using multi-start helices or multi-start blades. Unlike the packed bed, all of the surface area is 'effective' area and available for mass transfer provided that the liquid sheet is continuous. However, making small scale versions of sufficient rigidity and strength proved challenging. This problem goes away at larger scales.

(viii) Forced draft experiments created turbulence in the liquid sheet, but did not break up the sheet nor add significantly to the entrainment. Therefore flooding (in the sense of what occurs in the packed bed) does not appear possible in the RLS contactor. This finding leads to the expectation that much higher gas velocities are achievable in the RLS contactor by combining the rotating contactor induced gas pumping with forced draft assist. The pressure drop through the entire column would still be minimal as discussed in Section 5.

(ix) Mass transfer rates are slightly affected by the gas rate but not by the rate of rotation (as hoped). Mass transfer rates are assumed to be only a function of the available surface area in the design procedure.

(x) The down-flow of liquid at the wall induces an undesired down-flow of gas. This was countered in the new column designs by separating the liquid flow from the gas stream as soon as possible.

(xi) The effect of the suction head, which is common to any axial fan system, implies that careful consideration must be made of the gas train inlet. A PCC plant (including any pre-treatment) would be placed downstream of the induction fan in a balanced draught furnace system. A slight positive pressure exists at the inlet point (though not enough to overcome the flow resistance of a conventional PCC plant). Similarly a slight negative pressure exists at the return point which is usually the base of the existing chimney. Note that the lower return temperature of any PCC plant may affect the natural draught of existing power station chimneys – an effect that must be taken into consideration in any retrofit design.
4 Computational Fluid Dynamics Modelling

4.1 Introduction

The computational fluid dynamics (CFD) flow modelling work performed as part of this project can be divided into three components:

1) Modelling of gas flow around a solid auger blade

This work examined the flow of air around a solid helical surface to provide insight into the fluid mechanics of the gas phase in an idealised case of a solid (rather than liquid) helical sheet. Model simulations of this type are denoted as “MSBxxxx”, meaning “Model – Solid Blade”.

2) Optimisation of flow through the slotted centrebody

This work analysed the liquid flow features in a large number of different centrebody geometries and identified characteristics that led to ideal flow behaviour through the centrebody slots. Model simulations of this type are denoted as “MCFxxxx”, meaning “Model – Centrebody Flow”.

3) Modelling of a full-scale RLS contactor geometry

The full-scale RLS contactor was analysed for key features of the flow, such as flow patterns and pressure loss through the centrebody, profile of the liquid sheet, and pressure losses of gas passing through the sheet. Models were performed as air only (MSB), liquid only (MCF) and also two-phase air/water simulations (MTPxxxx, meaning “Model – Two Phase”).

Details of the modelling campaign are provided in Appendix D. A summary of key aspects of the work is given here.

4.2 Modelling of gas flow around a solid auger blade

Throughout the modelling investigations of the RLS contactor it was clear that modelling gas and liquid phases simultaneously would be very challenging. Therefore idealised cases were investigated to provide insight into different aspects of the contactor operation.

In the first instance the fluid mechanics of the gas flow was investigated, and the helical liquid film was modelled as a thin solid sheet. An example model geometry, based on the dimensions of the air/water pilot scale experimental apparatus, is shown in Figure 23. Details of the model setup are given in Appendix D.

Using this model, not only could the gas mechanics be predicted in this idealised case, but the effect of varying the helical pitch and rotation speed could be investigated.

Figure 24a shows the predicted flow pattern of air passing up through the solid rotating auger blade. From this image the flow appears to be close to vertical for the majority of the flow passage. The central passage has a velocity equal to approximately 0.5 m s$^{-1}$, while it is higher towards the central tube (0.75 m s$^{-1}$) and higher still in the outer regions of the flow passage. Some recirculatory flow is predicted to occur near the outer surface of the flow passage. Also, as a consequence of the way the model was set up, there was a small (1 mm) gap at the outer surface of the flow passage between the auger blade and the wall itself, and a higher velocity air flow is predicted to occur through this gap. In the real system the solid auger blade is in fact a liquid film, and the liquid accumulates and then falls down the outer wall of the flow passage, so such a gap will not exist.

In Figure 24b the velocity distribution from Figure 24a is viewed from above, showing the tangential component of velocity. The velocity has a swirling component that is largest at the higher radii, although it is still much less than the tangential velocity of the auger blade itself.
Figure 23 Solid auger blade model - Isometric view of entire geometry as modelled for runs MSBa1H6, MSBb1H6, MSBc1H6
By stretching the geometry of the model it was possible to investigate the effect of varying the pitch of the auger blade. Investigations were performed using a 2-fold and 4-fold stretch, giving pitch variation from 23.2 mm up to 46.4 mm and then 92.8 mm. The parameter of interest in the comparison was the amount
of air driven through the geometry when the auger blade was rotated. A theoretical maximum value \( V_{\text{max}} \) could be determined corresponding to the vertical velocity of the auger blade,

\[
V_{\text{max}} = \frac{\text{pitch} - \text{blade thickness}}{\text{rotation rate}},
\]

then the efficiency of the device can be determined from the predicted average axial velocity of air through the auger blade normalised by \( V_{\text{max}} \) \( \left( \frac{V_{\text{av}}}{V_{\text{max}}} \right) \), as shown in Figure 25. The intermediate pitch (46.4 mm) in this case provides the maximum efficiency for driving the air. However, of interest is that there is a pitch that provides a local maximum. It is difficult to quantify what the geometrical conditions are that give a maximum efficiency. Analysis of the auger blade angle is troublesome, since with a solid auger blade geometry as defined here the angle changes with radial distance from the centreline. However, it is clear that using either of the extreme pitch values of 0 mm (horizontal rings) or else a very large pitch (giving longitudinal blades) would both be expected to give zero flow through the device, so some intermediate pitch should give the maximum efficiency.

As a first approximation, many of the future designs that were investigated used a pitch angle of 45° at the tube outer surface, this being the mean of 0° and 90°, the two extreme cases.

### 4.3 Optimisation of flow through the slotted centrebody

The key idea in the RLS contactor design was to have liquid flow through a slot that created a liquid sheet, over which gas could pass and mass could transfer from gas to liquid. By creating a helix or screw-type structure to the sheet it is possible to rotate it and allow pumping of gas through the system. Thus the fundamental design involved a helical slot in the wall of a central tube (see Figure 26a). Many variations on this basic design were then investigated. They included:

- The thickness of the centrebody wall \( T_{\text{wall}} = \text{d}_{\text{outer}} - \text{d}_{\text{inner}} \), see Figure 26
- The thickness of the slot \( t_{\text{slot}} \)
- The angle of the slot relative to the centrebody axis \( \theta_{\text{pitch}} \)
- The overall length of the slot
- The number of “starts” (i.e. the number of slots along a single length of the centrebody. Figure 26a shows a single start geometry, whilst Figure 26b and Figure 26c each show a four-start geometry)
- The number of “rows” (i.e. the number of times the slot design is repeated along the centrebody. Figure 26b shows a geometry with three rows)
- The existence (and diameter) of a rod passing down the centre of the centrebody (used to hold the structure in place)
- The profile of that central rod (e.g., should it be tapered or straight? Which way should the taper go?)
- The slot profile (i.e. should the thickness of the slot be constant, or should it vary along its length? If so, how should it vary?)
- The slot entry profile (i.e. should the slot vary in thickness from the inside to the outside of the tube?)
To allow comparison between geometries it was necessary to define the criteria that govern optimal flow behaviour. The criteria that were considered were:

- a uniform flow through the slots along their entire length.
- a controlled flow direction out of the slots, close to horizontal or else slightly upward.

These criteria were thought to ensure that the RLS contactor could produce reliable results at all scales, as well as allowing appropriate spacing between each sheet for gas flow.

Figure 26 shows the three main geometries considered. Note that the images show the region through which fluid can flow, rather than the material that actually makes up the slotted tube itself. Full details of the model are provided in Appendix D. Key findings are summarised here.

For all geometries investigated, the flow rate was greatest through the lower regions of the slot, with reduced flow in the upper regions. The non-uniform distribution became more pronounced with increasing wall thickness. Slight variations in uniformity could be gained through changing the slot thickness along its length or else including a taper along the central rod. However, the overall trend of an increase in flow at lower regions of the slot could not be eliminated.

In all geometries investigated, liquid was predicted to be directed slightly downward upon exiting the slot. This effect was greatest in the initial (upper) region of the slot, meaning that there would be a tendency for upper regions of the helical sheet to be directed onto lower regions of it. It was possible to minimise this effect by including horizontal ribs across the slot at several locations along its length.

The number of starts for the geometry controls the total flow of liquid through the system and the available gas-liquid contacting surface area. However, it does not affect the flow dynamics of the system.
Use of continuous slots (Figure 26a, Figure 26c) is preferable over several rows of shorter slots or blades (Figure 26b). This is because end effects of the slots disrupt the uniformity of flow, so having fewer slot ends produces a more uniform liquid sheet.

Profiling of the slots was necessary to increase uniformity of flow through the slots, in particular at either end of the slot to streamline end effects.

It was found that the use of horizontal ribbing across the slots enabled the fluid to exit the slots in a direction closer to horizontal. Figure 27 shows the calculated flow paths and exit velocity profiles for a geometry using three rows of four short helical slots, with and without horizontal ribbing across the slots. Run tbC (Figure 27a-c) shows the results without ribbing. Figure 27b demonstrates how the streamlines of the fluid travel diagonally downwards through each slot, so that the velocity vectors at the slot exit (Figure 27c) also have a downward component. This is particularly the case in the upper and middle rows of slots, where the velocity vectors are uniformly blue, indicating a downward component of velocity equal to approximately 1.25 m s\(^{-1}\). The lower row of slots have velocities between yellow and green, indicating downward velocity component of between 0.0 and 0.5 m s\(^{-1}\).

![Diagram of flow paths and exit velocity profiles](image-url)
With ribbing in place across the slots (Figure 27d-f) the streamlines entering each slot are closer to horizontal, and the vertical component of the exit velocity is between 0.0 and 0.5 m s\(^{-1}\) for all rows of slots. The velocity distribution is predicted to be less uniform with ribbing in place due to the interference the ribs contribute to the flow field. However, a more streamlined rib would be expected to provide a more uniform exit velocity. Experiments using a modified form of the geometry in Run tbD (Figure 27d-f) indicated that the exit velocity produced a uniform and stable liquid sheet, with a near-horizontal exit velocity.

4.4 Modelling of a full-scale RLS contactor geometry

Following calculations performed on a potential full-scale RLS contactor, a series of CFD models of this geometry were constructed to determine pressure loss and other characteristics of the device. The geometry of the centrebody is shown in Figure 28. Figure 28a shows the centrebody of length 1000 mm, using a 13-start continuous helical slot configuration. The geometry inlet is shown in Figure 28b, giving more detail of the slot arrangement around the centrebody. The surface mesh is shown in Figure 28c, with the very fine slot width of 0.09 mm shown. The model resolution across the slot is 8 cells.

Figure 29 shows some of the key exit features of the design. Figure 29a shows the velocity vector distribution out of one slot, and the vector magnitude is nearly constant for the entire length due to the very narrow slot width. The vectors are coloured by the vertical component of velocity, and again they are all shown to be directed slightly downwards. However, the magnitude of the vertical velocity is in this case between 0.00 m s\(^{-1}\) at the base of the unit, increasing to -0.25 m s\(^{-1}\) in the entrance region.

Figure 29b shows select streamlines passing through the centrebody and exiting through a particular slot. The streamlines are coloured by the local fluid pressure, and show that the pressure is almost constant within the centrebody, while almost all of the pressure loss occurs through the slot.

Figure 30 shows output from a model of the liquid film emanating from one of the slots. Figure 30a shows successive images of the film as it forms. Figure 30b shows a vertical slice through the modelled geometry, with the volume fraction of water depicted with coloured contours. Thus the dark blue region is air, and other colours represent the liquid film. It can be seen that, as the model resolution decreases farther from the slot, the stability of the solution is compromised and the liquid film is shown to waver. The trajectory of the stable component of the liquid film was digitised and plotted on the graph in Figure 30c. A parabolic line-of-best-fit was then superimposed over the trajectory, and the fit is very good. Thus it is reasonable to assume that the film follows a parabolic path dependant on the exit velocity of liquid through the slot.
Figure 28  CFD model of full-scale RLS contactor: 1000 mm section

Run MCFa13H

(a) 13-start (i.e. 13 equally spaced helical slots)

height = 1000 mm

(b) Wall thickness = 5 mm

$D_{inner} = 100$ mm

(c) Slot thickness = 0.09 mm
Figure 29  (a) Slot exit velocity vectors for one slot, coloured by vertical component of velocity; (b) Streamlines exiting one slot, coloured by local fluid pressure – Run MCFa13H
Figure 30 Film trajectory as predicted by CFD: (a) successive images of film; (b) vertical slice showing film trajectory; (c) parabolic line of best fit applied to film trajectory – Run MTPa13H
5 Design, scale-up and commercial implementation

This section briefly outlines the design procedure for the RLS contactor; discusses the scale-up issues for the possible implementation of this technology at the massive scale required for PCC; provides a preliminary module design for implementation at a PCC Pilot Plant and a proposed flow-sheet for implementation of a full scale unit equivalent to a packed bed.

While this technology is still in the development phase (between PDU and Pilot scale testing), sufficient information has been gained from this project to make an assessment of the performance at commercial scale and to propose a conceptual design at both Pilot and commercial scales. Results of CO\textsubscript{2} capture from power station flue gas by an RLS module installed in a PCC Pilot Plant would provide further technical and economic validation relating especially to controllability, component reliability and design performance to be applied to further scale-up.

5.1 Outline of RLS contactor design procedure.

The basic equations governing fluid flow in the RLS contactor are quite straightforward and are developed in this project in a way that allows direct comparison to an equivalent segment of a conventional random or structured packing. The design procedure can be summarized as follows. The detailed development of the design equations and example calculations are provided in Appendix E.

(i) The chemistry, gas and liquid compositions and performance criteria determine the range of gas to liquid ratios (L/G) for the operation of each of the contactors. In PCC processes this range proves to be very narrow for a given application.

(ii) Conventional packed bed calculations determine the required surface area for mass transfer and gas specific mass flowrate at the load point of the selected packing. These become the target values to be matched by the RLS contactor or exceeded by a given factor. The rate at which gas can be induced to flow through the RLS contactor is determined by the slot angle, the rotation rate and pumping efficiency. If there is to be no external gas pumping and the slot angle is set to an optimum value (Section 4), then in a design of given pumping efficiency, the required gas rate sets the rotation rate. Since L/G is fixed this calculation also sets the liquid rate.

(iii) The liquid sheet must travel, unbroken, to the wall of the column and the liquid velocity at the slot outlet must exceed the centrifugal velocity at this point, thus providing criteria for the minimum slot velocity.

(iv) Geometric considerations of the shape of the sheets determine the interfacial surface area per unit volume of the column gas space which can be compared to the target as set by the conventional random or structured packing. The total surface area of the liquid sheets for a given slot angle, can be increased by increasing the number of starts (helix design) or height and number of blades in each row and degree of overlap of rows (blade design). Note that both sides of the liquid sheet are in contact with the gas. Figure 31 shows such a calculation for the multi-start helix design and compares the surface area per unit total volume of the RLS contactor to quoted values for examples of conventional random and structured packing. Now that total liquid rate, slot exit velocity and total slot length has been set, the slot width can be determined.

(v) The liquid sheet now travels to the column wall becoming thinner in direct proportion to the radius travelled. At each point the criteria of stability must be applied to determine if the sheet will break up into droplets. An iterative process is now required to achieve the desired sheet stability. Given that the fluid properties also strongly influence the sheet stability, altering these properties of the capture solvent may also be advantageous.
5.2 Scale-up issues

The obvious question to ask regarding scale-up is whether the limited diameter of a single RLS contactor module can be developed into the largest technically possible gas-liquid contactors that would be required for commercial implementation of PCC. We have observed stable liquid sheets up to 1m diameter but this limit has not been pushed in rigorous investigation. However, the physics of a radially expanding sheet of liquid dictates that the sheet must break up into droplets at some point and this is a far cry from the tens of metres required for commercial scale PCC contactor columns.

A possible answer, illustrated in Figure 32, may be to place modules side by side in such a way that the interaction of the falling films seals the gas preventing the gas stream from by-passing the pumping action of the rotating liquid sheets. An hexagonal pattern of adjacent modules is appropriate as this provides a natural stability (as in the honeycomb or convection cell). If a stable coalescence of adjacent liquid sheets can be achieved, thus providing a gas seal between adjacent modules, then there is no physical limit to the diameter of the composite device. A plan is in place to test such an arrangement but this is outside the scope of this project. The discussion below assumes that this issue has been resolved from a technical stand-point.
A second scale-up issue is that a single module acts as a single equilibrium stage. This is because the liquid travels in a cross-flow pattern normal to the flow of the gas – as is the case in a conventional tray column. Unlike the tray column, where the liquid continues to travel from stage to stage under gravity, in the RLS contactor, the liquid must be collected and re-pumped to the slotted tube of the next stage counter-current to the gas. It is anticipated, therefore, that multiples of the device described above are arranged in such a way that an overall counter-current flow occurs between the gas stream and the liquid stream to create a multi-stage operation (as would have to be done for a spray column). The gas stream travels directly between adjacent modules (with minimal pressure drop) or is ducted suitably. The liquid is collected at the vessel wall in a suitable reservoir and re-pumped to the next module in the sequence as shown in Figure 33.
5.3 Savings and Costs at commercial scale

The implementation of RLS contactor technology at commercial scale can be envisioned to lead to capital and operating cost reductions of PCC plants on a number of fronts as detailed below, based on the results of this project. Cost savings are based on estimated changes to equipment sizes and power consumption and are relative to the baseline costs as detailed in the DOE/NETL 401/11907 (Case 1) study (Ramezan, Skone et al. 2007). This baseline cost information is outlined in Appendix A and discussed in Section 1. Figure 34 illustrates the breakdown of total capital cost by major equipment item for this baseline case.

![Figure 34 Baseline relative cost of a retrofitted PCC plant capturing 90% of CO2 emissions highlighting components affected by improved contactor design.](adapted from DOE/NETL 401/110907 Case 1 (Ramezan, Skone et al. 2007))

The following two sections detail, firstly, the potential cost savings and, secondly, the additional costs (e.g. motors, pumps, bearings) of implementing the RLS contactor technology. Clearly the costs savings must outweigh the extra costs to make implementation of this technology an attractive investment.

### 5.3.1 COST SAVING COMPONENTS

The following design parameters can lead to cost reductions with the successful implementation of the RLS Contactor.

(i) Elimination of the packing material which represents approximately half the packed column cost (Peters, Timmerhaus et al. 2003) can be achieved as the multi-start designs can readily match the gas-liquid interfacial surface area of conventional random or structured packing (Figure 31).

(ii) Reduction in column height due to improved mass transfer performance directly reduces the height of the column. For very tall columns, the cost saving is essentially linear in height.

(iii) Gas velocities exceeding those found in conventional packed beds represent a cost saving arising from reduction in diameter (and possibly column wall thickness – not considered here). Figure 35 provides a simple estimate of the cost saving achieved by reducing the column diameter based on the effect on column weight, with the cost of the column and associated structure.
assumed proportional to total weight. To realize this saving, the RLS contactor must pack the equivalent surface area into the smaller diameter column.

(iv) Reductions in column height and diameter and the removal of the packing would also have the effect of reducing the column weight and hence the cost of structure and concrete pad. At the preliminary budget stage, this cost is a multiplier to the total cost of the Major Equipment Items (MEI), which of course includes the columns.

(v) The reduction in flue gas pumping requirement leads to significant savings in both capital and operating cost.

(vi) Experimental results show that the cyclonic action of this device significantly reduces droplet entrainment rates. This may result in lower post-treatment costs, however, this is not included in the analysis.

![Relative Cost- estimated as steel surface area](image)

**Figure 35 Potential savings from increasing the gas velocity (ideal case)**

5.3.2 ADDITIONAL COST COMPONENTS

The following additional costs are imposed by the implementation of the RLS contactor at commercial scale.

(i) The use of rotating equipment is always problematic and this is especially true in the presence of aggressive solvents (amines), corrosive impurities (SO$_2$, NO$_x$) and particles (residual ash). The potential problems of a rotating tube with fine slots, bearings, seals should therefore not be underestimated. Identifying these problems is properly the role of Pilot scale testing as proposed in Section 6.4.1. These technical difficulties are not unknown in the gas processing and petrochemicals industries and in this analysis it is assumed that suitable engineering solutions can be found at acceptable cost.

(ii) The cost of rotating equipment can be related to the power to accelerate of the liquid in the slotted tube shaft. Modelling shows that this is approximately 10% of the equivalent cost (power consumption) of flue gas pumping per module. Assuming five equilibrium stages, the
cost of the rotating equipment is 50% of the cost of the flue gas pumping equipment in a conventional PCC plant (hence 25% of the total power cost).

(iii) The additional cost of pumping between stages is modelled by considering the power requirements to provide the additional pumping pressure. Since liquid must be pumped to the top of a conventional packed bed, only the power to provide the additional pumping pressure is costed.

5.3.3 POTENTIAL FOR REDUCTIONS IN CAPITAL AND OPERATING COSTS

Appendix A sets out the baseline cost analysis based on Case 1 of the DOE/NETL study (Ramezan, Skone et al. 2007) These baseline costs formed the basis of the argument that a novel gas-liquid contactor design was required that would break through the barriers imposed by conventional contactor designs. These limitations are discussed in Appendix B. The development of design equations for the RLS contactor and example calculations relating to equipment sizes and costs are set out in Appendix E and are summarized in Table 2 below.

Table 2 Summary of relative cost factors
[Details of calculations are provided in Appendix E]

<table>
<thead>
<tr>
<th>COSTS / SAVINGS COMPONENTS</th>
<th>1m diam column (Leva)</th>
<th>1m diam column (Billet &amp; Schultes)</th>
<th>2x Velocity</th>
<th>5x Velocity</th>
<th>2x Velocity</th>
<th>2x Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packing comparison</td>
<td>2&quot; Pall Rings</td>
<td>2&quot; Pall Rings</td>
<td>2&quot; Pall Rings</td>
<td>2&quot; Pall Rings</td>
<td>Mellapak 125Y</td>
<td>Mellapak 350Y</td>
</tr>
<tr>
<td>Velocity factor</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Packing reqd.</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Packing cost (%of column total)</td>
<td>50%</td>
<td>50%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Vessel Diameter</td>
<td>100%</td>
<td>100%</td>
<td>71%</td>
<td>45%</td>
<td>71%</td>
<td>71%</td>
</tr>
<tr>
<td>Vessel cost saving</td>
<td>0%</td>
<td>0%</td>
<td>29%</td>
<td>55%</td>
<td>29%</td>
<td>29%</td>
</tr>
<tr>
<td>external FG blower reqd.</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Power for volume equiv blower [kW]</td>
<td>0.4804</td>
<td>0.4804</td>
<td>0.9608</td>
<td>2.4021</td>
<td>0.9608</td>
<td>0.9608</td>
</tr>
<tr>
<td>Total RLS power [kW]</td>
<td>0.0207</td>
<td>0.0097</td>
<td>0.0868</td>
<td>5.9140</td>
<td>0.0630</td>
<td>0.0174</td>
</tr>
<tr>
<td>RLS/Packing power</td>
<td>4.32%</td>
<td>2.03%</td>
<td>9.04%</td>
<td>246.2%</td>
<td>6.56%</td>
<td>1.81%</td>
</tr>
<tr>
<td>Possible # stages</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Total Power (cost) RLS/Packed Bed</td>
<td>21.6%</td>
<td>10.1%</td>
<td>45.2%</td>
<td>1231%</td>
<td>32.8%</td>
<td>9.0%</td>
</tr>
</tbody>
</table>

From these example calculations the following conclusions can be drawn on possible cost savings and additional costs for the implementation of the RLS contactor.

(i) In the design procedure for the RLS contactor the total interfacial area is set to equal to that of the equivalent segment of packed bed column with random or structured packing. It has been shown that with a reasonable number of starts in the helix design or the equivalent number of rows in the blade design, that the surface area of conventional packing can be matched. Given that the mass transfer is based on surface area, then it reasonable to conclude that the removal of the packing can be counted as a direct cost saving. To achieve this, the RLS contactor must achieve the same surface area per unit height by having a equivalently higher surface area in the smaller diameter column.
It has been shown that the gas flowrate generated by the rotation of the liquid sheet can match those of the packed bed in simple non-optimized geometries at modest rotation rates. It is considered reasonable to extrapolate gas flowrates to twice that of conventional packing by higher rotation rates or, more appropriately by improved design leading to higher pumping efficiencies. A potential doubling of the gas velocity (achievable by increased rotation rates, but more appropriately by improved pumping efficiency) would lead to a column cost reduction (weight of steel) of approximately 30%.

Given that a significant increase in mass transfer was not seen on the application of rotation, no savings from reduced height are claimed in the costing. It is also necessary to match the surface area to the packed bed sized to process an equivalent amount of gas. This leads to the ridiculous value for total power in the 5x Velocity target case seen in Table 2. A compromise design would lead to more sensible numbers, while improved mass transfer would make the design more realistic.

The cost of the central slotted tube and drive mechanism is determined by the power requirement for rotation and for liquid pumping beyond the requirement to exceed the centrifugal velocity (discussed in Section 3.5). The power required to form the liquid sheets in a given unit volume is an order of magnitude less than that required to pump gas through the same volume of packing (primarily due to the significantly less tortuous path for the gas). Assuming five equilibrium stages, the cost of the rotating equipment is 50% of the cost of the flue gas pumping equipment in a conventional PCC plant.

The cost for externally pumping the gas is based on the pressure drop for gas to pass between adjacent sheets of the RLS device. This applies in cases where higher gas flowrates are required than can be provided by the rotation of the liquid sheets alone (as is assumed to be the case for the five-fold increase requirement in gas velocity). As discussed above a compromise design is required.

The additional pumping requirements for multiple modules is accounted for by assuming that, in the case of the RLS contactor, as with the spray column, each module is a single theoretical plate and the liquid must be collected and redistributed a number of times. Given that 4-5 theoretical plates are typical for an absorber, we allow this number of modules aligned vertically. The cost of rotating equipment for the RLS contactor and additional cost of liquid pumping can then be pro-rated against the avoided cost of the flue gas blower based on power requirement. The overall savings are 2.5% of capital and 25% of the electrical cost (operating cost).

The flue gas blower represents 5% of the capital and draws 50% of the electrical load of the capture process (discounting CO₂ compression). With no benefit from the pumping ability of the RLS contactor there is still a significant saving due to the reduction in the pressure drop compared to that required for the packed bed. The gas is assumed to travel in the helix path between liquid sheets. Apart from the energy saving, it may be possible to replace the flue gas blower with an axial fan at approximately one tenth the cost.

Further increase in gas velocity (stretch target of 5x conventional) may be possible based on experimental results that show that the cyclonic action of this device significantly reduces droplet entrainment rates and that forced draft does not break up the liquid sheet. It is clear from Figure 35 that there are diminishing returns from increasing the rotation rate in an effort to reduce column diameter. A break-even point therefore exists as gas velocities are increased. It is assumed in this analysis that a limit of 1200rpm is imposed on the rotation rate (the limit of our experimental equipment) and that further increases in gas rate are achieved by external pumping. Achieving a 5x target would reduce column diameters by 55% corresponding to an overall column cost reduction of 25%, however a sensible design is predicated on a compromise between the surface area requirements (vessel size) and the power requirements.

The impact of the savings and costs for the case of a doubling of gas velocity are shown in Figure 36. This should be compared to Figure 34 which illustrated the baseline costs. Overall the capital cost savings (on
conservative targets) are approximately 30% assuming 2x conventional gas velocity applied to all columns, complete elimination of the flue gas pump and a multi-module RLS contactor system with recycle.

Figure 36  Estimated cost savings through implementation of RLS contactor technology – impact on the cost of various components (refer to text for assumptions made in the analysis). Total savings are 33.5%.
6 Business Development and Future Work.

6.1 IP Register

The following is the status of the IP Register at the close of this project. The unique nature of the device under investigation has meant that very little in the way of conflicting IP has been found, despite extensive searching. There are no immediate plans to create further patents from the results, however, material from this project could support further invention developed during possible pilot scale testing.

6.1.1 PRE-EXISTING MATERIAL

The concept of the Rotating Liquid Sheet (RLS) contactor was developed and patented by CSIRO (Wardhaugh, Chase et al. 2012) prior to this project agreement.

6.1.2 THIRD PARTY MATERIAL

There was no 3rd party confidential material used in this project.

6.1.3 AGREEMENT MATERIAL

This report provides the technical outcomes of this project.

6.1.4 OTHER RELEVANT MATERIAL

Although there is no known outside work on devices in any way similar to the RLS contactor, the following developments, patents and published literature are, however, of particular interest:

i. The Neustream® contactor device which utilizes vertical streams of liquid and higher gas velocities in a compact contactor device.

ii. Research into the various absorptive cooling devices face the same technical and cost challenges that the RLS contactor device addresses. (Palacios, Izquierdo et al. 2009)

iii. Research into the various rotating contactors where the solid surfaces are rotated (i.e. later generations of the ‘Higee’ device) e.g. (Wang, Fei et al. 2002, Chen, Lin et al. 2005, Jassim, Rochelle et al. 2007).

6.2 Business Development

Presentations concerning the RLS contactor have been made to the following conferences and organizations. In all cases considerable interest was shown in the concept.

1. 7th Trondheim Conference on CO₂ Capture, Transport and Storage (TCCS-7), 5-6 June 2013, Trondheim, Norway.
2. University of Texas (Rochelle Research Group)/NTNU (Prof. H. Svendsen) joint meeting, 7 June 2013, NTNU, Trondheim, Norway.
3. IFP Energies Nouvelles - Chemical Engineering Dept., Solaize, France, 10 June 2013
IFPEN carried out a feasibility study to determine whether an RLS module could be incorporated into one of their extensive testing facilities. At this stage, however, off-site construction costs and operating schedules precluded this option.

Market assessments in this specific technology area are being undertaken under the leadership of David Lambourne (CSIRO IP & Licensing). Business development continues under the umbrella of the PCC project stream under the leadership of Paul Feron with assistance from Meity Mandagie.

6.3 Outstanding technical challenges

The following lists what we see as the outstanding technical challenges between our present position and full commercial realization:

- The primary scientific challenge is to optimize the design so that it can operate effectively at the massive scale required by full-scale PCC, a challenge which is not unique to this technology. A scheme for parallel operation (within a single column) is proposed that may solve the scale-up problem. This concept has been outlined in Section 5.2.
- Rotating equipment always adds complexity and maintenance cost. An assessment of the extent of this issue can be made at the pilot scale but is difficult at the laboratory scale at which we have been working. Capital cost estimates are based on models of power consumption and assume that these difficulties, not unknown in the process industries, have been adequately solved.
- Further improvements in pumping efficiency seem likely with further improvements in tube internal design (improved liquid flow patterns), improved gas inlet design and multi-start slot design.
- The short liquid residence time of the RLS contactor (similar to the spray column) may yet prove an impediment to the slower CO$_2$ capture reactions, but may be highly suited to implementation in the pre-treatment column where SO$_2$, NO$_x$ and residual ash are the intended capture targets. Alternately, a recycle of solvent is possible and allowance has been made for this in the costing assumptions. This aspect would be tested at Pilot scale.
- The question of whether the RLS technology is suitable for the stripper column has not been addressed. There is no technical reason why it should not be suitable as the basic physics remain the same. Experimental results with desorption of water from concentrated TEG using dry air are encouraging. There may be advantage in recycling heated solvent to or through cooler parts of the stripper column as currently practiced in ‘inter-heating’ process improvements.

The next proposed stage of development is to construct and test a module at pilot scale on flue gas slip stream derived from a coal fired power plant (at one of CSIRO’s operating pilot plants or potential vendor). A conceptual design is provided in Section 6.4.1. It is intended that further testing and design optimization will be carried out on the existing larger scale flow visualization rigs and using CFD modelling as part of (proposed) strategic CSIRO PCC Novel Processes project. The concept of parallel operation will also be tested on a simple rig.
6.4 Further development

6.4.1 PROPOSED PILOT SCALE MODULE DESIGN

The obvious next step for further development of the RLS contactor is to incorporate a contactor module into an existing PCC Pilot Plant. The purpose of the test campaign would be to provide operational data over extended time periods under a range of operating conditions. The information collected would provide greater clarity on the economics of this device in comparison to other gas-liquid contactors and provide an opportunity to solve technical issues such as the impact of impurities, corrosive environments, controllability and turn-down. The module could be designed to be incorporated into an existing pilot plant column, or as a stand-alone modular system. The latter has the advantage of being able to receive gas and liquid feed from a variety of sources representing raw flue gas, pre-treated flue gas, partially or completely processed flue gas. As such, the pilot test facility would be able to assess the RLS contactor device in a pre-treatment; absorption; or post-treatment role. The addition of a heater (reboiler) at the base of the module would allow the RLS contactor to be assessed in the role of desorber (stripper).

A detailed experimental programme could look at the following operational and design aspects:

(i) Long term operability under steady state conditions. This would consider, in particular, the long term effects of corrosive components and of solids (e.g. residual ash, corrosion and solvent degradation products).

(ii) Turn-down and operability issues in the face of varying input conditions, especially flue gas composition, flowrate and properties.

(iii) Back-to-back comparison with existing contactor columns fitted with random or structured packing.

(iv) Performance data allowing more accurate commercial scale design and costings to be completed.

Figure 37 provides a sketch of a possible module suitable for the CSIRO-Delta Electricity Pilot Plant located at Vales Point power station.

![Figure 37 Sketch of proposed RLS contactor module at Pilot Plant scale](image)
6.4.2 PROPOSED COMMERCIAL DESIGN

To reach commercial scale questions of design and scale-up, as discussed previously, are assumed to have been resolved with suitable Pilot scale and further laboratory testing and modelling having been completed. It is clear that a modular design is required both vertically (or countercurrent to the gas flow) and in parallel (normal to the gas flow) since a single module, comprising a single radius of liquid sheet, has a limited extent in width and acts in cross-flow (as in a tray column) requiring multiple stages. It is presumed that this can be achieved with minimal structure contained within a single vessel that operates at essentially zero pressure as the device generates its own flow. The vessel could be a conventional steel vessel, or ceramic lined concrete as has been installed in the Boundary Dam demonstration plant in Saskatchewan.

Figure 38 illustrates the arrangement of modules that might occur in a commercial scale contactor column. Note the possibility of inter-cooling (or inter-heating) that might occur between one or more stages which would require only the addition of suitable heat exchangers.
7 Conclusions

7.1 Objectives and Outcomes

This 2 year project commenced on 25 May 2012 and was resourced at 1.5 FTE (full-time equivalents) per year through this time, to achieve the two main objectives summarized as follows:

1. To prove that the concept of the Rotating Liquid Sheet contactor has the technical potential to compete favourably with conventional packed bed contactors in PCC applications with the target of doubling the flue gas velocity.

Experimental work was carried out on a 150mm and a 500mm diameter Flow Visualization Test Facility to provide an understanding of the parameters that influence the performance of various designs of the RLS contactor. The primary technical challenge has been to determine slotted tube designs that would provide continuous stable liquid sheets across the column diameter then, on rotation, would give high induced gas pumping rates. Successful operation was achieved with the 500mm diameter test column (directly equivalent to Pilot Plant absorber column sizes). Gas flowrates, induced by the rotation of well formed liquid sheets, could be achieved matching velocities seen in conventional packing. Given that these results were from simple non-optimized designs it was reasonable to extrapolate to velocities twice that of conventional packing by increasing the rotation rate, or, more appropriately, improved designs that increase the efficiency of gas pumping at modest (<1200rpm) rotation rates. Model calculations have provided estimates of the capital and operating cost savings for this operation. Cost savings come predominantly from the deletion of the packing and from a reduction in column diameter. Net capital savings, after an estimate of the extra costs of the RLS contactor are approximately 30%

2. To utilize the larger diameter flow visualization columns to collect experimental data to establish the full-scale potential of the concept and to show whether the stretch target (5-fold increase in gas velocity) was feasible and whether this would lead to further cost savings.

Experimental results showed that there are diminishing returns in continuing to increase rotation rate as the means to achieve higher gas flowrates. Therefore the 5x target could possibly be achieved with the use of a forced draft fan to provide some of the pressure balance. Normally such high gas velocities would be impossible in the packed bed, which suffers from flooding at high gas rates, or the spray column, in which entrainment becomes excessive at high gas rates. However, the RLS contactor appears to have a wider operating range based on two experimental observations. Firstly, although the surface area per unit volume of the RLS contactor matches that of the packed bed, the pressure drop is more like that of a spray column allowing higher throughputs without back resistance. Secondly, the cyclonic action of the device significantly reduces entrainment of droplets at these higher rates. It appears likely that, with further refinement at larger scales, this goal could be achieved or exceeded.
Appendix A  Analysis of Capital and Operating Cost Components

This appendix studies the available literature relating to the design and detailed costing of proposed full-scale PCC plants with a view to understanding which of the unit operations contributes most to the capital and operating costs of a PCC plant.

Detailed engineering and costing studies have been carried out on proposed PCC plants as a retrofit as part of the DOE/NETL-401/110907 report (Ramezan, Skone et al. 2007) or as new facilities (Black, Haslbeck et al. 2013). The study by Ramezan et.al. in particular provides an understanding of the components of the plant that contribute to these costs, an understanding of the engineering parameters that must be changed and the limitations that must be overcome to reduce the costs. The focus in this section is on the Major Equipment Items (MEI) of the capture plant.

Although the costs are slightly dated, it is the relative costs of the process components and the parameters that drive them that are of interest here and these relative costs are assumed not to have substantially changed in the intervening time. The DOE/NETL study is based on the design of a fully integrated PCC plant retrofitted to a single unit of the AEC Conesville, Ohio coal fired power plant as a series of case studies for the United States government. The focus here is only on the 90% CO\textsubscript{2} recovery case (Case #1 in the DOE/NETL study).

A.1  Capital costs

Table 3 below shows the breakdown of relative costs for the major equipment items. Only the costs of equipment in the capture plant are included in Table 3. Note that the (considerable) cost of CO\textsubscript{2} compression to pipeline conditions is omitted in this analysis as this cost is in direct proportion to the CO\textsubscript{2} product rate rather than to the total flue gas rate. A recent trend in PCC design is to reduce the compression cost by operating the stripper column at higher pressures which of course has an effect on the capital and operating cost of the stripper. To the extent that indirect costs are pro-rated from the total major equipment item costs, the percentages shown in Table 3 can be translated to the total capital cost of the PCC plant.
Table 3  Possible reduction in Major Equipment Item investment costs arising from the use of the proposed RLS contator.

<table>
<thead>
<tr>
<th>Major Equipment Item (MEI)</th>
<th>Baseline Item Cost (% of total MEI)</th>
<th>Minimum target (% of baseline MEI)</th>
<th>Stretch target (% of baseline MEI)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Columns / Internals</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flue Gas Cooler</td>
<td>10%</td>
<td>7%</td>
<td>4%</td>
</tr>
<tr>
<td>Absorber</td>
<td>28%</td>
<td>19%</td>
<td>11%</td>
</tr>
<tr>
<td>Stripper</td>
<td>10%</td>
<td>7%</td>
<td>4%</td>
</tr>
<tr>
<td>Total all Columns / Internals</td>
<td>48%</td>
<td>33%</td>
<td>19%</td>
</tr>
<tr>
<td><strong>Heat Exchangers</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solvent Stripper Reboiler</td>
<td>13%</td>
<td>13%</td>
<td>13%</td>
</tr>
<tr>
<td>Solvent exchangers</td>
<td>16%</td>
<td>16%</td>
<td>16%</td>
</tr>
<tr>
<td>Condenser</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>other exchangers</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Total all Exchangers</td>
<td>35%</td>
<td>35%</td>
<td>35%</td>
</tr>
<tr>
<td><strong>Other equipment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flue Gas FD Fan</td>
<td>5%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>Pumps</td>
<td>4%</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Special Equipment (filters etc)</td>
<td>8%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>Total other equipment</td>
<td>17%</td>
<td>15%</td>
<td>12%</td>
</tr>
<tr>
<td><strong>Total MEI:</strong></td>
<td>100%</td>
<td>83%</td>
<td>66%</td>
</tr>
</tbody>
</table>

Source: [based on Ramezan et al., 2007] (Baseline costs are from DOE/NETL-401/110907 Case 1 - 90% CO$_2$ Capture). Minimum target assumes a doubling of gas velocities in all contactor towers and a 50% reduction in gas pumping requirement. Stretch target assumes a five-fold increase in gas velocities in all contactor towers and elimination of gas pumping requirement. Refer to the text for further discussion.

From Table 3 it can be seen that the contactors (towers and internals) are the most significant capital cost item representing nearly 50% of the total equipment costs. Note that the huge scale of PCC operations will likely require multiple trains of towers per power station boiler unit. The flue gas cooler (direct contact cooling column) conditions the flue gas to be suitable for the capture solvent. The flue gas wash column (post-treatment tower), included in the top section of the absorber in Table 3, acts to recover solvent from the exiting flue gas stream. Various proposed designs in the patent and open literature reviewed by Cousins (Cousins, Wardhaugh et al. 2011) combine these functions into single columns. However, as the total height is not changed, the overall effect of these design options on total capital cost is minimal.

It is clear that a process development that does not address the cost of the contactors will not make a significant impression on the total capital cost. The cost of the contactor column can be directly related to the cost of steel in the column, the internals and the supporting structure. The column diameter is determined by gas throughput and the entrainment constraints of the contactor type (limiting gas velocity). Column height is determined by the physical (diffusivity) and chemical (reaction kinetics) properties of the solvent package which is assumed here to be optimized. The direct contact cooler (integral to the absorber in the DOE/NETL design) adds 10% to the capital cost but may, in alternate designs, be incorporated in the Flue Gas Desulphurization (FGD) plant (an additional cost in Australia where, unlike the Conesville plant and elsewhere in North America and Europe, no pre-existing FGD facilities exist).
Another significant capital cost item to be noted from Table 3 is the flue gas blower which alone represents a greater capital cost than all of the liquid pumps combined for a modest pressure rise (typically 0.1 bar). It would be an important part of the overall analysis of a contactor design to consider is the possible increase the required flue gas inlet pressure that may increase the overall capital cost and may add significantly to the operating cost as discussed below.

A.2 Operating costs

Table 4 provides a breakdown of the power requirements for electrically driven components of the PCC plant. The power also relates to size and hence to capital cost. It is clear that the largest consumer of electrical power in the PCC plant is the flue gas blower, consuming over 50% of the electrical load. This also adds to the parasitic load on the power station.

<table>
<thead>
<tr>
<th>ITEM</th>
<th>No. per train</th>
<th>Power per unit [kW]</th>
<th>Total Power [kW]</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wash Water Pump</td>
<td>2</td>
<td>52</td>
<td>104</td>
<td>2.1%</td>
</tr>
<tr>
<td>Direct Contact Cooler Water Pump</td>
<td>2</td>
<td>90</td>
<td>180</td>
<td>3.7%</td>
</tr>
<tr>
<td>Rich Solvent Pump</td>
<td>2</td>
<td>430</td>
<td>860</td>
<td>17.8%</td>
</tr>
<tr>
<td>Lean Solvent Pump</td>
<td>2</td>
<td>291</td>
<td>582</td>
<td>12.0%</td>
</tr>
<tr>
<td>Semi-Lean Pump</td>
<td>2</td>
<td>130</td>
<td>260</td>
<td>5.4%</td>
</tr>
<tr>
<td>Solvent Stripper Reflux Pump</td>
<td>2</td>
<td>11</td>
<td>22</td>
<td>0.5%</td>
</tr>
<tr>
<td>Filter Circ. Pump</td>
<td>2</td>
<td>21</td>
<td>42</td>
<td>0.9%</td>
</tr>
<tr>
<td>LP condensate booster pump</td>
<td>2</td>
<td>108</td>
<td>216</td>
<td>4.5%</td>
</tr>
<tr>
<td>Flue Gas FD Fan</td>
<td>1</td>
<td>2579</td>
<td>2579</td>
<td>53.2%</td>
</tr>
<tr>
<td>TOTAL (PCC plant):</td>
<td></td>
<td></td>
<td>4845</td>
<td>100%</td>
</tr>
</tbody>
</table>

Source: [based on Ramezan et al., 2007] (Baseline costs are from DOE/NETL-401/110907 Case 1 - 90% CO₂ Capture).
Appendix B  Limitations of existing contactors

To understand why a new contacting method is required it is first necessary to understand the fundamental limitations of existing devices and to use this information to make a step change improvement.

B.1  Packed Beds

The conventional PCC process is centred on counter-current packed bed gas-liquid contactors. Packed beds represent a high interfacial area density (surface area per unit total volume) and most of the flue gas pumping requirement. Significant improvements have been made in packing materials to suit the demands of the PCC process (Zhao, Smith et al. 2011) but this must be seen as a mature technology. The cost of the contactor is essentially the weight of material (steel or, more recently, concrete with ceramic liner) as determined by the overall dimensions of the column, the volume of packing and support structure. Novel packing designs must out-perform conventional packing designs to be cost effective for the user. Column height is determined by the performance of the solvent, here assumed optimized, while the tower cross-sectional area is fixed by the maximum allowable gas velocity to limit liquid entrainment or prevent flooding. However, the opportunity for further improvement is limited by the fact that the energy necessary to create surface area by distributing the liquid over the packing surface is provided by gravity alone which also limits the maximum practical viscosity of the solvent that can be used in a packed bed. While the pressure drop of conventional packed beds is modest by most industrial scales, the massive volume of flue gas that must be moved through multiple contactor columns results in the substantial pumping cost as capital and electrical power, while the packing materials themselves constitute a substantial fraction (>50% for large columns) of the overall packed column costs. (Peters, Timmerhaus et al. 2003).

B.2  Spray columns

Of all the gas-liquid contactor types, the spray column offers the lowest pressure drop per unit of gas flow, possibly low enough to operate without supplementary gas pumping (i.e. operating from the natural draught of the chimney) so that it is curious why the spray column is not the contactor of choice in PCC. Spray columns are best suited to fast reactions and processes in the liquid phase, such as the capture of SO$_2$. The residence time of the droplets in the spray column is significantly less than in the equivalently sized packed column resulting in less scope for application to the slower CO$_2$ capture reactions.

The performance of spray columns diminishes markedly as the distance from the nozzle increases due to coalescence and/or collection at the walls but, more importantly, as shown in Figure 39, due to the increasing voidage as the droplets spread out from the spray nozzle leading to the often reported inverse dependence of mass transfer coefficient with tower height.
Multiple overlapping sprays can of course be utilized to improve the effective liquid hold-up, however, the increased interaction of the droplets in the overlapping sprays will lead to coalescence and may be counter-productive. Collection and re-spraying of the liquid is necessary in a multi-stage process as would be the case for the relatively slow reaction of CO$_2$ capture by amine solvents.

Potentially very high specific surface areas (per unit volume of liquid) can be achieved in ultra-fine spray devices and the temptation would be to aim for the finest possible spray. This, however, is counter-productive as entrainment of the fine droplets demands lower gas velocities thus increasing the column diameter. It can be shown (Wardhaugh 2010) that an optimum droplet size exists that minimizes the relative cost of the spray column compared to the equivalent packed column. The optimum droplet size is in the range of conventional low pressure nozzles, although the spray column must operate very close to entrainment velocities to compete with packed beds from a cost perspective.

Spray columns have nevertheless received renewed interest in the efforts to reduce PCC capital costs and are reported to be quite competitive to the best of the structured packings. (Kuntz and Aroonwilas 2008) claimed that a variety of spray designs could remove CO$_2$ at rates 2-7 times that of an equivalent sized bed with structured packing, although coalescence at the nozzle tip may have been a significant factor in these experiments suggesting that further improvement is possible. It will be argued in the following sections that the majority of the mass transfer occurs during the formation of the spray and that this process can be controlled to the extent that gas-liquid interaction is maximized and droplet formation is reduced to a minimum.

**B.3 Vortex and venturi contactors.**

Vortex (Javed, Mahmud et al.) and venturi (Hoffmann, Kurten et al. 1973) contactors provide high surface areas with the energy provided by the pressurized gas stream, while various rotating devices (Jassim, Rochelle et al. 2007, Cheng and Tan 2009) improve the surface area of coverage of the liquid at the cost of the internals and the power to drive the rotation of the entire bed. From the results in Table 3 there is a significant cost for pumping gas through the flue gas train. Contactor designs that increase the required
flue gas inlet pressure, no matter how efficient, may not reduce the overall capital cost and may add significantly to the operating cost.

B.4 Rotating contactors

Improvements to static packed beds have been implemented, for example, the entire packing can be rotated (Higee process developed by ICI (Ramshaw 1983) which improves performance by providing a more even distribution of the liquid through the application of centrifugal energy. While successful in applications where space is critical (e.g. offshore oil & gas facilities), the huge size of the contactors in PCC applications make this option impractical. An adaption of “Higee” has been suggested for CO₂ capture by Jassim (Jassim, Rochelle et al. 2007). Such systems are predicated on whether the cost of rotating a very large packed bed at high speed will be compensated by the reduced size of the bed.

Rotating components within the contactor such as the spinning-cone contactor (Makarytchev, Langrish et al. 2004) or rotating disks (Wang, Fei et al. (2002); (Luo, Chu et al.) are of interest in that energy is provided more directly to the liquid to improve contact while providing the opportunity to minimize or recollect entrained liquid. Within such devices, however, the gas must still find its way through a convoluted passage creating additional pressure drop and therefore requiring additional external pumping. Any attempt to use the rotating solid devices within the contactor to pump the gas is no different (and probably less efficient) than external pumping.

B.5 Stream contactors

Recent developments in gas and liquid contactors such at the Neustream contactor (Neumann, Miller et al. 2010) promises significant cost reduction by passing the gas at higher velocity horizontally through a stream of vertically oriented liquid sheets. As with the Neustream contactor the RLS device described in this project seeks to break through the limitations of existing mature technologies by rethinking the concept of gas-liquid contacting. The Neustream-C technology utilizes a flat jet of liquid forming a sheet or wall of liquid with the gas stream passing cross-flow between adjacent sheets of liquid. A 10-fold reduction in equipment size (volume) is claimed and the technology will be tested at the 0.5MWe scale at the Colorado Springs Utilities Drake #7 power station.
Appendix C  Details of Experimental Investigations

Appendix C provides further details of the experimental procedures and results that are not immediately germane to the final conclusions but are nevertheless important in understanding the development of this technology.

C.1  Development of the slotted tubes

A slotted tube device that would provide a stable continuous liquid sheet proved to be more challenging than first envisioned. The following sections briefly describe the various construction methods that have been attempted in the initial development leading up to and during this project. Figure 40 illustrates the various techniques for manufacturing the slotted tubes discussed in the next sections.

![Figure 40: Various techniques for manufacturing the slotted tubes](image)

**Figure 40** Various techniques for manufacturing the slotted tubes (from left to right) (a) spring wound from 22mm x 1.5mm stainless steel strip; (b) laser cut 1” diameter tube to match geometry of tube ‘a’; (c) laser cut triple helix; (d) laser cut triple blade; (e) 3-d printer triple blade (Verawhite); (f) 3-d printer triple blade (Veraclear); (g) printer triple blade (Titanium-raw product)

C.1.1  SPRING MANUFACTURE TECHNIQUES

As the helical slotted tube design resembles a spring, this appeared to be the obvious starting point for manufacture. Off-the-shelf springs could not be found with a suitable pitch. In all cases the gap was larger than the tube and the spacing could not be adequately controlled to produce distinct sheets. A local spring manufacturer attempted to wind a spring in a mandrill from 22 mm by 1.5 mm cut strip (Figure 40a). A skilled operator, however, could not control the spacing adequately. An attempt was made to control the alignment and spacing of the slots using a centrally located spacer (Figure 41) that was tightened using a central rod, however, the spacer severely affected the flow of liquid from the slot. As we were later to...
learn from CFD analysis, the flow field of the liquid inside the slotted tube critically affects the shape and stability of the resultant liquid sheet formation. The open ends of the spring (which also showed the greatest distortion) were sealed with a flexible epoxy.

Of greater consequence, upon winding, the metal strip itself distorted (Figure 41) giving a rounded edge to the liquid exit and it was not possible to create a distinct helical liquid sheet over the available range of flows and gap spacings.

![Figure 41](image)

**Figure 41** Distortion of device made from wound stainless steel strip
[also visible is the internal frame fitted in an attempt to control spacing]

### C.1.2 LASER CUT TUBE

Following a suggestion by Mr Don Chase, the possibility of providing a thin and well defined cut in a metal surface using precision laser cutting was pursued. A local manufacturer was located who had the facility to rotate the cut piece in a mandrill, while moving the laser longitudinally and provided a slotted tube made from 1 inch diameter thin wall stainless steel tube with a single 1 mm cut (5 turn 22 mm pitch) shown in Figure 40b. These dimensions were chosen to resemble the previously manufactured spring. Control of the laser power and speed prevents the laser from cutting right through thin walled tube, although burn marks on the opposite wall were common. The laser cutting process left a rough edge and considerable weld spatter material. This was manually cleaned and polished and starting point holes (of larger diameter) were plugged with epoxy.

This laser cut slotted tube proved to be the first successful device for producing a distinct continuous sheet of liquid resembling the shape of the slot as shown in Figure 7. Subsequent experimental work proved that rotation of the tube led to a rotating liquid sheet that was capable of pumping gas. A provisional patent was taken out in 2010 which led to a full patent (Wardhaugh, Chase et al. 2012).

For the initial section of this project a series of laser cut slotted tubes were prepared in the shape of multi-start helices (SxnH) and blades (SxnB) as shown in Figure 42. Honing and grinding equipment was purchased to improve the precision of the finishing of the raw product produced by the laser cutter. To test the honing process, the duplicate slotted tubes were set up outdoors and connected to a mains water supply with flow going to drain as shown in Figure 18. Any imperfection in the honing process was immediately apparent from distortions or breaks in the continuous section of the liquid sheet. In this manner the superior of the duplicate slotted tubes was chosen for further experimentation in the Flow
Visualization facility. Note also that Figure 18 displays the classic features of sheet oscillation leading to breakup into droplets. The theory and practical consequences of droplet breakup are discussed in Appendix E.1.

![Figure 42 Laser cut slotted tubes](image)

(a) Single, double and triple start helix designs (each 45° to horizontal; 1 turn)
(b) Single, double and triple row blade designs (each blade ¼ turn; 45° to horizontal)

Laser cut metal tubes had the following disadvantages:

1. The cutting process is started with a pin-hole (formed by an initially stationary laser) that ends up being larger than the slot as shown in Figure 43a. This did not matter as much for the helix design, however, for the blade design the larger flow of liquid leaving these pin-holes distorted the edge of the blade-shape liquid sheets. Starting the manufacture with a moving laser created a grooved end to the cut which was an improvement but required more careful honing and diminished control over the slot length. Again the error was less critical for the helix design compared to the blade design.

2. Too many long cuts in the tube (as in the case of the multi-start helix design) led to a distortion of the tube due to the relaxation of residual stresses in the tube itself. This led to a widening of the slot width in the centre of the tube and a misalignment of the slot edges (Figure 43b), both of which severely affected the formation of the liquid sheet. The suggestion was made to pre-machine a tube from annealed bar stock, however this was not pursued as we were already moving towards fabrication using 3-d printing technology as described in the next section.
Figure 43 Distortions in laser cut slotted tubes during manufacture.
(a) Pin-hole formed at start of laser cut
(b) Unravelling of stainless tube due to relaxation of residual stresses

C.1.3 MACHINED SLOTTED TUBE

Several attempts were made to find a local machine shop that could machine cut a suitable slotted tube. The scale of the job (in physical size and quantity) could not attract any local interest. In principle, a machined metal slotted tube would provide the most accurate fabrication technique if it is possible to machine the slot from the inside, followed by machine honing. As the scale of the device increases, so does the slot width and tube diameter, making computer aided machining a more practical alternative. Should the opportunity present to test this technology at larger (pilot) scale, this option would be pursued as the preferred manufacturing technique.

C.1.4 3-D PRINTER

Manufacture in Plastic

CSIRO’s Energy Technology Division purchased a 3-d printer (Alaris 30) to manufacture pre-programmed shapes from Verowhite RGD835 Plus plastic (Figure 44a) and, more recently from Veroclear RGD810 (Figure 44b). 3-d printing uses a CAD design file to control a laser that welds either an engineering plastic powder (the solid part of the device) or a water soluble plastic (the void parts of the device) to form a 3-dimensional shape based on a CAD design file. Soaking the manufactured component in dilute caustic solution overnight followed by washing in water effectively removed most of the void component, followed by a light hand polishing leaving a finished component. Colleagues (who had been successful in manufacturing high tolerance fuel injection nozzles) suggested that it might be a suitable means of manufacturing highly detailed geometric designs for our slotted tubes. It was now possible to alter the inside design of the tube and in the first instance a simple curved entry design was applied. An inside view (using a boroscope) of the 3-d printed tube is shown in Figure 45a.

Results provided in this report include those produced from 3-d printed helix and blade designs and are listed in Table 5 including optimized designs that incorporated an internal vane to redirect liquid flows as discussed in Section 4. The hand finishing process was found to be much easier than was the case with the laser cut tubes and the finished product was of higher precision. The results of the consequence of this improved precision is discussed in Section 3.
The disadvantage of the use of a stiff plastic component (Verawhite) was that torsional forces on the plastic tube eventually lead to stress fractures running laterally from the edges of the slots, as shown in Figure 45b. These slotted tubes however lasted long enough to gather sufficient experimental data. The use of transparent Veraclear plastic which is an inherently tougher plastic led to a longer life, however, care needed to be taken in tensioning the centre rod, as the plastic was more easily deformed on compression, even for the blade designs, closing the gap and severely effecting the sheet formation.

![Examples of slotted tubes manufactured using 3-d printer technology](image)

Figure 44  Examples of slotted tubes manufactured using 3-d printer technology
from left to right: (a) Verawhite plastic (b) Veraclear plastic (c) Titanium (raw product)

![Boroscope view of 3-d printed slotted tube (Pa3B) showing curved inlet; (b) fractured Verwhite tube showing internal structure.](image)

Figure 45  (a)Boroscope view of 3-d printed slotted tube (Pa3B) showing curved inlet; (b) fractured Verwhite tube showing internal structure.

Manufacture in titanium

An opportunity was presented to use the metal 3-d printer located in the CSIRO-CMIS group based at the Clayton, Victoria Facility. This unit is an ‘Arcam A1’ 3-d printer (Arcam AB Sweden) that can utilize a range of metal powders, but specifically 45-100micron Ti6Al4V Titanium alloy metal powder. The coarser particle size (compared to the plastic), however, limited the minimum slot width to 1mm and yielded a much
rougher printer product (Figure 44c) that would require considerable hand honing and polishing. The 3-d printed metal slotted tube would allow the manufacture of multi-start helix designs, however the limited minimum slot width would require a liquid pumping rate that was beyond the capability of our Flow Visualization test facility. A duplicate set (triple blade with internal vanes) was manufactured but could not be honed and polished to an adequate level in the time limit of this project.

Table 5 Dimensions of slotted tubes used in preliminary work and the first part of this study

<table>
<thead>
<tr>
<th>Slotted tube code</th>
<th># Helices or blades</th>
<th>Angle to horizontal [deg]</th>
<th>pitch [mm]</th>
<th># turns</th>
<th>slot length [mm]</th>
<th>Nominal slot width [mm]</th>
<th>Actual slot width-min (mm)</th>
<th>Actual slot width-max (mm)</th>
<th>Nominal slot area [mm²]</th>
<th>Actual slot area [mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wa1H5</td>
<td>1</td>
<td>17.7</td>
<td>25.5</td>
<td>5</td>
<td>419</td>
<td>1</td>
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<td>2.05</td>
<td>418.8</td>
<td>858.6</td>
</tr>
<tr>
<td>La1H5</td>
<td>1</td>
<td>16.1</td>
<td>23</td>
<td>5</td>
<td>415</td>
<td>1</td>
<td>1.7</td>
<td>1.7</td>
<td>415.3</td>
<td>706</td>
</tr>
<tr>
<td>Lb1H5</td>
<td>1</td>
<td>16.1</td>
<td>23</td>
<td>5</td>
<td>415</td>
<td>1</td>
<td>0.75</td>
<td>0.75</td>
<td>415.3</td>
<td>311.5</td>
</tr>
<tr>
<td>Lc1H5</td>
<td>1</td>
<td>16.1</td>
<td>23</td>
<td>5</td>
<td>415</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>415.3</td>
<td>415.3</td>
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<tr>
<td>Sa1H</td>
<td>1</td>
<td>45</td>
<td>79.8</td>
<td>1</td>
<td>112.8</td>
<td>0.5</td>
<td>0.2</td>
<td>1</td>
<td>56.4</td>
<td>67.7</td>
</tr>
<tr>
<td>Sb1H</td>
<td>1</td>
<td>45</td>
<td>79.8</td>
<td>1</td>
<td>112.8</td>
<td>0.5</td>
<td>0.2</td>
<td>1</td>
<td>56.4</td>
<td>67.7</td>
</tr>
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<td>79.8</td>
<td>1</td>
<td>225.7</td>
<td>0.5</td>
<td>0.2</td>
<td>1</td>
<td>112.8</td>
<td>135.4</td>
</tr>
<tr>
<td>Sb2H</td>
<td>2</td>
<td>45</td>
<td>79.8</td>
<td>1</td>
<td>225.7</td>
<td>0.5</td>
<td>0.2</td>
<td>1</td>
<td>112.8</td>
<td>135.4</td>
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<td>169.3</td>
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<tr>
<td>Sb3H</td>
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<td>1</td>
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<td>0.1</td>
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<td>79.8</td>
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<td>112.8</td>
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<td>0.1</td>
<td>0.1</td>
<td>56.4</td>
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<td>225.7</td>
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<td>0.1</td>
<td>0.1</td>
<td>112.8</td>
<td>22.6</td>
</tr>
<tr>
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<td>45</td>
<td>79.8</td>
<td>0.25</td>
<td>225.7</td>
<td>0.5</td>
<td>0.1</td>
<td>0.1</td>
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<td>0.1</td>
<td>0.1</td>
<td>169.3</td>
<td>33.9</td>
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<tr>
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<td>45</td>
<td>79.8</td>
<td>0.25</td>
<td>338.5</td>
<td>0.5</td>
<td>0.1</td>
<td>0.1</td>
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<td>97.1</td>
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<td>0.25</td>
<td>188.6</td>
<td>94.3</td>
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<td>97.1</td>
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<td>0.25</td>
<td>0.25</td>
<td>188.6</td>
<td>94.3</td>
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<td>188.6</td>
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Legend: Slotted tube code can be read as follows: AxnBm where A=manufacture method (W=wound spring; L=prototype laser cut; S=stainless laser cut duplicates; P=3-d printed plastic; C=3-d printed clear plastic; T=3-d printed Titanium); x=unit designator (sequential letter); n=number of starts or rows; B=design type (H=helix; B=blade); m=number of turns (default=1).

C.2 Instrument calibration results

Calibrations were carried out routinely through the course of the experimental work. Typical results are shown below.

C.2.1 GAS FLOW CALIBRATION

Flow calibration was carried out by connecting all flow measurement devices in series and using the AL-425 as the internal standard. The calibration of the Kimo CV-210 anemometer was checked against a Drycal flow calibrator with the results shown in Figure 46.
C.2.2 PRESSURE CALIBRATION

The gas inlet line was connected to the High and Low tap of identical Dwyer Model 607-2 Differential Pressure transmitter so that both positive and negative pressures could be detected in the one experiment. The calibration of each was against a standard pressure calibrator. Typical results are shown below in Figure 47 a & b.
### List of experimental runs and measurements

Table 6  List of experimental runs.

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<th>Run No.</th>
<th>Contactor Used</th>
<th>Rotation (rpm)</th>
<th>Liquid Flow (L/min)</th>
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C.3.1 LIST OF PHYSICAL PROPERTY MEASUREMENTS

Samples were taken during experiments using concentrated solutions of triethylene glycol (TEG). Measurements were made as follows:

(i) Density (Anton Paar DMA 38),
(ii) Viscosity (Anton Paar AMVn)
(iii) Surface tension (Sigma 700/701)

Results at 25°C are listed below. For a number of samples, measurements were also made at 15°C and 20°C to determine the temperature index for each physical property.

Table 7 Physical property measurements at 25°C.

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Surface Tension Exp start @25°C (Nm/m)</th>
<th>Surface Tension Exp End @25°C (Nm/m)</th>
<th>Density Exp Start @25°C (g/cm³)</th>
<th>Density Exp End @25°C (g/cm³)</th>
<th>Viscosity Exp Start @25°C (mPa.s)</th>
<th>Viscosity Exp End @25°C (mPa.s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>62</td>
<td>46.032</td>
<td></td>
<td>1.1166</td>
<td></td>
<td>28.2166</td>
<td></td>
</tr>
<tr>
<td>68</td>
<td>46.439</td>
<td></td>
<td></td>
<td>1.1165</td>
<td>28.2576</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>45.872</td>
<td></td>
<td></td>
<td>1.11789</td>
<td>30.7283</td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>45.54</td>
<td></td>
<td></td>
<td>1.11765</td>
<td>30.0911</td>
<td></td>
</tr>
<tr>
<td>73</td>
<td>45.474</td>
<td></td>
<td></td>
<td>1.11778</td>
<td>30.3089</td>
<td></td>
</tr>
<tr>
<td>74</td>
<td>45.403</td>
<td>46.439</td>
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<td></td>
<td>30.4839</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>45.33</td>
<td>45.33</td>
<td>1.11789</td>
<td></td>
<td>30.3184</td>
<td></td>
</tr>
<tr>
<td>76</td>
<td>45.353</td>
<td>45.422</td>
<td>1.11805</td>
<td>1.11816</td>
<td>30.7759</td>
<td>30.8131</td>
</tr>
<tr>
<td>77</td>
<td>45.257</td>
<td>1.11818</td>
<td></td>
<td>30.869</td>
<td></td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>45.375</td>
<td>1.11842</td>
<td></td>
<td>30.9929</td>
<td></td>
<td></td>
</tr>
<tr>
<td>86</td>
<td>44.889</td>
<td>1.11789</td>
<td></td>
<td></td>
<td>30.2698</td>
<td></td>
</tr>
<tr>
<td>89</td>
<td>44.478</td>
<td></td>
<td>1.11786</td>
<td></td>
<td></td>
<td>30.8598</td>
</tr>
<tr>
<td>94</td>
<td></td>
<td></td>
<td>1.11797</td>
<td></td>
<td></td>
<td>31.1042</td>
</tr>
<tr>
<td>96</td>
<td>43.205</td>
<td>1.11797</td>
<td></td>
<td></td>
<td>31.4230</td>
<td></td>
</tr>
<tr>
<td>97</td>
<td>43.946</td>
<td>1.11810</td>
<td></td>
<td></td>
<td>31.3324</td>
<td></td>
</tr>
<tr>
<td>98</td>
<td>36.364</td>
<td>39.158</td>
<td>1.10634</td>
<td>1.10704</td>
<td>16.3203</td>
<td>15.8107</td>
</tr>
</tbody>
</table>
Appendix D  Details of Computational Fluid Dynamics (CFD) modelling

D.1 Mathematical Modelling Equations

The mathematical models used in the current work were built using the commercial software suite ANSYS-CFX Versions 12.0-14.0. ANSYS-CFX is a versatile Reynolds-Averaged Navier-Stokes equation (RANS) solver and was used in conjunction with appropriate mesh generation tools to investigate different aspects of the RLS contactor.

D.1.1 CONSERVATION EQUATIONS

To calculate the flow field in a two-phase (air-water) simulation, ANSYS-CFX solves the time-dependent Reynolds averaged Navier-Stokes equations (1) and (2) for each of the two Eulerian phases (ANSYS 2012).

\[
\frac{\partial}{\partial t}(r_\alpha \rho_\alpha) + \nabla \cdot (r_\alpha \rho_\alpha \mathbf{u}_\alpha) = 0
\]  

(1)

\[
\frac{\partial}{\partial t}(r_\alpha \rho_\alpha \mathbf{u}_\alpha) + \nabla \cdot (r_\alpha (\rho_\alpha \mathbf{u}_\alpha \mathbf{u}_\alpha)) = -r_\alpha \nabla p_\alpha + \nabla \cdot (r_\alpha \mu_\alpha (\nabla \mathbf{u}_\alpha + \rho_\alpha \mathbf{u}_\alpha \mathbf{u}_\alpha)) + \rho_\alpha g + M_\alpha
\]

(2)

In these equations the subscript \( \alpha \) refers to each of the two phases (\( \alpha = 1 \) for water; \( \alpha = 2 \) for air), while \( r_\alpha \) is the volume fraction of phase \( \alpha \). The term \( \mathbf{u}_\alpha \mathbf{u}_\alpha \) represents the fluctuating component of velocity so that \( \mathbf{u}_\alpha \mathbf{u}_\alpha \mathbf{u}_\alpha \) denotes the Reynolds stress terms. Additionally it is required that the volume fractions (\( r \)) sum to unity, and that each phase shares the same pressure field, \( p \), so

\[
r_1 + r_2 = 1; \quad p_1 = p_2 = p
\]

(3)

The presence of Reynolds stress terms on the right hand side of equation (2) (denoted with superscript \( T \)) mean that the above equations are not closed. To obtain values for the Reynolds stress terms and close the equation set a turbulence model is used. Furthermore, the term \( M_\alpha \) on the right hand side of equation (2) represents interphase momentum transfer terms. It should be noted that these equations as written do not allow for the possibility of interphase mass transfer, which was not considered in the modelling current work. All additional source terms of momentum (apart from buoyancy, denoted by the term \( \rho_\alpha g \)) are neglected. For single phase (air only and liquid only) calculations, \( r_1 = 1, \ p_1 = p \), and only two (rather than four) equations need be solved.

D.1.2 TURBULENCE MODEL

The most widely used turbulence model is the k-\( \varepsilon \) model (Launder and Spalding 1974) which is based on the Boussinesq approximation. In the current work the k-\( \varepsilon \) model was implemented for both phases, although
for two-phase calculations applying a turbulence model to a thin film may not be strictly valid. Reynolds stress terms are approximated by

\[ \rho_a \mathbf{u}_a \cdot \nabla \mathbf{u}_a = \mu_{t\alpha} \nabla \mathbf{u}_a - \frac{2}{3} \rho_a k_{\alpha} \delta \]  

(4)

where \( \mu_{t\alpha} \) is the turbulent or eddy viscosity for phase \( \alpha \) obtained from:

\[ \mu_{t\alpha} = C_\mu \rho_a \left( \frac{k_{\alpha}^2}{\varepsilon_{\alpha}} \right) \]  

(5)

An effective viscosity can then be defined \( (\mu_{a,\text{eff}} = \mu_a + \mu_{t\alpha}) \). Equations (6) and (7) are solved to obtain \( k_{\alpha} \) and \( \varepsilon_{\alpha} \), which are the turbulent kinetic energy and turbulence energy dissipation rate, respectively, for phase \( \alpha \).

\[ \frac{\partial}{\partial t} (r_a \rho_a k_{\alpha}) + \nabla \cdot \left[ r_a \left( \rho_a \mathbf{u}_a k_{\alpha} - \left( \mu + \frac{\mu_{t\alpha}}{\sigma_k} \right) \nabla k_{\alpha} \right) \right] = r_a \left( p_a - \rho_a \varepsilon_{\alpha} \right) \]  

(6)

\[ \frac{\partial}{\partial t} (r_a \rho_a \varepsilon_{\alpha}) + \nabla \cdot \left[ r_a \left( \rho_a \mathbf{u}_a \varepsilon_{\alpha} - \left( \mu + \frac{\mu_{t\alpha}}{\sigma_\varepsilon} \right) \nabla \varepsilon_{\alpha} \right) \right] = r_a \frac{\varepsilon_{\alpha}}{k_{\alpha}} \left( C_1 \rho_a - C_2 \rho_a \varepsilon_{\alpha} \right) \]  

(7)

Shear production, \( P_a \), is defined in equation (8).

\[ P_a = \mu_{a,\text{eff}} \mathbf{u}_a \cdot \nabla \left( \mathbf{u}_a + \left( \nabla \mathbf{u}_a \right)^T \right) - \frac{2}{3} \nabla \cdot \mathbf{u}_a \left( \mu_{a,\text{eff}} \nabla \cdot \mathbf{u}_a + \rho_a k_{\alpha} \right) \]  

(8)

Constants for the standard \( k-\varepsilon \) model are given elsewhere (Launder and Sharma 1977).

D.2 Solid Auger Blade Model

Initial work was performed investigating the flow field through a solid helical vane in the shape of an auger blade, rotated about its longitudinal axis. The purpose of the work was to investigate an ideal gas flow through a rotating helical vane, where the fluid dynamics of the liquid film could be ignored.

D.2.1 GEOMETRY AND BOUNDARY CONDITIONS

The geometry and mesh of the model is defined in Figure 48 and Figure 49, and represent a centrebody or central tube of outer diameter 25.4 mm rotating in an enclosure of internal diameter 150 mm. The centrebody has a solid helical vane attached, that represents an idealised liquid film of thickness 0.7 mm and pitch 22.5 + 0.7 = 23.2 mm.

The figures show details of the overall extent of the model flow domain and the boundary conditions. The upper and lower horizontal surfaces were given “opening” boundary conditions, meaning that the average pressure at these surfaces was specified and flow allowed to enter or exit through them as the model predicted. The pressure was specified on these surfaces to equal atmospheric pressure \( (P = 0 \text{ Pa g}) \) and the surfaces themselves were positioned 2 m before and after the helical vane to limit any inlet or outlet interference with the main flow through the helix. With the geometry defined as shown, the rotation was specified to be negative (using the right hand rule on the rotational axis, with positive-z being upwards). This in turn drove the flow upwards, as was anticipated for the physical system. The outer surface of the flow passage, together with the centrebody and all vanes surfaces were modelled as no-slip walls.
D.2.2 MESH

The hexahedral mesh was generated using CFX-MESHBUILD. Having a structured mesh in this geometry required a helically based blocking structure. Some block manipulation was necessary in the upper and lower reaches of the modelled region to allow the upper and lower surfaces to be horizontal. This modification is highlighted in Figure 49b. The mesh itself had a resolution of approximately 1 mm both radially and vertically. Circumferential resolution was 5°. The final mesh had approximately 1 200 000 elements.
D.2.3 MODEL ROTATION

In order to model the rotation of the centrebody and helical vane, a second mesh was generated. The main rotating mesh in Figure 49a-b was placed within a “stator” mesh, this being a cylindrical mesh 1 mm (and three cells) thick, highlighted in pink in Figure 49c. The outer surface of the stator mesh was specified as a no slip wall boundary. The interface between the stator and rotor was then a well-defined cylindrical surface which allowed well-defined rotation of the helical vane whilst still giving a stationary no-slip condition at the outer wall. Thus there is effectively a 1 mm gap between the outer edge of the helical vane and the stationary outer wall of the geometry.

![Figure 49 Mesh detail of Solid Auger Blade model](image)

D.2.4 SOLID AUGER BLADE MODEL RUNS

A summary of the solid auger blade modelling runs is given in Table 8. The model was initially run as a transient rotating simulation with a time step of 0.008333 s, corresponding to a rotation of 30° using 600 RPM (Run MSBa1H6, Table 8). A total of 120 time steps were simulated, giving 10 full rotations of the central tube and solid blade. The rotation rate was increased to 3600 RPM and 18000 RPM (Run MSBb1H6 and MSBc1H6, Table 8) with a corresponding decrease in transient time step to ensure each time step corresponded to a rotation of 30°. This enabled the investigation of rotation rate on flow characteristics. Then the entire geometry was stretched by a factor of two and then four, to investigate the effect of using a longer pitch on the helix (Run MSBd1H6 and MSBe1H6, Table 8).
Table 8 Summary of Solid Auger Blade Model CFD runs at pilot plant scale

<table>
<thead>
<tr>
<th>Run</th>
<th>Pitch (mm)</th>
<th>Vane thickness (mm)</th>
<th>Rotation rate (RPM)</th>
<th>$V_{av}$ (m/s)</th>
<th>$V_{max}$ (m/s)</th>
<th>$V_{av}/V_{max}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSBa1H6</td>
<td>23.2</td>
<td>0.7</td>
<td>600</td>
<td>0.171</td>
<td>0.225</td>
<td>76</td>
</tr>
<tr>
<td>MSBb1H6</td>
<td>23.2</td>
<td>0.7</td>
<td>3600</td>
<td>0.944</td>
<td>1.350</td>
<td>70</td>
</tr>
<tr>
<td>MSBc1H6</td>
<td>23.2</td>
<td>0.7</td>
<td>18000</td>
<td>4.51</td>
<td>6.75</td>
<td>67</td>
</tr>
<tr>
<td>MSBd1H6</td>
<td>46.4</td>
<td>1.4</td>
<td>18000</td>
<td>11.55</td>
<td>13.5</td>
<td>86</td>
</tr>
<tr>
<td>MSBe1H6</td>
<td>92.8</td>
<td>2.8</td>
<td>18000</td>
<td>20.20</td>
<td>27.0</td>
<td>75</td>
</tr>
</tbody>
</table>

* In the run description, “MSB” means “Model – Solid Blade” while “1H6” means 1 helical slot that continues for 6 turns

Modelling predictions for these runs are given in the main body of the report.

D.3 Optimisation of Flow through the Slotted Centrebody

In the next stage of the work, modelling investigations focussed on the flow of liquid through the slotted centrebody of the RLS contactor. By changing the slot and associated geometry it was possible to try and predict a flow pattern that gives an evenly distributed flow through the slots as they form the continuous liquid sheet.

The geometrical changes investigated are summarised in Table 9, and fall into three categories, these being:

- Flow through a single full-pitch helical slot (runs MCFx1H, where “x” varies between runs)
- Flow through three rows of four short blades (runs MCFx4B, MCFx4BV)
- Flow through a single row of four three-quarter-pitch helical slots (runs MCFx4H)

Typical surface meshes for these runs are shown in Figure 50, which is the geometry of Run MCFc4H. An unstructured mesh was used, with inflation on solid surfaces to provide good resolution of fluid flow through the narrow slots. Note also that shown in these figures is the flow domain: that is, the region through which liquid flows. Thus the solid outer surface of the piece is not visible, only the wetted surface.

Images of each of the geometries in Table 9 are given in Figure 51 to Figure 55. Variations in the geometrical parameters such as wall thickness, slot thickness, slot profile, number of helices (# starts), length of the helices (# pitches), and so on, were all investigated. The aim was to determine the effect of these changes on the predicted distribution of water through the slots, so that a uniform flow of water through each slot at each vertical position could be produced, together with control over the direction of the flow (preferably horizontal or slightly upwards).
Figure 50  Typical surface mesh for the MCF geometries at pilot plant scale

(Run MCfc4H)
### Table 9  Summary of centrebody liquid flow model CFD runs at pilot plant scale

<table>
<thead>
<tr>
<th>Run*</th>
<th>t&lt;sub&gt;wall&lt;/sub&gt; (mm)</th>
<th>d&lt;sub&gt;o&lt;/sub&gt; (mm)</th>
<th>d&lt;sub&gt;i&lt;/sub&gt; (mm)</th>
<th>t&lt;sub&gt;slot&lt;/sub&gt; (mm)</th>
<th>θ&lt;sub&gt;pitch&lt;/sub&gt;</th>
<th># turns</th>
<th># starts</th>
<th>d&lt;sub&gt;rod&lt;/sub&gt; (mm)</th>
<th>rod taper (mm)</th>
<th># rows</th>
<th>slot profile</th>
<th>slot ends</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single helical slot</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCFe1H</td>
<td>1.6</td>
<td>25.4</td>
<td>22.2</td>
<td>1.6</td>
<td>45°</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>straight</td>
<td>flat</td>
</tr>
<tr>
<td>MCFf1H</td>
<td>1.6</td>
<td>25.4</td>
<td>22.2</td>
<td>1.2</td>
<td>45°</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>straight</td>
<td>flat</td>
</tr>
<tr>
<td>MCFg1H</td>
<td>3.2</td>
<td>25.4</td>
<td>19.0</td>
<td>1.2</td>
<td>45°</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>straight</td>
<td>flat</td>
</tr>
<tr>
<td>MCFh1H</td>
<td>1.6</td>
<td>25.4</td>
<td>22.2</td>
<td>1.2</td>
<td>45°</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>-</td>
<td>1</td>
<td>straight</td>
<td>flat</td>
</tr>
<tr>
<td>MCFi1H</td>
<td>1.6</td>
<td>25.4</td>
<td>22.2</td>
<td>1.2</td>
<td>45°</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>10-15</td>
<td>1</td>
<td>straight</td>
<td>flat</td>
</tr>
<tr>
<td>MCFj1H</td>
<td>1.6</td>
<td>25.4</td>
<td>22.2</td>
<td>1.2</td>
<td>45°</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>10-5</td>
<td>1</td>
<td>straight</td>
<td>flat</td>
</tr>
<tr>
<td>MCFm1H</td>
<td>1.6</td>
<td>25.4</td>
<td>22.2</td>
<td>1.2</td>
<td>45°</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>16</td>
<td>1</td>
<td>straight</td>
<td>flat</td>
</tr>
<tr>
<td>MCFn1H</td>
<td>2.6</td>
<td>27.4</td>
<td>22.2</td>
<td>1.2</td>
<td>45°</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>-</td>
<td>1</td>
<td>curve</td>
<td>flat</td>
</tr>
<tr>
<td>MCFo1H</td>
<td>4.6</td>
<td>31.4</td>
<td>22.2</td>
<td>1.2</td>
<td>45°</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>-</td>
<td>1</td>
<td>curve</td>
<td>flat</td>
</tr>
<tr>
<td><strong>Three rows of four short helical blades</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCFb4B</td>
<td>5.0</td>
<td>25.4</td>
<td>15.4</td>
<td>0.5</td>
<td>39°</td>
<td>0.25</td>
<td>4</td>
<td>6.25</td>
<td>-</td>
<td>3</td>
<td>curve</td>
<td>streamline</td>
</tr>
<tr>
<td>MCFc4B</td>
<td>5.0</td>
<td>25.4</td>
<td>15.4</td>
<td>0.5</td>
<td>39°</td>
<td>0.25</td>
<td>4</td>
<td>6.25</td>
<td>-</td>
<td>3</td>
<td>curve</td>
<td>curve</td>
</tr>
<tr>
<td>MCFd4B</td>
<td>5.0</td>
<td>25.4</td>
<td>15.4</td>
<td>0.7, 0.3</td>
<td>39°</td>
<td>0.25</td>
<td>4</td>
<td>6.25</td>
<td>-</td>
<td>3</td>
<td>curve</td>
<td>curve</td>
</tr>
<tr>
<td>MCFe4B</td>
<td>5.0</td>
<td>25.4</td>
<td>11.4</td>
<td>0.7, 0.3</td>
<td>39°</td>
<td>0.25</td>
<td>4</td>
<td>6.25</td>
<td>-</td>
<td>3</td>
<td>curve</td>
<td>curve</td>
</tr>
<tr>
<td>MCFf4B</td>
<td>5.0</td>
<td>25.4</td>
<td>11.4</td>
<td>0.5</td>
<td>39°</td>
<td>0.25</td>
<td>4</td>
<td>6.25</td>
<td>-</td>
<td>3</td>
<td>curve</td>
<td>curve</td>
</tr>
<tr>
<td>MCFg4B</td>
<td>5.0</td>
<td>25.4</td>
<td>11.4</td>
<td>0.5</td>
<td>39°</td>
<td>0.25</td>
<td>4</td>
<td>6.25</td>
<td>-</td>
<td>3</td>
<td>curve</td>
<td>curve</td>
</tr>
<tr>
<td><strong>Three rows of four short helical blades, with ribbing in the slots</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCFb4BV</td>
<td>5.0</td>
<td>25.4</td>
<td>15.4</td>
<td>0.5</td>
<td>39°</td>
<td>0.25</td>
<td>4</td>
<td>6.25</td>
<td>-</td>
<td>3</td>
<td>curve</td>
<td>curve</td>
</tr>
<tr>
<td>MCFd4BV</td>
<td>5.0</td>
<td>25.4</td>
<td>15.4</td>
<td>0.5</td>
<td>39°</td>
<td>0.25</td>
<td>4</td>
<td>6.25</td>
<td>-</td>
<td>3</td>
<td>curve</td>
<td>curve</td>
</tr>
<tr>
<td><strong>Four helical slots</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCFa4H</td>
<td>5.0</td>
<td>25.4</td>
<td>15.4</td>
<td>0.5-1.0</td>
<td>39°</td>
<td>0.75</td>
<td>4</td>
<td>6.25</td>
<td>-</td>
<td>1</td>
<td>curve</td>
<td>curve</td>
</tr>
<tr>
<td>MCFb4H</td>
<td>5.0</td>
<td>25.4</td>
<td>15.4</td>
<td>1.0-0.5</td>
<td>39°</td>
<td>0.75</td>
<td>4</td>
<td>6.25</td>
<td>-</td>
<td>1</td>
<td>curve</td>
<td>curve</td>
</tr>
<tr>
<td>MCFc4H</td>
<td>5.0</td>
<td>25.4</td>
<td>15.4</td>
<td>0.5</td>
<td>39°</td>
<td>0.75</td>
<td>4</td>
<td>6.25</td>
<td>-</td>
<td>1</td>
<td>curve</td>
<td>curve</td>
</tr>
</tbody>
</table>

* In the run description, “MCF” means “Model – Centrebody Flow”; “1H” and “4H” mean 1 (or 4) helical slots, “4B” means 4 blade-like slots, and “4BV” means 4 blade-like slots with ribbed vanes
Figure 51 Samples of the different geometries studied, where the region accessible to the flow of water is shown, rather than the solid material that water would flow within
Figure 52  Samples of the different geometries studied, where the region accessible to the flow of water is shown, rather than the solid material that water would flow within.
Figure 53  Samples of the different geometries studied, where the region accessible to the flow of water is shown, rather than the solid material that water would flow within
Figure 54  Samples of the different geometries studied, where the region accessible to the flow of water is shown, rather than the solid material that water would flow within.
Figure 55  Samples of the different geometries studied, where the region accessible to the flow of water is shown, rather than the solid material that water would flow within.
D.3.1 SINGLE FULL-PITCH HELICAL SLOT

The most extensive analysis performed so far investigated the single full-pitch helical slot, represented by modelling runs MCFe1H – MCFo1H (Table 9). Geometries are shown in Figure 51 and Figure 52. In these runs the helical slot was divided into eight sections of equal area from the top to the bottom of the slot, and the flow through each section was monitored to determine the uniformity of flow along its length.

Figure 56 shows the variation in flow rate (shown as a slot Reynolds Number) with distance along the slot, where Outlet-01 is at the top of the slot and Outlet-08 is at the bottom. For Runs MCFe1H, MCFf1H, MCFh1H, MCFi1H, and MCFj1H the Reynolds number increases along the slot length. The flow is slightly more uniform for Runs MCFf1H, MCFh1H and MCFj1H, suggesting that a thinner slot increases flow uniformity, while using a tapered central rod may make the flow less uniform along the slot. Run MCFg1H (not shown) used a thicker wall and was predicted to generate a far less uniform flow distribution.

Predicted flow patterns through the slot indicated that recirculation of air into the slot was possible, with probable increases in pressure loss and disturbances to the uniformity of the generated helical water film. Thus the runs MCFn1H and MCFo1H were performed using a profiled inlet to the slot, and consequently a thicker wall. Recirculations were eliminated using this design, however, the increased wall thickness led to a less uniform distribution of water through the slot, on par with that predicted for run MCFg1H.

![Figure 56 Reynolds Number variation along slot for various single helical slot runs](image)

D.3.2 BLADE GEOMETRY

The blade geometry was physically constructed using 3D printing technology. The design explored the use of multiple banks of short helical slots (blades). The wall thickness was increased from previous designs, and the slots themselves were profiled on the inner surface of the part to ensure a smooth transition into the slot itself.

A CFD model of this geometry was constructed and results are presented as run MCFc4B in Figure 57a-c. Figure 57a shows detail of the geometry immediately around the outlet, with the curved profile approaching the outlet itself both on the sides of the slot and at its end. Figure 57b shows streamlines passing into and through the triple blade geometry. The streamlines are coloured by local water velocity and the Figure shows that water approaches each outlet at a downward angle.
Figure 57  a-c) Run MCFc4B, and d-f) Run MCFb4B, showing geometry/mesh in region of an outlet, streamlines coloured by velocity, and outlet velocity vectors coloured vertical component of velocity

The velocity appears relatively uniform through each slot, however, the downward component of velocity is greater in the upper bank of outlets. This is shown in Figure 57c, where outlet velocity vectors are coloured by their vertical velocity components. The upper bank of outlets have most vectors coloured blue, corresponding to a downward velocity component of approximately 1.0 to 1.5 m s\(^{-1}\). Vectors at the lower bank of outlets are mainly green, corresponding to a downwards velocity of approximately 0.5 m s\(^{-1}\).

However, the upper and lower ends of each outlet have velocity close to horizontal (yellow vectors) in keeping with the horizontal orientation of the outlet slot at these locations. The effect of this velocity distribution is to cause the water film generated by the outlet to be twisted, which is undesirable for good operation. Note, this twisted film structure is evident when operating the experimental rig using the MCFc4B geometry.
Based on the MCFc4B results, a new design was investigated, that aligned the upper and lower ends of the outlet slots with the local streamline direction. This design (MCFb4B) is shown in detail in Figure 57d, with the predicted streamlines and outlet velocity distributions presented in Figure 57e and Figure 57f respectively. Although the flow is still directed downwards, the velocity distribution is more uniform from the top to the bottom of each outlet. For this reason the MCFb4B geometry is expected to generate water films without any twist.

**D.3.3 EXTENDED HELIX GEOMETRY**

A further investigation was performed using an extended helix geometry (typical examples are shown in Figure 55). This geometry was essentially the same as the blade geometry, but with the central row of outlets rotated by 45° with respect to the upper and lower rows, thus allowing all outlets to line up and producing four long helices rather than 12 short ones.

The triple helix run MCFc4H produced results very similar to that of the blade geometry shown in Figure 57, but with fewer outlet end effects. For this reason, it is thought that the use of long continuous outlets is preferable to multiple series of short ones. This contributes to the experimentally observed superior performance of the helical design.

**D.4 Full Scale RLS Contactor Modelling**

**D.4.1 SUMMARY OF FULL-SCALE RUNS**

In order to better understand a full scale operating RLS contactor, three models were developed using the two approaches previously shown, together with a fully two-phase model of a liquid film exiting the helical slot. The three run conditions are summarised in Table 10, where MCFa13H represents a model of liquid flow through the centrebody, MSBa13H is a model of gas flow through a series of 13 helical blades (representing the rotating liquid sheet, and MTPa13H is a two-phase model of the liquid film flowing from a helical slot in the centrebody, into the annular gas/liquid contacting space.

In all cases the geometry represents a 1.0 m long section of the RLS contactor, with 13 continuous helical slots equispaced around the centrebody. The slots have a width of 0.09 mm, and a pitch angle of 45°.

<table>
<thead>
<tr>
<th>Run</th>
<th>t\text{wall} (mm)</th>
<th>d\text{o} (mm)</th>
<th>d\text{i} (mm)</th>
<th>t\text{slot} (mm)</th>
<th>θ\text{pitch}</th>
<th># turns</th>
<th># starts</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCFa13H</td>
<td>5.0</td>
<td>100</td>
<td>110</td>
<td>0.09</td>
<td>45°</td>
<td>2.89</td>
<td>13</td>
</tr>
<tr>
<td>MSBa13H</td>
<td>5.0</td>
<td>100</td>
<td>110</td>
<td>0.09</td>
<td>45°</td>
<td>2.89</td>
<td>13</td>
</tr>
<tr>
<td>MTPa13H</td>
<td>5.0</td>
<td>100</td>
<td>110</td>
<td>0.09</td>
<td>45°</td>
<td>2.89</td>
<td>13</td>
</tr>
</tbody>
</table>

* In the run description, "MCF" means “Model – Centrebody Flow”; “MSB” means “Model – Solid Blade”; “MTP” means “Model – Two-Phase”

**D.4.2 FULL SCALE MODEL OF CENTREBODY FLOW**

The geometry of the full scale model of liquid centrebody flow is shown in Figure 58. Figure 58a shows the extend of the model, being a 1.0 m long section of the centrebody with 13 helical slots equispaced around it. Figure 58b-d show the surface mesh in increasing levels of detail. The mesh was generated using CFX-MESHBUILD, to create a multi-block structured mesh. This allowed for mesh concentration in regions of specific interest (such as the 0.09 mm slots) without unnecessary refinement in regions of bulk flow like the
central portion of the centrebody. The uniform mesh through the slots had an 8-cell resolution across the slot width while not requiring large numbers of cells along the slot length (Figure 58d). Using the mesh resolution it was possible for the CFD to capture the expected parabolic velocity distribution across the slot, as shown by the vectors in Figure 59.

![Figure 58](image-url)  
*Figure 58  Geometry and mesh for full scale model of liquid flow through centrebody, Run MCFa13H*
D.4.3 FULL SCALE MODEL OF GAS FLOW THROUGH SOLID AUGER BLADES

To create a model of the gas flow through the full scale RLS contactor it was necessary to capture the geometry of all 13 helical vanes extending out to the wall of the 1.0 m diameter contactor. As this model was primarily used to estimate pressure losses through the vanes, it was also necessary to model the flow upstream and downstream of the vanes themselves. Therefore the full model geometry is shown in Figure 60a, with upstream and downstream extending over a metre from the vane flights. Details of the closely spaced vanes are shown in Figure 60c, while the centrebody surface mesh is pictured in Figure 60d. It was necessary to create a mesh that allowed mesh elements with minimal skew within the vane passages, and Figure 60d shows how this was achieved, again using a structure multi-block mesh. The passages between the vanes had rectangular mesh elements with decreasing width as each vane was approached, hence allowing the capture of boundary layer effects near the vanes themselves.
Figure 60  Geometry and mesh for full scale model of gas-only flow through solid helical vanes, Run MSBa13H
FULL SCALE MODEL OF LIQUID FILM EMANATING FROM A HELICAL SLOT

In order to investigate the flow path of the liquid film itself, a two-phase model was created that allowed prediction of the liquid as it passed through the annular space between the centrebody and the RLS contactor outer wall.

Due to the very thin nature of the liquid film, high mesh resolution was required in the vertical direction of the model. Such a requirement created a very large mesh size (in terms of total number of elements), and so only a single film could be modelled, and only for a 30° sector of the geometry. A stylised image of the centrebody is shown in Figure 61 with some of the helical slots sketched onto its outer surface. A very small square section of the centrebody surface (blue square, Figure 61) was modelled. This square had a 45° helical slot passing along its diagonal. The flow domain then extended from this square out to the outer wall of the RLS contactor, and also downward so that the film had a region into which it could fall. As previously mentioned, the square covered a single slot through a sector of 30°. The side boundaries of the flow domain were both modelled as free-slip walls, while the outer wall was a no-slip wall.
Figure 62  Mesh detail for full scale two phase model of liquid film, Run MTPa13H
Details of the mesh are shown in Figure 62, with Figure 62a giving a plan view of the mesh and Figure 62b an elevation view of the mesh near the inlet slot. Another elevation view, this time looking directly at the slot, is shown in Figure 62c. It was necessary to create the mesh shown in order to allow a structured Cartesian mesh through the flow domain while still having a slot at 45° to the flow domain walls.

As with the centrebody flow model (Run MCFa13H) the resolution of mesh elements across the inlet slot was 8 (see Figure 62d). However, such high resolution could not be maintained into the flow domain. Therefore there is some numerical diffusion in the solution as the liquid film is predicted to flow into the annular space.

Using this model it was possible to predict the path taken by the film in the annular space, and as shown in the results of the report’s main body, that path is close to parabolic. Therefore a more detailed analysis of the film flow is not required, and a parabolic distribution can be assumed for future work.
Appendix E  Development of the design procedure of the Rotating Liquid Sheet contactor

This Appendix will outline the design procedure for the RLS contactor developed in such a way as to allow a direct comparison to a conventional packed bed contactor (with random or structured packing). We commence with a brief discussion of the physics of droplet breakup (Appendices E.1 and E.2). This is followed by the full development of the design equations (Appendix E.3) and example calculations (Appendix E.4) that in turn provide the basis for the cost comparisons presented in Section 5.3 of the main report.

E.1  Film and droplet formation fundamentals

Since the stated objective of the RLS contactor is to avoid as much as possible the breakup of the liquid sheet into droplets, it is first important to understand the physics of droplet formation.

From the work of Dombrowski (Dombrowski and Johns 1963), the formation of the droplets of a spray results from instabilities that occur due to oscillations in the continuous liquid sheet issuing from the nozzle forming first fibrils or ligaments then, with further unstable oscillation, droplets. The average droplet size formed by this process is greater than the thickness of the ligament (by 89% in an ideal case) and even greater than the thickness of the sheet from which it is formed (determined by fluid properties and process conditions as discussed below). The ligament therefore has a higher surface area in the ideal (mono-disperse) case by 26% compared to the droplets that are formed from it and the sheet can have a surface area significantly greater than the resulting droplets depending on the process conditions. Lower liquid velocities and higher viscosities promote stability in the sheet leading to thinner sheets prior to breakup and hence greater surface area (Dumouchel, Bloor et al. 1993).

Investigating LiBr absorption air-conditioning systems, Palacios and co-workers (Palacios, Izquierdo et al. 2009) showed that a sheet of liquid was at least 5 times as effective as the equivalent spray. Palacios and co-workers attributed this to the absence of droplet coalescence at the point of formation of droplets and the continuous distortion that occurs in the sheet prior to breakup. This was particularly advantageous in reducing the energy consumption per unit surface area and hence reducing the size of the absorber – both keys to commercialization of these systems.

The practical consequence of the above is that, in a conventional spray, most of the mass transfer occurs during the formation of the spray rather than during the journey of the droplets to the bottom of the contactor column. During this journey the mass transfer is further limited by coalescence of the droplets and impingement of droplets on the wall. Increasing liquid viscosity leads, however, to increased average drop size. Droplets do not readily form at all for liquid viscosities above 50 mPas (Eisenklam 1987) – a feature which may be able to be used to advantage in such a device with higher viscosity novel solvents.

The rationale of the gas-liquid contactor design should therefore be to control the liquid stream so as to delay the onset of the breakup of the sheet for as long as possible.

E.2  Specific area changes during droplet formation

The physics of droplet breakup can be used to determine the change in the specific surface area of the liquid throughout the droplet formation process. The following analysis is based on the summary of flow instabilities in various types of spray systems presented by Eisenklam (1987).
Consider a row of $n$ droplets formed from a single fibril of length $L$ which in turn formed from a section of sheet of length $L$ and of width and thickness determined by the nature of the oscillation. The arrangement and terminology are illustrated in Figure 63.

If the oscillation has a wavelength $\lambda$, it can be shown from the Kelvin-Helmholtz analysis (Squire 1953) that the oscillating sheet becomes unstable when the Weber number (We), which is a measure of the ratio of inertial to surface forces, is greater than one. i.e.,

$$We = \frac{\rho L U^2 h}{\gamma} > 1 \text{ for instability} \quad (1)$$

From the Raleigh instability, the fibril diameter ($D_f$) can be related to the diameter of the droplet that forms from it by:

$$D = 1.89 D_f \quad (2)$$

The volume of the fibril and the resulting drops must be the same, therefore

$$\frac{\pi}{6} D^3 n = \frac{\pi}{4} D_f^2 L \quad (3)$$

substituting for $D_f$

$$L = \frac{4D^3 n \pi}{6} \left(\frac{1.89}{D}\right)^2 = 2.38nD \quad (4)$$

We are interested in the change in surface area in going from fibrils to droplets

Ignoring end effects (i.e. $n$ is large) –

$$\frac{SA_{fibril}}{SA_{droplets}} = \frac{\pi D_f L}{n\pi D^2} = \frac{2.38n\pi D^2}{1.89n\pi D^2} = 1.26 \quad (5)$$
Therefore the fibril has a surface area that is 26% higher than the droplets that result from it. This reduction in surface area should not be a surprise since the sphere is the ultimate shape that minimizes specific surface area. However, the droplets do not form spontaneously but require the condition of instability (a sufficient degree of oscillation) to instigate the breakup. This is why, with careful control, it is possible to extend the range of stability of the sheet beyond the theoretical limit.

The fibril in turn has formed from oscillations that occur in the sheet issuing from the nozzle or spray device. Once again we are interested in the ratio of the surface area of the section of sheet to the droplets that ultimately form from it. This is a more complex problem to solve being determined by the nature of the spray device, the liquid flowrate and the properties of the liquid and the gas into which the spray is being emitted.

If a total of \( n \) droplets have formed from a strip of sheet of length \( L \), width \( \lambda^*/2 \) and thickness \( h^* \), where \( \lambda^* \) is the wavelength of the oscillation and the superscript * indicates the condition where the strip separates from the sheet to begin to form the fibril. The volume of the strip is identical to the droplets that form from it, therefore

\[
Lh^*\lambda^* = 2.38nDh^*\frac{\lambda^*}{2} = \frac{n\pi}{6}D^3
\]

(6)

\[
h^*\lambda^* = \frac{2n\pi D^3}{6 \times 2.38nD} = 0.44D^2
\]

(7)

and the ratio of surface areas is given by:

\[
\frac{SA_{\text{sheet}}}{SA_{\text{droplets}}} = R = \frac{2\times\lambda^*/2 \times L}{n\pi D^2} = \frac{2.38\lambda^*}{\pi D}
\]

(8)

At the point of instability, the Weber number is equal to or greater than one, therefore

\[
We^* = \frac{\rho_l U^2 h^*}{\gamma} \geq 1
\]

(9)

Substituting for the surface area ratio and volume relationship,

\[
R \leq 0.477 \frac{D\rho_l U^2}{\gamma}
\]

(10)

The above relationship is plotted as the curved dotted lines in Figure 64 for three droplet sizes. Droplet diameter is closely related to velocity with a unique relationship for each spray device. The dotted line in Figure 64 represents the upper limit for the surface area ratio \( R \). As expected, higher velocities enable the sheet to be spread thinner and the ratio of surface areas to increase. This process cannot continue. Another limit results from the action of the gas phase. At very high Weber numbers the critical width, \( \lambda^* \), is fixed by the following relationship:

\[
\lambda^* = \frac{4\pi\gamma}{\rho_l U^2} \text{ for } We \gg 1
\]

(11)
Re-substituting into the above equations,

\[ R < \frac{9.52 \gamma}{\rho_U U^2} \]  \hspace{1cm} (12)

For the same 3 cases of droplet size, the ratio of surface areas is plotted as solid curved lines on Figure 64. This would represent a cap on possible ratios for a given droplet size. Given a specific spray device design (which sets the relationship between U and D), a solution would be found in the area below that bounded by the two curves. Joining the points of intersection (dashed line) suggests a maximum possible surface area of the sheet as some 40 times that of the droplets that ultimately form from the sheet and that this is independent of velocity and droplet size.

From Figure 64, two results can be observed – the first is that it is theoretically possible for the sheet surface areas to be significantly greater than the resulting droplets, but more importantly an optimum velocity exists that maximizes the specific surface area of the sheet.

Equation 12 also sets a design limit between the slot width at the slotted tube exit and the extent of the continuous sheet. As has been shown in Section 3.5, the rotation rate and the liquid flowrate also play a role in determining the design limit.
E.3 Development of the design procedure for the Rotating Liquid Sheet (RLS) contactor

A design procedure and mechanistic model of the RLS contactor system based on fluid dynamics and mass transfer considerations has been developed for use in scale-up calculations and to explain the features described in the Experimental Results (Section 3).

The basic equations are developed here in a way that allows direct comparison to an equivalent segment of a conventional packing. Given that the RLS contactor is a cross-flow contactor and therefore should be considered a single stage and that it operates over a finite width (the limit of the continuous sheet before breakup), it is necessary to define a single RLS module and compare this to an ‘equivalent segment’ of conventional random or structured packing in a packed bed contactor. ‘Equivalent segment’ is taken to mean a segment of a packed bed that is equivalent to some aspect of the geometry and/or performance of a single module of an RLS contactor. Cost comparisons must therefore compare the correct number of RLS modules mounted vertically and aligned horizontally in a possible arrangement as described in Section 5.2. Example calculations are provided in the Appendix E.4 which are used to justify the costing results outlined in Section 5.3.

E.3.1 LIQUID TO GAS RATIO

For any given industrial gas-liquid contacting process there will be a relationship between the required liquid flow for a given gas flow (or vice versa) dictated by the reaction stoichiometry or physical absorption/desorption loadings. In the case of Post-Combustion Capture (illustrated as a simple block diagram in Figure 65) a lean solvent (depleted in CO₂) is contacted with a flue gas in any contacting device usually operated in a counter-current fashion, capturing a required fraction of the CO₂ and delivering a rich (CO₂ enriched) solvent which in turn is stripped of most (but never all) of the CO₂ in the stripper or desorber column then returned to the absorber via a heat recovery system. If there is no pre-existing Flue Gas Desulphurization (FGD), always the case in Australia, the flue gas is delivered to the PCC plant from the outlet of the Induced Draught (ID) fans at approximately 120°C and must be cooled (to approximately 40°C) and cleaned of contaminants (SO₂, most NOₓ components and residual ash) in a pre-treatment column. For this column the liquid rate is set by the cooling requirement. For the desorption (stripper) column, the liquid rate is fixed by the absorber and the gas rate is determined by the boil-up rate at the base of the column and the heat transfer and CO₂ liberation that occurs along the length of the column.

![Figure 65 Simple block diagram of the PCC process showing the 4 gas-liquid contactors](image)
The RLS contactor technology could be applied to any one of these PCC gas-liquid contactor columns, however the focus in this example calculation is on the absorber column which is the largest and most expensive of the contactor columns in a PCC plant. For the absorber, the nature of the flue gas, the chemistry of the selected capture solvent and the expected performance of the capture process (absorber/desorber) determine entirely the ratio of Liquid mass rate (L) to Gas mass flow (G) as described below. In PCC processes this range proves to be quite narrow and is independent of the choice of contactor.

Consider a typical amine absorption process as shown in Figure 66

![Figure 66 Typical amine absorption process showing process notation used in the model.](image)

An aqueous amine solvent of Molecular Weight \((MW_{am})\); number of active sites per amine molecule \((N_{am})\); weight fraction in clean (unloaded) solvent \((w_{am})\) has been selected as the capture solvent. \(W_{am}\) is set as high as possible but is usually limited by corrosivity, foaming or viscosity considerations. The absorber is designed to achieve a particular capture efficiency \((E_{CO2} = \text{mole fraction of CO}_2 \text{ captured from inlet gas stream})\).

Pilot scale tests determine the optimum values of solvent lean loading \((\alpha_L)\) and rich loading \((\alpha_R)\) which vary with the choice of solvent. This range is determined by the \(CO_2\) molar content of the flue gas \((v_{CO2})\); the absorption capacity of the solvent and the economic limit of \(CO_2\) removal in the desorber. The energy optimum is usually determined in pilot plant trials by varying the liquid rate for a given gas rate and adjusting the heat input to maintain a constant capture performance. The optimum \(L/G\) value is that which yields the minimum heat input per unit of \(CO_2\) captured. Operation at higher \(L/G\) would increase the sensible heat load per unit of \(CO_2\) captured. Operation at lower \(L/G\) would place greater demand on the solvent to maintain capture rates requiring a leaner return solvent and thus increasing the latent heat load per unit of \(CO_2\) captured on the system to provide for the required lower \(CO_2\) partial pressure in the desorber. At sites where energy costs are high, e.g. in Asia and Europe, minimizing the heat input is a good approximation to minimized overall costs. In locations where capital is expensive, e.g. in Australia and (to a lesser extent) in North America, a more complete economic analysis is required. The design/evaluation process could be repeated for different capture rates, different solvents and different process configuration options to determine the overall economic optimum (minimum total cost over the expected life of the plant). Here it is assumed that the optimum solvent lean loading \((\alpha_L)\) and rich loading \((\alpha_R)\) are known. Any alternate contactor device must meet the same \(L/G\) criteria.
The scale of the process determines the flue gas inlet mass flowrate \( (G_{in}) \) and the flue gas source determines the flue gas composition, flue gas molecular weight \( (MW_{FG}) \) and specifically the \( CO_2 \) volume fraction \( (v_{CO2}) \).

\[
CO_2 \text{ captured } [kg mol/hr] = \frac{E_{CO2} \cdot v_{CO2} \cdot G_{in}}{MW_{FG}} \quad (13)
\]

\[
\text{Gas mass rate out } [kg/hr] = G_{out} = G_{in} \left( 1 - \frac{E_{CO2} \cdot v_{CO2} \cdot MW_{CO2}}{MW_{FG}} \right) \quad (14)
\]

\[
\text{Unloaded solvent rate } [kg/hr] = L_o = \left( \frac{E_{CO2} \cdot v_{CO2} \cdot G_{in} \cdot MW_{am}}{(\alpha_R - \alpha_L) \cdot MW_{FG} \cdot N_{am} \cdot w_{am}} \right) \quad (15)
\]

\[
\text{Lean solvent rate } [kg/hr] = L_L = L_o \left( 1 + \frac{w_{am} \cdot \alpha_L \cdot MW_{CO2}}{MW_{am}} \right) \quad (16)
\]

\[
\text{Rich solvent rate } [kg/hr] = L_R = L_o \left( 1 + \frac{w_{am} \cdot \alpha_R \cdot MW_{CO2}}{MW_{am}} \right) \quad (17)
\]

From the equations above, the \( L/G \) value for the top \( (L_L/G_{out}) \) and bottom \( (L_R/G_{in}) \) of the absorber can be determined independently of the type of contactor if energy consumption is the primary economic consideration (a detailed design would have to consider the overall cost including capital and operating cost, aspects of which are discussed below as they relate to the RLS contactor). An arithmetic average of inlet and outlet values \( (L_{avg}/G_{avg}) \) is used here to illustrate the design method. A more detailed incremental design carried out along the length of the column (Saimpert, Puxty et al. 2013) could be applied. Note that the kinetics of the reactions / rates of physical absorption/desorption determine the height of the contactors, but do not affect the basic relationship in equations 13 to 17. A blended solvent can be treated in the same way, though an accurate analysis would require that the ionic species formed from each solvent component be known.

**E.3.2 GAS VELOCITY – THE BASIS OF COMPARISON.**

Given that the overall objective of the Rotating Liquid Sheet contactor is to reduce the diameter of the contactor columns by increasing the allowable gas velocity before flooding or entrainment adversely affects the performance of the contactor columns, the comparison is made by determining an optimum gas velocity in a given packed column, then using this value or a multiplier to determine the design of the equivalent RLS contactor.

Having set the \( L/G \) ratio (which is independent of contactor type) the next task is to determine the capacity (gas velocity or specific gas rate) in an optimally designed packed bed section, for which several well established design techniques are available. Two will be discussed here, the simpler empirical Generalized Pressure Drop Correlation (GPDC) of Leva and others (Green and Perry 2008) and the more detailed method of Billet and Schultes (Billet and Schultes 1999) which is based on equating the shear stress of liquid streams and gas streams at the interface to determine the flood point. It has been noted throughout the literature that there is a degree of disagreement between design methods mainly due to differences in definitions such as flood point. For our purposes here, while the choice of models gives slightly different results, the design procedure process and overall conclusions remain essentially the same.

For a selected packing material with defined packing factor \( (F_p) \) and material surface area (as distinct from effective interfacial area as discussed below), it is possible to determine the capacity (gas flow rate) of the packed bed at the ‘loading point’ where the gas and liquid streams begin to interact by virtue of the shear stresses occurring at the interfaces thus improving the mass transfer, but just prior to the point where this interaction becomes severely detrimental to the pressure drop or operability (the flooding point). The
optimum operating point is usually expressed as a percent of the flood point which in turn relates to the pressure drop per unit of packing height, for example, the relationship proposed by Kister and Gill (Green and Perry 2008):

\[
\Delta P_{\text{flood}}[\text{"g/ft}^2] = 0.12F_P^{0.7}
\]

(18)

where \(F_P\) is the Packing Factor \([\text{ft}^{-1}]\) determined experimentally for each packing type including random and structured packings. In practice, other limitations or experience may come into play such as a recommended maximum pressure drop, foaming or entrainment limits.

The GPDC provides a graphical relationship between Flow parameter (density adjusted \(L/G\)) and the required pressure drop per unit height to determine the allowable superficial gas velocity \((U_{Gs})\) and hence the column diameter. However, since in the PCC process the absorption and desorption (stripping) columns operate in a very narrow range of \(L/G\) and \%flood, in practice, the design equation becomes a single line relating column diameter to packing factor, \%flood and fluid properties:

\[
U_{Gs} = \frac{G_{in}}{A_S} = \frac{G_{in}}{\pi D_c^2} = f_n(F_P; \rho_L; \rho_G; \nu_L; L/G)
\]

(19)

The same standard methods can be used to determine mass transfer rates so that the column dimensions (diameter and total height) and total pressure drop information can readily be determined. Given that costing information is also available for column, packing and flue gas pumps, an optimum design (packing type and column dimensions) can be determined. The optimum packing type and operating gas velocity \((U_{Gs})\) have now been fixed and become the basis for comparison with the RLS contactor.

### E.3.3 RLS GAS PUMPING RATE AND ROTATION RATE

Now that the optimum superficial gas velocity in a packed bed is determined and based on the criterion of matching or exceeding (by a certain factor) the superficial gas velocity, the next step is to determine the design of the RLS contactor module that would match the required performance of the packed bed equivalent segment.

![Diagram](image)

**Figure 67 Notation used to define RLS contactor design equations**
Consider a single RLS module shown in Figure 67 comprising a vertical column (inner diameter $D_c$) with gas passing through the column from a gas inlet adjacent to the column base to a gas outlet adjacent to the column top. A liquid feed tube of outer diameter $D_o$ and inner diameter $D_i$ runs the active length of the vertical axis of the cylinder and is able to be rotated using a suitable motor, bearings and rotating seals at a rotation rate of $n$ (rpm). Liquid is pumped into the tube at the top or bottom of the rotating tube and exits into the gas space of the column via specially designed slots as defined below. The liquid travels in a parabolic arc as unbroken but continually thinning sheets from the slot exit to the column wall, travels down the column wall and is collected in a suitable reservoir. The tube outer diameter ($D_o$) is much smaller than the column diameter ($D_c$) and tube assembly is the only internal.

The rate at which the rotating liquid sheet can pump gas is determined by the sheet angle ($\theta$) and the rotation rate ($n$) [rpm] and pumping efficiency $\eta_p$. A perfect pump would displace a volume of gas defined by the gas column cross sectional area (annulus defined by column diameter ($D_c$) and slotted tube outside diameter ($D_o$) and the distance travelled in one rotation of the slotted tube – i.e. the pitch ($P$). In practice, slip at the sheet surface and formation of eddies leading to back-mixing contribute to a loss of efficiency ($\eta_p$)

$$\text{ideal gas volume pumping rate} = G_{id} = \eta_p \frac{\pi}{4} (D_c^2 - D_o^2) \frac{n}{60} \pi D_o \tan(\theta)$$

and the average gas velocity is given by:

$$U_{G,s} = \eta_p \cdot P \cdot n / 60$$

The sheet angle is chosen to give the optimum efficiency (determined by modelling or experiment) and the slotted tube rotation rate is set to give the gas superficial velocity matching the required target. This in turn sets the number of modules required to match the total throughput of the absorption column (affecting the total column diameter).

### E.3.4 EFFECTIVE SURFACE AREA

The total interfacial area per unit volume of the column gas is determined by geometric considerations based on the slot configuration of the slotted tube. It has already been shown that realistic designs for the RLS contactor can readily match the surface area of conventional packing materials by altering the slot angle (angle to the longitudinal direction of gas flow) of the liquid sheet and the number of starts for the intertwining helices Figure 31. As the angle of the slot increases, the axial thrust on the gas increases and a lower rate of rotation is required, however, gas slip (recirculation patterns) also increases reducing the efficiency of pumping the gas. An optimum therefore exists (in the vicinity of 45°). Even more compact designs could, in principle, be achieved with overlapping rows of blades (provided the slot design can counter the effect of surface tension that tends to draw blade shaped sheets into a point). Note that, unlike the packed bed, both sides of the liquid sheet are in contact with the gas.

The total surface area of the RLS contactor is given by:

$$A_{\text{sheet}} = 2 \cdot \frac{\pi}{4} \left( \frac{D_c^2 - D_o^2}{\cos(\alpha)} \right) N_{st} \cdot N_t$$

Where $N_{st}$ is the number of starts of the helices and $N_t$ is the number of turns through the active length of the tube. This equation assumes that the sheets are perfectly formed. If breakup occurs before the sheet reaches the wall, the surface area is reduced (droplets have a smaller surface area than the sheet from which they form—refer to Appendix E.2) giving an effective area lower than the theoretical value. This effect can be compared to the ‘effective’ area factor of conventional random or structured packing, however in the case of packing material, the ‘ineffectiveness’ results from less than full coverage of the
liquid over the packing surface due to various factors such as mal-distribution of the liquid at the top of the packing, surface tension (Marangoni) effects

### E.3.5 SLOTTED TUBE DESIGN.

Now that the total liquid flow and the slot configuration is known, it is possible to determine the full design of the slotted tube. As discussed in Section 4, the liquid flow field determines the shape and stability of liquid sheet and requires a reasonably complex design. For process design and costing, however, only the tube inner and outer diameters need be specified. The tube acts as a liquid distributor, so that the tube inner diameter is set to give an even flow of liquid to all points in the active (slotted section). This requires an iterative design, but in the first pass, an average liquid velocity ($U_{LT}$) in the tube can be specified, defining the tube inner diameter. A rule-of-thumb requirement that the pressure drop from top to bottom of the slotted section of the tube must be less than 10% of the slot pressure drop to achieve good liquid distribution provides a check on this assumption of tube liquid velocity. The tube outer diameter is set by the mechanical considerations of the strength of the tube wall.

The slot width is determined by the liquid velocity at the slot outlet which is next set to meet criteria relating to the avoidance to sheet breakup and the reach of the liquid sheet to the column wall as follows:

(i) the velocity must be sufficient for the liquid sheet to reach the wall.

(ii) The liquid slot velocity must exceed the centrifugal velocity induced by rotation of the liquid in the slotted tube. This means that the liquid must be pumped at a slightly greater rate than the rate at which liquid can be thrown out of the slots by centrifugal force. This effect is discussed in Section 3.5.

The liquid sheet, upon exiting the tube slot follows a parabolic path to the column wall determined by the slot exit velocity, the exit angle and under the influence of gravity. The resistance of the gas and surface tension effects will alter the flight path slightly but in this analysis these effects are assumed to be negligible. Intuitively it would be advantageous to direct the flow of liquid at a slightly upward angle ($\alpha$), but this has not been attempted experimentally. The flow path is defined in cylindrical ($r:\theta:z$) coordinates as:

$$z = \frac{-g. (r - r_0)^2}{2V^2 \cos^2(\alpha)} + \tan(\alpha) \cdot (r - r_0) + z_0$$

(23)

and the angle at the column wall, important in determining the appropriate angle and velocity of throw is given by:

$$\frac{dz}{dr} = \frac{-g. (r - r_0)}{V^2 \cos^2(\alpha)} + \tan(\alpha)$$

(24)

The liquid sheet should reach the column wall at an angle $\beta$ (to the horizontal) that is not too steep (poor use of vertical space) nor too shallow (too high a velocity leading to droplet formation from splashing).

The centrifugal velocity of the liquid due to tube rotation is given by:

$$V_c = r \cdot \Omega = \frac{D_o}{2} \cdot \frac{60n}{2\pi}$$

(25)

The actual slot velocity is the greater of $V$ and $V_c$. The slot velocity in turn sets the slot width since total liquid rate and total slot length are already known.

As the liquid sheet travels to the wall, the thickness of the sheet will be reduced (by the inverse of the radius) to maintain the mass balance. The velocity in the radial direction ($V_r$) remains essentially constant. Breakup of the sheet is inevitable at some point as discussed in Appendix E1 and E2. Ideally this radius should be greater than that of the column wall, however it has been shown experimentally that performance drops only slightly if breakup occurs near the column wall. If this is not the case, an iterative
process is required to determine a more suitable design. The desired result could be achieved by reducing the column diameter, increasing the liquid flowrate or altering the fluid properties (all of which have a detrimental impact on cost).

**E.3.6 PRESSURE DROP AND POWER CONSUMPTION FOR GAS PUMPING**

In the GDPC method, the operating pressure drop per unit height \(dP_{op}\) is fixed by the choice of packing material and the operating point (as \%flood). Power requirement can then be calculated as the product of volumetric flow and pressure drop for the ‘equivalent’ packing section of height \(H_{seg}\). The equivalence is based on the cross sectional area of packing required to achieve the same volumetric throughput as the RLS contactor and a packing height having the same effective surface area as discussed in Section E3.4.

Pressure drop total = \(dP_{seg} = dP_{op} \times H_{seg}\) \(\text{(26)}\)

And the power requirement for external pumping \((P_{pack})\) is the product of the total segment pressure drop and the total segment gas volumetric rate \((Q_{in})\). Since the RLS module is designed to have the same surface area as the packing segment, the comparison is the same regardless of the total column height (i.e. we are assuming that the mass transfer is comparable on the basis of total interfacial area).

\[ P_{pack} = dP_{seg} \times Q_{in} \]  \(\text{(27)}\)

For the RLS contactor, the power to pump the gas by rotation of the liquid sheet comes from the pressure in the liquid provided by the liquid pump and the momentum gained from rotating the tube (discussed below). If external pumping is required, then the pressure drop in the RLS contactor can be modelled as the pressure to drive gas through the space between adjacent liquid sheets (assumed to be stationary). This is given by the standard duct equation:

\[ dP_{duct} = \frac{f}{2} \cdot \frac{4L_s}{D_H^2} \cdot \rho_g V_G^2 \]  \(\text{(28)}\)

where \(f\) is the standard friction factor, \(L_s\) is the total slot length; \(D_H\) is the hydraulic diameter of the duct space between adjacent sheets and \(V_G\) is the average gas velocity as the gas travels in a helical pattern through this space. This result has been validated by CFD modelling as discussed in Section 4.

The external power requirement for pumping gas through the RLS \((P_{duct})\)is therefore given by:

\[ P_{duct} = dP_{duct} \times Q_{in} \]  \(\text{(29)}\)

This proves to be significantly less than the power required to pump gas through the equivalent amount of packing. The reason for this would appear to be that surface area of the packing material is provided for the benefit of the liquid – to create surface area where the only available force to do so is gravity and to mix and remix the liquid with additional energy providing by the gas to create shear to the surface of the liquid. Therefore, the gas is expected to travel a much more tortuous path around the packing and the down-flowing liquid.

This gas side power comparison between packing and the RLS contactor remains true regardless of the number of horizontal (parallel) or vertical (series) segments of packing or module RLS units since each element is treated as the same of volumetric flow of gas and the same equivalent height to achieve the same total surface area.
E.3.7 POWER CONSUMPTION FOR LIQUID PUMPING

Liquid must be pumped to the highest point of whichever type of contactor is selected so that the comparison is with the extra pumping requirement to deliver liquid to the slot exit. Rather than this energy being dissipated as would be the case of liquid in a distributor at the top of a packed bed, the excess energy in the liquid is used to pump the gas. Part of the power in the liquid is delivered by the liquid pump, but most comes from the rotation of the slotted tube (discussed below), which itself acts as a centrifugal pump, if the liquid is fed into the centre of the rotating liquid feed tube. Therefore, the power required to pump the liquid in each RLS module \( P_{\text{Liq}} \) is defined using the difference between the required slot velocity \( V_{\text{slot}} \) and the centrifugal velocity \( V_{\text{rot}} \) as:

\[
P_{\text{Liq}} = (V_{\text{slot}} - V_{\text{rot}})A_{\text{slot}} \times dP_{\text{slot}} \tag{30}
\]

where \( A_{\text{slot}} \) is the total slot cross section area and \( dP_{\text{slot}} \) is the pressure drop across the slot (conventional entry pressure equation). If recycling of liquid is required, then an additional power is required which is essentially the power to lift liquid the height of each segment.

E.3.8 POWER CONSUMPTION FOR ROTATION

The power required to accelerate the liquid from the tube centreline to the centrifugal velocity at the slot can be calculated from equation for the kinetic energy of a solid body, where the ‘solid’ is the mass of liquid in the tube.

\[
KE_{\text{rot}} = \frac{1}{2} I \omega^2 = \left( \frac{2\pi r^2}{60} \right) \left[ \frac{1}{2} \rho_L \frac{\pi}{4} D_t^2 \ell_t \left( \frac{D_l}{2} \right)^2 \right]
\]

The power is the kinetic energy per unit time, where the residence time of liquid in the feed tube. Therefore:

\[
P_{\text{rot}} = KE_{\text{rot}} \cdot \frac{L_{\text{avg}}}{\frac{\pi}{4} D_t^2 \ell_t}
\]

Power is also required to start the tube itself rotating but, once in motion, maintains a constant momentum. Energy is lost in the reaction force of the liquid pushing against the gas and in the friction resistance of bearings and seals. This is captured by the efficiency term \( \eta_{\text{rot}} \).

E.3.9 LIQUID HOLD-UP AND RESIDENCE TIME

The liquid hold-up in the packed bed section is a function of the packing and the fluid viscosity and is simply a function of the time it takes liquid to drain down a solid surface. Values of 2-5% are typical for most packing types. Above the loading point the action of gas shear increases the amount of liquid being retained in the column (typically as spray) until flooding is reached. Liquid hold-up in turn relates directly to liquid residence time which for a typical packed bed is adequate for the relatively slow reaction of amines with CO\(_2\).

The RLS contactor is a cross-flow device similar in this respect to the tray column but requires the liquid to be re-pumped to re-establish the sheet in a series arrangement. Residence time of the liquid in the sheet can be estimated from:

\[
\tau_{\text{sheet}} = \left( \frac{D_e}{2} - \frac{D_o}{2} \right) / V_{\text{slot}} \tag{33}
\]

and the residence time of the liquid draining down the column wall is given by:

\[
\tau_{\text{wall}} = \frac{L_t}{V_{\text{wall}}} \tag{34}
\]
and, assuming laminar flow,

\[ V_{\text{wall}} = \frac{\rho_L g \delta^2}{2\mu} \]  

and \( \delta \), the thickness of the liquid is given by:

\[ \delta = \left( \frac{3\mu Q}{\rho_L g \pi D_0} \right)^{1/3} \]  

This calculation can be carried out for each turn of the helix if required.

The RLS contactor has a similar residence time to the spray column (typically an order of magnitude less than the equivalent packed column) which creates a disadvantage for this device as an absorber in the PCC process. The RLS contactor may find its first application as the pre-treatment column where reaction rates are faster. As liquid is always draining down the boundary between adjacent modules, this should always be included in the calculation of hold-up and residence time. This is not the case for the packing as the boundaries of the packing ‘equivalent’ segment are imaginary. There is a wall effect for packed columns, but in large diameter columns this is negligible and is usually neglected.

### E.3.10 MASS TRANSFER AND HETP

Direct mass transfer measurements on physical absorption and desorption processes have been carried out using concentrated triethylene glycol solutions and humid and dry air. Measurements showed the expected small effect of varying the gas rate and minimal effect of varying the rotation rate (contrary to expectations). Mass transfer rates were essentially proportional to available surface areas and therefore the above design procedure of matching surface area to that of an equivalent packed bed section appears valid. Improved pumping efficiency through improved slot design still holds the promise of improving mass transfer through more intimate contact of gas and liquid, but this has not been taken into account in the analysis presented in the next section. Mass transfer rates can be converted to ‘height equivalent theoretical plate (HETP) by standard methods.

### E.4 Example calculation

The foregoing section outlined the general equations for the RLS contactor set up in a way that allows a direct comparison to a conventional packed bed. An example calculation is now given with comments on the practicality of design limits of both devices and comments on the various types of packing and packed bed design procedures. The example calculations will show the relative size of the equipment and power requirements from which direct cost comparisons will be made (Section 5.3.3).

The following parameters will be varied to provide a comparison matrix:

(i) The relative superficial gas velocity will be compared on a 1x; 2x (initial target) and 5x (stretch target) gas velocity determined for the design of the equivalent packed bed. In the case of the 5x velocity, it will be assumed that the sheet rotation in the RLS contactor can deliver 2x the design velocity, with the remaining coming from a forced draft (FD) fan. As discussed above in Section 5.3.3, an optimum combination is likely to exist at these ‘stretch’ velocities. Note that as the specified superficial gas velocity increases the column diameter is reduced (the point of the exercise) creating a tighter specification for the slot configuration to match the equivalent interfacial area.

(ii) Random Packing (2” (50mm) Pall Rings) and structured packing (Mellapac 125Y and 350Y) will be considered.
E.4.1 ASSUMPTIONS USED IN THE CALCULATIONS

The following assumptions are used in the example calculations. Varying any of these assumptions does not alter the overall conclusions markedly.

(i) A generic 50mm metal Pall Rings operating at a maximum recommended pressure drop of 0.75"wg/ft (corresponds to 62% of loading based on Kister’s correlation for flood point – equation (18) (Green and Perry 2008) is selected as the economic optimum for conventional random packing materials (Eckert 1970).

(ii) The use of Mellapac 125Y and 350Y is well documented and thus provides a second convenient point of comparison. Any number of other packing types could be considered in a similar fashion during detailed design.

(iii) It has been shown experimentally that a continuous sheet can reach a radius of at least 1m so a nominal module diameter of 1m for the RLS Contactor is chosen as the basis for comparison in this example calculation. A volume segment of packing material of dimensions to match the required height and ‘equivalent’ cross-sectional area allows surface area and pressure drop to be determined for each case as described in detail below. Any number of packing volume segments can be stacked vertically and horizontally limited only by construction restrictions and liquid distribution issues. The RLS contactor, on the other hand, is modular, requiring multiple units vertically and horizontally, with attendant cost implications as discussed below.

(iv) Note that 50mm packing meets the criteria of Dc/Dp > 10 (Eckert 1970) in a 1m diameter bed.

(v) The example solvent system is 30wgt% monoethanolamine (MEA). The differential loading (α_R - α_L) is 0.3 (mol CO₂/mol MEA).

(vi) The flue gas contains 15vol% CO₂ (typical for coal fired power stations) from which 90% is captured in the absorber.

(vii) Physical properties are taken as averages over the column and are provided in Table 11. These values were calculated using the MEA absorption example provided by Aspen Technology Aspen Plus® process simulator. The default property package ‘electro-nrtl’ is the basis for the physical properties in this model.

(viii) Efficiencies are taken for all devices as 80% It is reasonable to assume that improvements would be made throughout the piloting development stage to be able to match this value for the RLS contactor components.

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ normal density</td>
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</tr>
<tr>
<td>N₂ normal density</td>
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<tr>
<td>Mol. Wgt - Gas</td>
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<tr>
<td>Mol. wgt - Liquid</td>
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<tr>
<td>Density - Gas</td>
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<td>Density - Liquid</td>
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<tr>
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E.4.2 COMMENTS ON CALCULATIONS

Table 8 lists the key parameters and calculated values to determine cost savings that are possible by designing an RLS contactor that:

(i) matches the gas velocity of a packed bed (cost saving is from deletion of the packing)
(ii) 2 x gas velocity (further cost saving from reduced diameter)
(iii) 5 x gas velocity (further cost saving from reduced diameter – requires compromise in required surface area as noted below).
(iv) Comparison with 2 types of structured packing that matches either the packing factor or the specific surface area and with a target of 2 x gas velocity.

Based on values for $F_{LG_{avg}}$ and the recommended pressure drop at the loading point of 0.75”wg/ft, the corresponding Capacity Factor is determined and hence the superficial gas velocity $V_G$ is determined to be 2.60 m/s. The total gas and liquid rates can now be determined for the packing segment.

Note that the method of Billet & Schultes uses a slightly more conservative definition for the onset of flooding but recommends a higher operating point (80% of flood) resulting in a net flow slightly lower than the above figures. We will continue to use the Leva values as being a greater challenge to match.

The material surface area of the packing is 82.5 m$^2$. The packing segment is assumed to be located in a column of diameter of tens of metres and wall effects are neglected. An RLS contactor module will always have a wall of liquid contributing to the surface area (of 3.14 m$^2$ in this example). The number of helix starts can be determined assuming an optimum sheet angle (to axial direction of gas flow) of 45°. A 10-start helix will match the packing area of the 2” Pall ring example. Rotation at 1090rpm will match the allowable gas velocity of 2.59 m/s. These values are readily achieved. Operation at a gas velocity target of 2x velocity is a reasonable extrapolation from results already seen with the resultant savings in reduced column size.

Operation at the stretch target of 5x gas velocity leads to some challenging design numbers in this once through example calculation. Mostly this results from the assumption that mass transfer is not enhanced by the higher gas velocities and therefore the same surface area must be crammed into the smaller vessel. An iterative approach in which the design assumptions are relaxed could readily provide a workable design. The comparison to the structured packing examples give intermediate results. The comparison to the higher surface area example is more extreme, but the same approach in terms of compromise design would provide a workable solution.
Table 12  Example calculations for various targets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>1m diameter column calculation by Leva</th>
<th>1m diameter column calculation by Billet &amp; Schultes</th>
<th>Target 2x Velocity</th>
<th>Target 5x Velocity</th>
<th>Target 2x Velocity</th>
<th>Target 2x Velocity</th>
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<tr>
<td>Selected Packing</td>
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<td>Pall Rings metal 50mm</td>
<td>Pall Rings metal 50mm</td>
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<td>50</td>
<td>50</td>
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<td>a</td>
<td>[m²/m³]</td>
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<td>105</td>
<td>105</td>
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<td>operating dP</td>
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RLS CONTACTOR MODEL FOR ABSORBER
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<td>spiral pressure drop [kPa]</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.13%</td>
<td>122.25%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>spiral power reqm [kW]</td>
<td>0</td>
<td>0</td>
<td>0.0082</td>
<td>0.74778</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>shortfall fraction of packed bed dP [kPa]</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.13%</td>
<td>122.25%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Tube volume [m³]</td>
<td>0.00219</td>
<td>0.00178</td>
<td>0.00456</td>
<td>0.01141</td>
<td>0.00324</td>
<td>0.00215</td>
</tr>
<tr>
<td>Tube residence time [s]</td>
<td>0.48068</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Energy for rotation [kJ]</td>
<td>0.00997</td>
<td>0.00486</td>
<td>0.08668</td>
<td>1.40544</td>
<td>0.03050</td>
<td>0.00867</td>
</tr>
<tr>
<td>Power for rotation [kW]</td>
<td>0.02074</td>
<td>0.00972</td>
<td>0.17336</td>
<td>2.81089</td>
<td>0.06101</td>
<td>0.01734</td>
</tr>
<tr>
<td>K-slot</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>Slot extra dP [kPa]</td>
<td>0</td>
<td>0.00525</td>
<td>0.00320</td>
<td>0.02103</td>
<td>0.31187</td>
<td>0.01061</td>
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<tr>
<td>slot extra power [kW]</td>
<td>0</td>
<td>1.874E-05</td>
<td>2.93E-05</td>
<td>0.00048</td>
<td>0.0020224</td>
<td>4.567E-05</td>
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<tr>
<td>total RLS power [kW]</td>
<td>0.02074</td>
<td>0.00974</td>
<td>0.17351</td>
<td>5.91398</td>
<td>0.06303</td>
<td>0.01738</td>
</tr>
<tr>
<td>RLS/packed bed total power each segment 4.32%</td>
<td>2.03%</td>
<td>18.06%</td>
<td>246.20%</td>
<td>6.56%</td>
<td>1.81%</td>
<td></td>
</tr>
<tr>
<td># vertical modules</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>RLS/packed bed total power-column 21.59%</td>
<td>10.14%</td>
<td>90.29%</td>
<td>1231.%</td>
<td>32.80%</td>
<td>9.05%</td>
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<tr>
<td>Packed bed volume [m³]</td>
<td>0.78539</td>
<td>0.78539</td>
<td>1.57079</td>
<td>3.92699</td>
<td>1.57079</td>
<td>1.57079</td>
</tr>
<tr>
<td>Packing surface (total) [m²]</td>
<td>82.4668</td>
<td>82.4668</td>
<td>164.933</td>
<td>412.344</td>
<td>196.349</td>
<td>549.778</td>
</tr>
<tr>
<td>Packing surface (effective) [m²]</td>
<td>82.4668</td>
<td>64.9424</td>
<td>164.933</td>
<td>412.344</td>
<td>196.349</td>
<td>549.778</td>
</tr>
<tr>
<td>wall surface [m²]</td>
<td>3.14159</td>
<td>3.14159</td>
<td>3.14159</td>
<td>3.14159</td>
<td>3.14159</td>
<td>3.14159</td>
</tr>
<tr>
<td>reqd area [m²]</td>
<td>79.325</td>
<td>61.3508</td>
<td>161.792</td>
<td>409.192</td>
<td>193.207</td>
<td>546.637</td>
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<tr>
<td>Slot pitch (theta) [m]</td>
<td>0.17860</td>
<td>0.16220</td>
<td>0.25205</td>
<td>0.39123</td>
<td>0.21441</td>
<td>0.17696</td>
</tr>
<tr>
<td>Slot angle (from vertical) [rad]</td>
<td>0.78539</td>
<td>0.78539</td>
<td>0.78539</td>
<td>0.78539</td>
<td>0.78539</td>
<td>0.78539</td>
</tr>
<tr>
<td>Slot angle (from vertical) [deg]</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
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<tr>
<td>Slot length (1 turn) [m]</td>
<td>0.25258</td>
<td>0.22939</td>
<td>0.35645</td>
<td>0.55328</td>
<td>0.30323</td>
<td>0.25026</td>
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<tr>
<td># turns in segment</td>
<td>3.95902</td>
<td>4.35921</td>
<td>2.80536</td>
<td>1.80738</td>
<td>3.29780</td>
<td>3.99577</td>
</tr>
<tr>
<td>surface area (1 turn/both sides) [m²]</td>
<td>2.21426</td>
<td>2.21551</td>
<td>2.20714</td>
<td>2.18699</td>
<td>2.21109</td>
<td>2.21439</td>
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<tr>
<td>Req'd # starts</td>
<td>10</td>
<td>7</td>
<td>27</td>
<td>104</td>
<td>27</td>
<td>62</td>
</tr>
<tr>
<td>calcd slot width [m]</td>
<td>0.00012</td>
<td>0.00033</td>
<td>3.39E-05</td>
<td>3.52E-06</td>
<td>4.77E-05</td>
<td>3.13E-05</td>
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<tr>
<td>calcd slot width [mm]</td>
<td>0.12286</td>
<td>0.33464</td>
<td>0.03386</td>
<td>0.00351</td>
<td>0.04766</td>
<td>0.03129</td>
</tr>
<tr>
<td>Sector area [m²]</td>
<td>0.27693</td>
<td>0.27589</td>
<td>0.27337</td>
<td>0.27638</td>
<td>0.27679</td>
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<tr>
<td>Sheet thickness at wall [mm]</td>
<td>1.73E-05</td>
<td>2.72E-06</td>
<td>4.38E-07</td>
<td>3.25E-06</td>
<td>1.76E-06</td>
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<tr>
<td>average sheet thickness [m]</td>
<td>3.28E-05</td>
<td>5.03E-06</td>
<td>7.79E-07</td>
<td>6.09E-06</td>
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<tr>
<td>Number sectors</td>
<td>122.058</td>
<td>302.979</td>
<td>751.874</td>
<td>356.162</td>
<td>990.951</td>
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<tr>
<td>Total volume in sheets [m³]</td>
<td>0.00111</td>
<td>0.00042</td>
<td>0.00016</td>
<td>0.00059</td>
<td>0.00091</td>
<td></td>
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<tr>
<td>Liquid holdup (superficial vol)</td>
<td>0.1414%</td>
<td>0.0268%</td>
<td>0.0041%</td>
<td>0.0382%</td>
<td>0.0583%</td>
<td></td>
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</tbody>
</table>
References


Wardhaugh, L. T., D. R. Chase, E. A. Garland and C. B. Solnordal "Gas and liquid phase contactor used in oil and gas industries, has gas inlet that directs gas through gas liquid contacting space into contact with each side of liquid sheets projected from outlets in housing", Commonwealth Sci&Ind Res Org (Csr).

Wardhaugh, L. T., D. R. Chase, E. A. Garland and C. B. Solnordal (2012). "Gas and liquid phase contactor used in oil and gas industries, has gas inlet that directs gas through gas liquid contacting space into contact with each side of liquid sheets projected from outlets in housing", Commonwealth Sci&Ind Res Org (Csr).


Internet References

1. http://neumannsystemsroup.com/co2
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