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Integrating Concentrating Solar Thermal Energy into the Bayer Alumina Process

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Lessons Learned Report - Development of Solar Expanding Vortex Receiver (SEVR)

Authors: Woei Lean Saw, Alfonso Chinnici, Daniel Ang Jin Tung, Evatt Hawkes, Rey Chin, Tim Lau, Xincheng Zhang, Yining Tang, Zhao Feng Tian, Graham Nathan

Project website: www.adelaide.edu.au/cet/solar-alumina/

make history.

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1. Project Summary

The project will establish a path to progressively integrate three complementary concentrating solar thermal (CST) energy technologies into the current energy-intensive Bayer Process, which produces calcined alumina from bauxite with natural gas as the energy source. Alumina production, with an annual production of approximately 18 million tonnes [1] [2], is the largest high temperature mineral processing industry in Australia. In 2020, more than $7 billion in revenue for Australia was contributed by its exports, rendering Australia the second largest global exporter [2]. Approximately 14 million tonnes of CO_2 is released annually from the alumina refineries, corresponding to 24% of Australia's Scope 1 manufacturing carbon emissions, all of which typically burn natural gas to drive the process [3] [4]. Adding solar energy to this process has potential to offer significant benefits to Australia by decreasing fuel consumption (the cost of which is anticipated to rise) and by opening up access to new markets for low-carbon, high value products. However, its technical and economic feasibility for this application is not well understood. Hence project has further developed and evaluated three classes of hybrid technologies, considering both the low and high temperature processes, with potential to enable a 29% − 45% solar share. In doing so, we will ensure that continuous operation can be maintained, and that only minimal changes would need to be made to the refinery process, hence minimising the risk to industry in introducing a new technology like this.

The project will advance the commercial readiness of each of these technology platforms, together with a plan for staged development and implementation into the process, considering both retrofit and greenfield sites. In particular:

- The assessment of commercially-ready steam production via established molten salt storage technology has found this technology has potential to be comparably economically viable compared with the other alternatives that were assessed for net zero, based on the criteria adopted in the project. However, the viability is strongly dependent on the quality of the solar resource is sufficiently prospective.
- The assessment of solar reforming of natural gas has found that significant advantages can be obtained by on-site reforming and directly introducing the hot syngas into the calciner, since this avoids the enthalpy losses of cooling the hot syngas. However, this can only be used to also achieve net-zero emissions if the methane itself is net-zero. Otherwise it is likely to be most viable to conduct methane reforming off-site at locations with coincidence of good solar resource and sequestration sites, which would then require transporting the hydrogen to the plant via a pipeline.
- The assessment of the technology options with which to introduce CST into the high temperature calcination process has identified some configurations with good potential to be economic compared with the non-solar alternatives that were assessed, within the range of uncertainty of future projections for each pathway. Although the cost of CST for the reference configuration that we selected is significantly greater than the current unmitigated processes using natural gas, the project also identified a wide range of options with good potential to lower cost. In particular, one option has been identified with significant potential in lower cost, the details of which are still under evaluation. The study also found that the cost of integrating the solar heat into an industrial process is significant. Indeed, this cost is of the same order as the cost of the heliostat field and tower.

In particular, the project has:

- Developed the process and techno-economic models to reliably estimate the economic viability of commercially available low temperature (<280°C) solar concentrators for their novel application to digestion, drying and pre-heating in the Bayer process.
    - These models account for solar resource variability and identify the more prospective opportunities to apply commercially available thermal storage.
    - It also delivered a plan for full-scale demonstration of this technology;
- Developed the process and techno-economic models to estimate the economic viability of an innovative technology that has been demonstrated at pilot-scale to reform natural gas with CST, increasing its heating value.
    - The models identified technology options for a solar thermal based steam reforming system for production of solar syngas that can be applied to the Bayer process through the existing fuel systems and burners.
    - The models will also be used to optimise the solar plant sizing and storage systems to maximise the impact.
- Develop a highly innovative, patent-pending solar expanding vortex receiver (SEVR), together with the validated engineering design tools for reactor design and an approach for its integration into the process, for the high temperature calcination of alumina continuously.
    - Computational fluid dynamics (CFD) models will be developed and validated by the joint application of laser diagnostic techniques to provide in-situ measurements of the heat transfer and transport processes in the reactor, while new experiments will be performed to provide the data needed for reliable process models.
    - These results will be fed into the techno-economic assessments to identify high value opportunities for its implementation. The project will deliver a plan for on-sun demonstration of this technology at pilot-scale.

The development of an integrated suite of technologies for the one industrial process has significant advantages over the individual development of each technology in isolation. It will establish the parallel paths of progressively increasing the penetration of renewable energy into the sector as confidence and expertise in CST grows, together with the progressive development of different technologies that are presently at different stages of technology readiness. It will also achieve a greater transfer of knowledge of the process requirements of the end-user to the CST technology development chain. In addition, it will achieve synergies in the research program through commonalities in the process models and techno-economic assessments for each model. Furthermore, it will allow opportunities to be identified for additional gains in efficiency and/or cost reduction through integration of the solar processes to achieve greater heat recover and/or infrastructure sharing, even though such integration may take time to implement to lower the risk. The project will identify those combinations of technologies and applications to the Bayer alumina process with strong commercial potential and develop a commercialisation plan for their implementation.

References

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[3] “Sustainability | The Australian Aluminium Council,” Oct. 04, 2017. https://aluminium.org.au/sustainability/ (accessed Dec. 21, 2021).

[4] “Supporting a low emissions future in alumina refining | Ministers for the Department of Industry, Science, Energy and Resources.” https://www.minister.industry.gov.au/ministers/taylor/media-releases/supporting-low-emissions-future-alumina-refining (accessed Nov. 30, 2021).

2. Purposed of this report

The purpose of this document is to provide a progress update to the Australian Renewable Energy Agency (ARENA) and the industry regarding lessons learned to date for Program 3, focusing on development of a windowless Solar Expanding Vortex Receiver (SEVR).

The full report of ‘Program 1 - Low temperature process heat’ and ‘Program 2 - Solar reforming of natural gas’ can be found in the follow link, https://www.adelaide.edu.au/cet/solar-alumina/

3. Development of Solar Expanding Vortex Receiver (SEVR)

3.1. Flow and scalar fields for single-phase and two-phase flow fields under iso-thermal conditions

3.1.1. Project overview

The project selected a high temperature gas (air or steam) as the preferred heat transfer media which to transfer thermal energy from the solar energy to the plant, on the basis that these are the media that are already used in commercial alumina processes. On these bases, technology assessments also identified the need for a high temperature solar receiver suitable for heating either air or steam to temperatures of order 1000 °C, since no suitable ones were available at pilot-scale at the start of the project. This technology is referred to as the Solar Expanding Vortex Receiver (SEVR). In the meantime, a commercial supplier of a solar steam receiver has been established, with whom a partnership has also been established.

Windowless configurations of the SEVR at 50-150MW$_{th}$ scale have been developed and evaluated in this project. Since insufficient measured data of the flow in and around these devices was available before the project, we have performed these for both single-phase and two-phase environments. These data are needed for model development and validation, together with optimisation, all of which are needed for the scale-up processes. These processes were performed with a wide range of experimental and numerical methods, spanning those that evaluate the overall performance of the reactor, both alone and coupled to the system, through to detailed measurements of the flow-field, internal and external, using laser diagnostics and numerical models using Computational Fluid Dynamics (CFD), techno-economic models of the technologies integrated within an alumina process were also performed.

3.1.2. Project Outcomes

The following outcomes were derived from the development of solar expanding vortex receiver:

- **New understanding of the mechanisms that control ingress and egress of flow and particles through an open aperture:** New measurements and modelling advanced understanding of the complex flow within a SEVR results in simultaneous ingress and egress through the aperture of a windowless SEVR. This flow is highly three-dimensional, so that that egress occurs through the outer edges of the aperture at the same time as an accompanying inflow to the cavity along the axis of the aperture. This understanding seeded the development of a series of both primary and secondary control measures, with the primary mechanism being balancing total in-flows and out-flows and the pressure at the neutral plane, while secondary measures include an air curtain and secondary chamber.
- The use of the over-ventilation at the outlet was found to enable fluid phase egress through the open aperture to be mitigated. However, over-ventilation brings both an energetic and an exergetic penalty, by lowering temperature. Egress can also be mitigated by varying the aerodynamics, such as by reducing the swirl intensity at the aperture.

- Higher injected air mass flow rate, smaller particle size, and larger aperture size all had adverse effect on mitigating particle egress. However, too much reduction in the injected air mass flow rate and too large particle size can adversely impact on particle deposition within the receiver. Similarly, reducing the aperture size impacts adversely on egress of particles and heat (equivalently, less concentrated solar radiation could enter the main cavity through the aperture).
- Vertical orientation of the receiver (i.e. aperture facing upwards, mimicking a beam-down receiver) was confirmed to have less particle egress than that of a horizontal orientation (i.e. aperture facing horizontally, mimicking a tower-mounted receiver). This is consistent with earlier work and highlights the advantages at the receiver of beam down. Nevertheless, this must be considered together with system impacts, as is done in the techno-economic assessments.
- A receiver with four symmetrical outlets had less particle egress than a single outlet on one side of the receiver, which is consistent with understanding that a symmetrical flow pattern represents the lowest case egress.
- Aperture size and the magnitude of over-ventilation were found to be the most significant and second important factors on mitigating particle egress for the open SEVR without additional control strategies, respectively.

3.1.3. Conclusion and next steps

The cold flow models of the SEVR were developed and used for understanding the flow features and patterns for both single-phase and two-phase flows. The use of iso-thermal assessments is a typical precursor to hot-testing, owing to the greater ease of measurement access and more complete nature of the data. Particle egress can be mitigated with the combination of different parameters and further reduced with an additional control strategy attached to the aperture of the receiver.

Further readings

Tang, Y, Sun, Z, Tian, ZF, Lau, TCW, Chinnici, A, Saw, WL & Nathan, GJ., (2022) Direct measurements and prediction of the particle egress from a vortex-based solar cavity receiver with an open aperture, Solar Energy, 105-117

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Davis D, Troiano M, Chinnici A, Saw WL, Lau T, Solimene R, Salatino P, Nathan GJ., (2019) Particle residence time distributions in a vortex-based solar particle receiver-reactor: The influence of receiver tilt angle, Solar Energy, 126-138.

3.2. Use of Computational Fluid Dynamics (CFD)

3.2.1. Project overview

The project advanced understanding of the impact of various simplifying assumptions and modelling approaches on the accuracy of various Computational Fluid Dynamics (CFD) models, which is a necessary step on capacity to develop and design optimal devices since requires reliable prediction of the transport of particles and heat transfer between suspended particles. Extensive validation was performed based on the transporting gas phase, together with assessments of two-phase flows as a function of particle size in the presence of radiative heating and convective cooling. Work was also undertaken to develop simplified models by comparison with results from detailed numerical methods in simplified environments, obtained with Direct Numerical Simulations (DNS). These are complementary because they provide complete data sets for validation, even though the environment is somewhat simpler.

3.2.2. Project Outcomes

- The CFD models of the 5kW$_{th}$ lab-scale receiver were found to predict that the temperature difference between the two phases is relatively small at a given location. However, it is expected that the temperature difference between the two phases may be more significant in a scaled-up device. This is because the increased reactor volume allows greater radiant heat absorption and residence time for the particle phase and therefore the temperature of particles at certain locations is likely to be considerably higher than that of the local gas phase.
- The Froude number (i.e, flow velocity) was found to have significant influence on the convective heat loss through the receiver aperture. This is consistent with previous trends, which have already shown that the flow recirculation in the chamber depends on this parameter. Importantly, new data were obtained that have been used both for model development/validation and for device optimisation,
- The validated CFD model was used to develop a configuration for an industrial-scale 50MW$_{th}$ SEVR. This 50MW$_{th}$ SEVR receiver was then developed further by using a control strategy to mitigate particle egress.
- The preliminary study estimated that receiver outlet temperatures of the air and particles can reach as high as 1373K and 1100K, respectively, for a total injected mass flow rate of air and particles of 67.5 kg/s and 6.75 kg/s, respectively. This corresponds to air and particle preheating temperatures of 873K. The preliminary results estimated that a configuration with a thermal efficiency of SEVR as high as 83% with the particle egress rate of <5%. The particle egress rate can be further reduced with a novel 'buffer' (to be patented) to less than 0.1%.
- For all cases assessed, radiative heat loss through the aperture was confirmed to be the dominant loss mechanism, rather than convection. While the trend was expected, the magnitude of the relative losses as a function of conditions is both new and important for technology optimisation and development.

3.2.3. Conclusion and next steps

The knowledge gained from this activity has been used to develop significantly more reliable models of heat and mass transport in these receivers, which is important to lower the cost of their development, scale-up and optimisation. There are also significant implications on many other classes of solar particle receivers and on particle-laden flows more generally. The final stage of the project will continue the optimisation work and will also inform the development of further research plans.

Further readings

Ang, D., Chinnici, A., Tian, Z. F., Saw, W. L., & Nathan, G. J., (2022) Influence of particle loading, Froude and Stokes number on the global thermal performance of a vortex-based solar particle receiver. Renewable Energy, 184, 201-214.

Tang, Y, Sun, Z, Tian, ZF, Lau, TCW, Chinnici, A, Saw, WL & Nathan, GJ., (2022) Direct measurements and prediction of the particle egress from a vortex-based solar cavity receiver with an open aperture, Solar Energy, 105-117

3.3. DNS and RANS tools for two-phase flow field activities.

3.3.1. Project overview

A project has also been undertaken to develop both new understanding of, and improved simplified models for, the flow and the heat transfer processes under conditions of relevance to the vortex particle receiver. Improved models are needed because of the extremely complexity of these heat and mass transport processes, which involve turbulence, radiative heat transfer, two-phase flows and non-linear physics spanning a very wide range of temporal and spatial scales. Also, the volumetric particle loading generates highly non-uniform particle distributions (termed clusters), which are preferentially distributed in regions of high strain and low vorticity. In addition, the mechanisms controlling heating and cooling processes within such devices remain poorly understood. For these reasons, simplified but reliable CFD RANS models are inevitably required for the design and development/optimisation of practical devices, which, in turn, requires detailed and reliable data for the development and refinement of such models. These data are best obtained from a combination of experiments and high-fidelity simulation (DNS)

One of the difficulties identified at the outset is that the existing RANS models are not able to accurately predict particle dispersion in such complex flows, particularly with regard to the effects of particle size and its distribution, together with volumetric particle loading. Understanding each one of these influencing parameters requires detailed knowledge of various physical processes. Each influencing parameter is coupled to the others because these parameters affect the particle behaviour such as preferential distribution, and the particle behaviour affects the local values of these parameters. There is therefore a need to develop more reliable RANS models of particle dispersion under conditions of relevance to the SEVR.

3.3.2. Project Scope

This project has developed an improved particle dispersion model for use in RANS simulations for isothermal, two-phase jet configuration under conditions of relevance to the SEVR. A two-phase jet flow is chosen in the initial stage for its well-controlled conditions and a simplified configuration compared to the actual device. Additionally, data are available of the effect of particle size on particle dispersion for these flows. While some previous work has been undertaken for these flows using DNS and LES models, no previous numerical works are available that aim to develop improved RANS approaches.

The modified dispersion model was developed, calibrated, and validated against DNS predictions of mean particle statistics in two-phase jets. The new model develops improved prediction of the impact of particle size on average particle dispersion statistics by accounting for Stokes number. These statistics include the rates of spread and decay of both particle velocity and concentration distribution under the influence of various particle sizes. While the limitations imposed by the nature of RANS simulations (Reynolds-average solutions of the flow field) limit the predictions to average particle statistics, rather than instantaneous particle behaviour, this is nevertheless an important advance for industrial prediction.

3.3.3. Project Outcomes

It is found that the new modified particle dispersion model yields improved predictions of mean particle statistics over the existing model for RANS simulations of two-phase jet configurations in comparison with DNS predictions.

- The mean error in the spread and decay of particle velocity in the jet is less than 6%.
- The mean error in the spread and decay of particle number density distribution in the jet is less than 15%.
- The dependence of the controlling coefficients in the modified model on particle size has been identified, enabling reasonable predictions of mean particle statistics under the particle size within a certain application range.
- The model modifications were simplified and easy to implement into the RANS simulations.

In addition, during the development of the new particle dispersion model, other parameters such as the volumetric particle loading, particle polydispersity, etc., were found to affect mean particle statistics significantly.

3.3.4. Transferability

Current work is focused on implementing the jet-configuration-based modified particle dispersion model into the RANS simulations for SEVR and assessing the validity of such a modified model for particle predictions in SEVR.

This work provides insights on improving the accuracy of RANS simulations for solid particles in anisotropic flows. It contributes to better modelling engineering processes like combustion, spray, and other types of concentrated solar thermal systems, where such particle-turbulence flows are significant.

The newly developed modifications of the particle dispersion model can be integrated into the commercial CFD tools/existing model for related engineering applications mentioned above.

3.3.5. Conclusion and next steps

The baseline RANS tools (an improved particle dispersion model) for the assessment of turbulent, multi-phase flows subjected to concentrated solar radiation and for the optimisation/scale-up of the actual device have been completed.

The next step is to verify and assess the validity of the tools in the RANS simulations for vortex particle receivers.

In addition to the particle-size-dependent controlling coefficients that have been identified and implemented into the modified particle dispersion model, their dependency on other parameters, like the volumetric particle loading and particle polydispersity, is expected to be identified in future work.

Further reading

Zhang, X., Nathan, G. J., Tian, Z. F., & Chin, R. C. (2021). The influence of the coefficient of restitution on flow regimes within horizontal particle-laden pipe flows. Physics of Fluids, 33(12), 123318-1-123318-19.

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Zhang, X., Nathan, G. J., Tian, Z. F., & Chin, R. C. (2021). Flow regimes within horizontal particle-laden pipe flows. International Journal of Multiphase Flow, 143, 1-12.

3.4. Lab scale demonstration of SEVR

3.4.1. Project overview

A systematic experimental study of a lab-scale, windowless configuration was performed to characterise the impact of all major variables on its global thermal performance. While previous investigations have identified that the SEVR design greatly reduces the transport of heat and mass through the aperture compared to other suspension-flow particle receivers proposed to date, making it potentially suitable for windowless applications, no data on its performance had previously been available. In addition, the available data on earlier windowed receiver designs was mostly limited to solar thermo-chemical applications, so that there is a lack in understanding on the use of this technology as either air or particle heater. This is also critical because of the complex, non-linear relations between heat transfer and heating requirements (the absorption of radiation scales with the square of the particle size, dp^2, while the mass loading scales with dp^3), and the high centrifugal motion in the device, which generates a variability in particle radial distributions, trajectories, and residence times. Hence, the overall objective of this investigation is to provide an experimental demonstration of the technical feasibility and performance of a laboratory scale, directly irradiated windowless vortex-based particle receiver. Various operational conditions of the SEVR were assessed, this includes looking at the effects of outlet overventilation, inlet flow speed, inlet particle loading and particle size on the wall and outlet temperatures, as well as thermal efficiency of the device. In addition, these experimental campaigns aim to generate useful datasets for the validation of the mathematical and computational fluid dynamics (CFD) model.

3.4.2. Project Outcomes

- A 5-kW SEVR experimental rig was constructed and commissioned under both single-phase (air-only) and two-phase (air with particles) under irradiated conditions.
- Successful operation of a directly irradiated windowless suspension-flow solar particle receiver has been reported here, using an outlet-suction strategy to “over-ventilate” by inducing a net inflow through the aperture as means to mitigate particle egress.

- As the inlet flow speed is increased, the outlet temperature is lowered which results in more thermal energy being captured by the device. Meanwhile, increasing the outlet temperature would lead to an increment of energy loss.
- The overventilation level at the outlet have significant influence on the thermal performance of the SEVR. The amount of air drawn through the aperture onto the inner chamber should be minimised to avoid decrement of fluid temperature at the outlet.
- The ratio of the thermal input to total heat capacity of the two-phase flow and the level of suction have controlling influence on the global performance of the SEVR. The amount of net ambient air ingress should be minimised to avoid exergy destruction and a decrease in the outlet fluid temperature. On the other hand, an increase in the particle loading leads to higher thermal efficiencies than that of the single-phase counterpart.
- Heat absorbed by the gas phase appears to be much higher than the solid phase which indicates that the presence of particles was found to enhance the heat absorbed by the flow, through lowering the value of outlet fluid temperature.
- The particle size has insignificant influence on the thermal efficiency of the SEVR for the range of size considered.
- A higher particle loading would result in the increment of particle residence time within the SEVR, mainly due to the reduced flow momentum, which allow particles to dwell within the receiver longer.
- The inlet flow speed significantly influences the convective heat loss thorough the aperture. This is because as the flow speed increases, the rate of air recirculation at the aperture also increases which allows more hot air to exit, while more cold air to be drawn in from the aperture through back mixing.

3.4.3. Commercial prospects

Despite being able to prove the windowless concept, operation under two phase flow were found to be challenging due to particle egress, which was minimised but not completely avoided. On the other hand, the aerodynamic control developed here allow for an easy scale up of a single phase SEVR, which was proven to be effective in minimizing mass and heat exchange through the aperture or mitigation below an acceptable level. Overall, the body of work carried out here highlighted the great commercial potential for an SEVR application equipped with a specifically designed aerodynamic control.

3.4.4. Transferability

The aerodynamic control specifically developed for the SEVR is highly transferrable to other solar cavity receivers featuring either under single or multi-phase flow. Nevertheless, as the flow features from the primary chamber impact on the performance of the aerodynamic control, specific design of the latter needs to be developed accordingly to the geometry and inflow condition of the specific solar device.

3.4.5. Conclusion and next steps

The particle loading has a strong influence on the particle residence time and thermal efficiency of the device. This is because the higher particle loading reduces the swirl intensity within the two-phase flow, which allow particles to dwell in the device for longer periods. The current study has successfully obtained new insights for the SEVR under hot conditions. A vast amount of dataset has been generated that could be used for the validation of mathematical and CFD models. Further research will be conducted to optimise the combined geometries of both the SEVR and the aerodynamic control for a given scale. In addition, the device is yet to be tested with preheated air and steam to determine its efficacy on heat transfer medium of different properties.

Further reading

Chinnici, A., Davis, D., Lau, T.C.W., Ang, D., Troiano, M., Saw, W.L., Tian, Z.F., Solimene, R., Salatino, P. and Nathan, G.J., 2022. Measured global thermal performance of a directly irradiated suspension-flow solar particle receiver with an open aperture. Solar Energy, 231, pp.185-193.

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