20th Australasian Fluid Mechanics Conference
Perth, Australia
5-8 December 2016

Effect of Jet Inclination Angle on the Flow Field within a Hybrid Solar Receiver Combustor

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Abstract

This paper reports on a systematic numerical study that investigates the interaction of four isothermal jets within an annular chamber under conditions relevant to a Hybrid Solar Receiver Combustor (HSRC). The HSRC features a cavity that is operable as a combustion chamber, an aperture to admit concentrated solar radiation into the chamber, multiple burners to direct a flame into the chamber, and a heat exchanger within it to absorb the heat from both energy sources (depending on the mode of operation). The HSRC geometry is simplified in this study to include a cylindrical cavity with four jets, representing the burners, which are configured in an annular arrangement and aligned at an angle to the axis. The aperture to the cavity is closed while the four jets interact with each other and with the cavity wall. The jet inclination angle (α_{jet}) was varied from 0° to 90°, while the jet Reynolds number and the number of jets were fixed at $Re_j = 15{,}000$ and 4, respectively. The numerical study utilised the commercial Computational Fluid Dynamics (CFD) code ANSYS CFX. The results show that the α_{jet} significantly influences the flow field with smaller α_{jet} ($0^{\circ} \leq \alpha_{jet} < 10^{\circ}$) leading to a strong inward annular recirculation while larger α_{jet} ($10^{\circ} \leq \alpha_{jet} < 90^{\circ}$) generates an outward annular recirculation with a strong back-flow through the aperture plane. Four flow regimes were identified, namely: inward recirculation dominant flow ($0^{\circ} \leq \alpha_{jet} < 10^{\circ}$); outward recirculation dominant flow($10^{\circ} \leq \alpha_{jet} < 40^{\circ}$); outward recirculation with back-flow($40^{\circ} \leq \alpha_{jet} < 60^{\circ}$); and jet impinging flow ($60^{\circ} \leq \alpha_{jet} < 90^{\circ}$). The findings are presented and discussed with relevance to heat transfer within the HSRC.

Introduction

With the growing need for a more sustainable living, clean energy generation has received increasing interest globally. Within the context of renewable energy, solar energy has received particular attention because it is both clean and abundant [7]. In recent years, Concentrating Solar Thermal (CST) systems have been developed because it offers opportunities to utilise energy at high temperatures, to allow the storage of thermal energy and to allow hybridisation with combustion devices [10]. However, a key barrier for developing CST technologies is the intermittent nature of the solar source.

The concept of integrating CST and traditional combustion systems is gaining prominence globally due to the complementary nature of these two thermal energy sources [12]. It offers a relatively low cost solution that minimises the need for costly large energy storage and also provides continuous power supply. While a number of hybrid systems have been proposed to date [9], none of them combine a solar receiver and a combustor directly within a cavity.

The concept of a Hybrid Solar Receiver Combustor (HSRC) has been recently proposed by the Centre for Energy Technology (CET) at the University of Adelaide. The HSRC configuration has the potential to reduce heat losses relative to equivalent hybrids by integrating CST and combustion energy sources into a single device [11]. The HSRC features a cavity operable as a combustion chamber, an aperture to admit concentrated solar radiation into the chamber, multiple burners to direct a flame into the chamber and a heat exchanger within it to absorb the heat from both energy sources. The burners are configured in an annular arrangement and aligned at an angle to the axis of chamber. This causes the jets to interact with each other as well as with the wall and the aperture. The HSRC design allows the device to operate in any of three operational modes, namely, the 'combustion only mode', the 'solar only mode' and the 'mixed mode'. For the 'solar only mode', the shutter of secondary concentrator (SC) is open to allow the concentrated solar radiation to enter the chamber. Under this mode, the only heat source for the HSRC is solar energy. In contrast, the heat source in the 'combustion only mode' is derived only from the burning of injected fuel and the shutter is closed. In the 'mixed mode', the power of the HSRC is derived from both solar energy and combustion, with the percentage of each being dependent on the solar intensity available at the time. A schematic diagram of the HSRC is presented in Figure 1. Owing to the annular arrangement of jets and the range of operational modes, it can be expected that different flow regimes, flame structures and dominant heat transfer mechanisms will occur inside the HSRC depending on the mode of operation. Ideally, the optimised flow patterns would lead to an enhanced mixing while preventing fluid to escape through the aperture plane. A larger flow through the aperture would lead to a larger convective heat losses in the mixed mode of operation. More importantly, an optimised flow field would be characterised by a reduced in-flow since this would alter the equivalence ratio of the flame, and therefore altering the heat transfer, fuel conversion and pollutant emissions. Hence, a comprehensive understanding of the influence of interacting jets on the overall flow-field within the HSRC is needed.

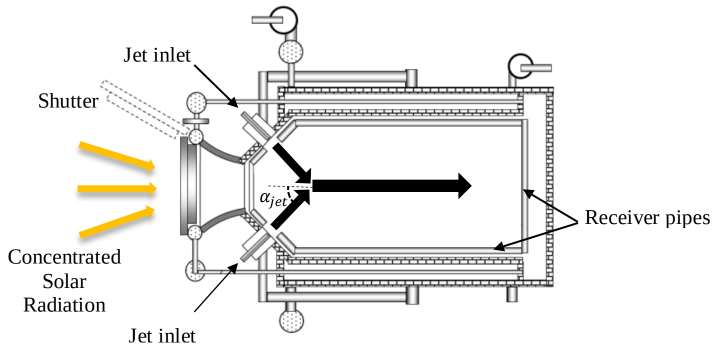

Figure 1. Hybrid Solar Receiver Combustor [11].

A number of researchers have studied the behaviour of interacting jets using experimental techniques [1,2,3], numerical techniques

[4], or a combination of both experimental and numerical techniques [5, 6]. However, there are only limited investigations with regard to multiple inclined annular jets inside a cylinder. The relationship between the variation of inclination angle and flow regimes is still not fully understood, and the fundamentals of these variations in the flow-field have not been fully quantified. Also, previous studies have only provided a detailed understanding of the flow-field for collinear inclined jets configurations ($\text{number of jets} \leq 3$) [1,2,3,4,5,6], while the impact of other configurations such as annular jets ($\text{number of jets} \geq 4$) on the overall flow-field within a confined space is still not well understood.

In light of the needs above, the aim of the present paper is to conduct a Computational Fluid Dynamics (CFD) study to a) investigate the iso-thermal flow-field of interacting jets within the HSRC configuration, b) identify potential flow regimes as a function of jet inclination angles within a circular chamber, and c) select the preferred flow regimes for 'combustion only mode' (closed-shutter) of the HSRC.

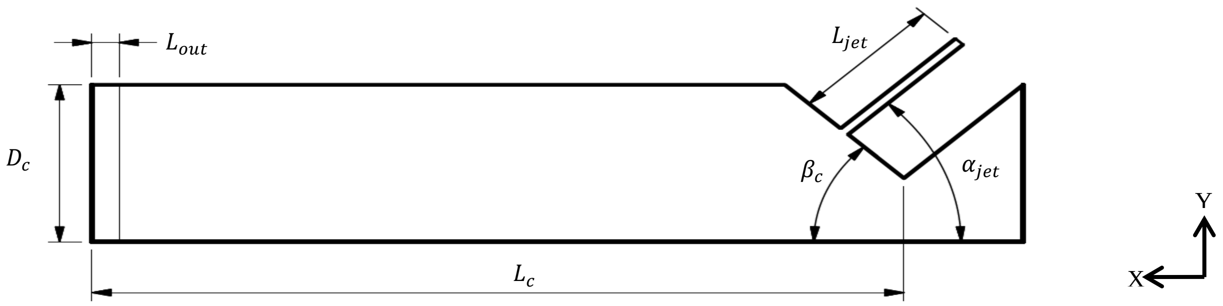

Figure 2. Geometry of the CFD domain (not to scale).

Methodology

A computational study was conducted using a commercial CFD code ANSYS CFX. The computational model of the HSRC shown in Figure 2 was generated with a commercial CAD package PTC Creo. 19 models of the HSRC were constructed for the cases from $\alpha_{jet} = 0^{\circ}$ to 90°, with an increment of 5° for each case. The dimensions of the HSRC are shown in Table 1.

Due to the symmetric nature of the geometry and to reduce computational cost, only a quarter of the full domain (Figure 2) was modelled utilising the symmetry boundary option in the code. The ANSYS Meshing code was used to generate the mesh of this computational model. The mesh quality was checked for expansion factor, aspect ratio, skewness and orthogonality. The influence of the number of mesh nodes on the CFD results was evaluated through a mesh independence test, which showed that 8 million mesh nodes represents a compromise between the accuracy of the calculated results and the simulation time. The convergence criterion for all cases was set to be 1×10^{-5}(RMS).

Shen et al. [8] reported a numerical investigation of an isothermal flow from a burner with three separated-jet inlets. This burner has similar features to the multiple-jet configuration of the HSRC. Shen et al. [8] found that the Baseline Reynolds Stress model (BSL RSM) is able to reproduce the velocity peaks and trends for interacting jets, due to the capability of the BSL RSM to calculate the anisotropic Reynolds stresses in different directions. Hence, the BSL RSM model was used for the current CFD study.

It is necessary to understand the isothermal flow-field before moving to the more complex cases of non-isothermal, therefore, the working fluid in the current CFD model was defined as isothermal water at $25^{\circ}C$. Water can provide a relatively high Reynolds number at a lower flow velocity. The Reynolds number in all cases was fixed at Re_j = 15,000 (Re_j is the jet Reynolds number), which ensured all calculated cases were performed in the fully-turbulent regime. The detailed boundary and inlet conditions are given in Table 2 and Figure 3.

Dimensions	Description	Value (mm)
$\boldsymbol{D_c}$	Chamber width (half)	37
$\boldsymbol{L_c}$	Chamber length	225
$\boldsymbol{L_{jet}}$	Jet inlet length	150
$\boldsymbol{\alpha_{jet}}$	Jet inclination angle	0° to 90°
$\boldsymbol{\beta_c}$	Conical chamber angle	45°
$\boldsymbol{L_{out}}$	Outlet length	3

Table 1. Geometric parameters.

Boundary Name	Boundary Type
1,2	Mass flow inlet
3	Opening outlet
4	Symmetric planes
Other	No slip wall

Table 2. Boundary conditions.

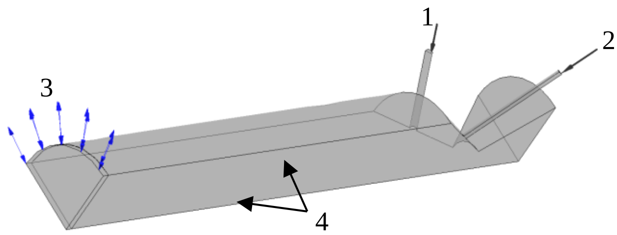

Figure 3. CFD domain.

Results and discussion

Figure 4 presents the calculated flow-patterns within the HSRC under 'combustion only mode' for four different α_{jet}. Four classes of flow can be identified from these CFD results. Figure 5 to Figure 8 present the key features of the different flow regimes:

Regime 1: Inward recirculation dominant flow regime. For an inclination angle of $0^{\circ} \leq \alpha_{jet} < 10^{\circ}$, an annular inward recirculation dominates the flow-field within the chamber, and a small annular outward recirculation is observed near the downstream wall ('outward' means from the axis towards the chamber wall, while 'inward' means from the wall to the axis).

Regime 2: Outward recirculation dominant flow regime. For an inclination angle of $10^{\circ} \leq \alpha_{jet} < 40^{\circ}$, the jets start to interact with each other and also with the cavity wall. An annular outward recirculation zone is found to dominate the flow-field inside the chamber. The recirculation length L_{re} in Regime 2 is much longer than that in Regime 1.

Regime 3: Outward recirculation with backflows regime. For an inclination angle of $40^{\circ} \leq \alpha_{jet} < 60^{\circ}$, the annular outward recirculation is still the dominating flow feature within the chamber. The recirculation length L_{re} is similar to Regime 2. However, annular outward backflows are observed around the impinging point (merging point) of multiple jets ('backflow' means the flow reversing into the SC).

Regime 4: Jet impingement regime. For an inclination angle $60^{\circ} \leq \alpha_{jet} < 90^{\circ}$, large annular outward backflows can be found within the secondary concentrator section, while the area of annular outward recirculation inside the chamber becomes smaller. Also, L_{re} has a significant decrease compared with Regime 3. Hence, annular outward recirculation zones are identified in both chamber and secondary concentrator sections.

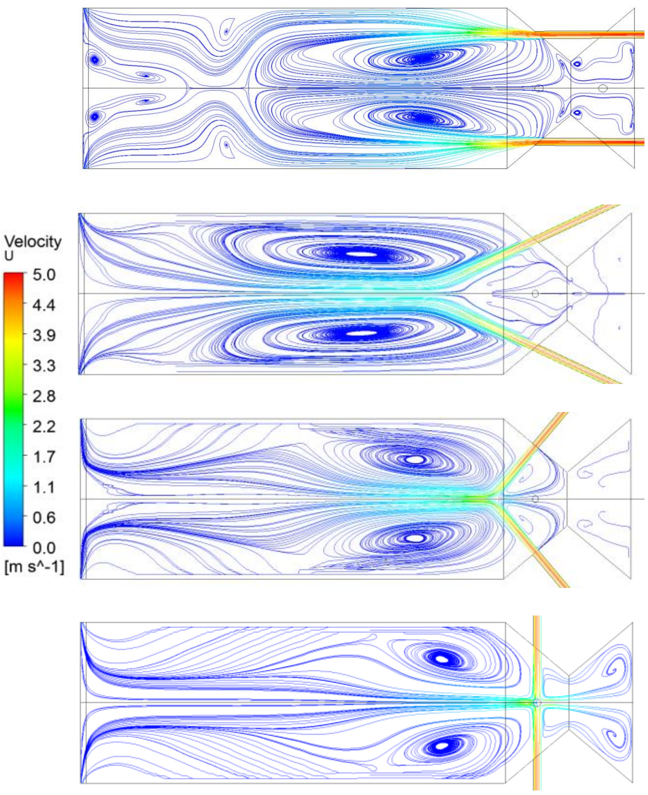

Figure 4. Calculated streamline for the case of $\alpha_{jet} = 0^{\circ}, 25^{\circ}, 50^{\circ}, 90^{\circ}$.

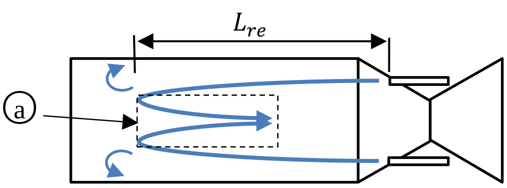

Figure 5. Flow regime 1 (a = annular inward recirculation, L_{re} = recirculation length).

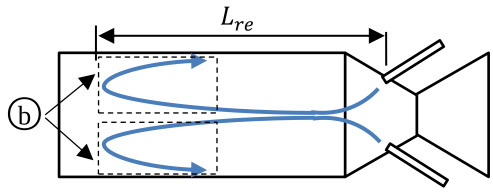

Figure 6. Flow regime 2 (b = annular outward recirculation).

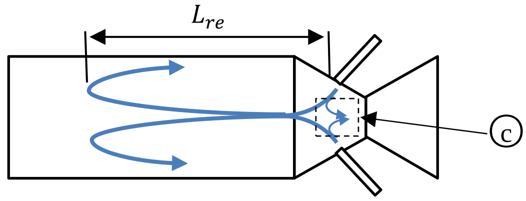

Figure 7. Flow regime 3 (c = outward backflows).

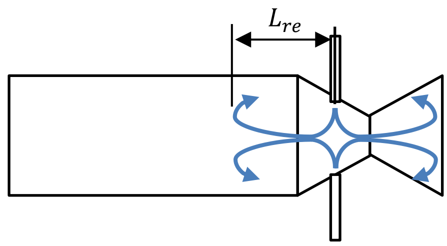

Figure 8. Flow regime 4.

This section would present the quantitative analysis for five distinct angles ($\alpha_{jet} = 0^{\circ}, 25^{\circ}, 50^{\circ}, 75, 90^{\circ}$). Figure 9 presents the dependence of the mean centreline velocity profile along the centreline on the inclination angles. It can be seen that the inclination angles 50°, 75° and 90° generate significant negative velocity profiles ($u_c/U_j < 0$) upstream of the impinging region ($x \leq 0.03\ m$). However, for small inclination angles (0° and 25°), the negative velocity profile was found to disappear. This indicates that the significant back-flow is likely to be found at larger inclination angles (Regime 3 and Regime 4). In addition, it can also be seen that with an increase of α_{jet} from 25° to 90°, the location of the positive velocity peak in the chamber varies from downstream (0.07 m) to the upstream (0.02 m) region, which indicates that the impinging point is moving from downstream to upstream. However, the impinging point does not depart significantly from the axis of the chamber.

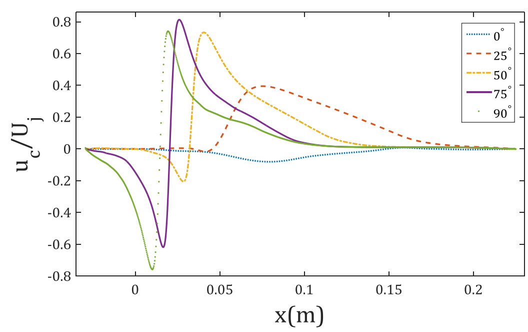

Figure 9. Calculated evolution of the axial velocity u_c along the HSRC centreline normalised by injection velocity U_j as a function of the HSRC length for five inclination angles, x = 0 m refers to the location of the aperture plane. The range of x < 0 m refers to the secondary concentrator.

Figure 10 presents the effects of the inclination angles ($\alpha_{jet} = 0^{\circ}, 25^{\circ}, 50^{\circ}, 75, 90^{\circ}$) on the normalised recirculation length (L_{re}/L_c), and mass flow rate through the secondary concentrator (M_{ap} refers to the mass flow rate through SC, and M_{in} refers to the injected mass flow rate). It can be seen that the recirculation zone increases significantly (L_{re}/L_c = 64% to 76%) varying α_{jet} from 0° to 25°, while it decreases in the range $25^{\circ} \leq \alpha_{jet} \leq 90^{\circ}$. The case of $\alpha_{jet} = 25^{\circ}$ provides the largest annular recirculation zone ($L_{re}/L_c = 76\%$) and very small back-flow rate ($M_{ap}/M_{in} \approx 0.3\%$) compared with the other four cases, which is able to enhance the mixing of reactants and heat transfer in 'combustion only' mode. It can also be seen that for $\alpha_{jet} < 50^{\circ}$, there is almost not injected flow entering the secondary concentrator ($M_{ap}/M_{in} \approx 0.3\%$). However, as the inclination angle is further increased ($\alpha_{jet} \geq 50^{\circ}$), the percentage of mass flow rate (M_{ap}/M_{in}) increases significantly from 0.3 % (at $\alpha_{jet} = 50^{\circ}$) to 66 % (at $\alpha_{jet} = 90^{\circ}$), which means more fluids will escape to the SC (closed-shutter mode) or even outside (open-shutter mode). The loss of hot reactants from the cavity through the aperture may lead to significant decreases in reactor efficiency.

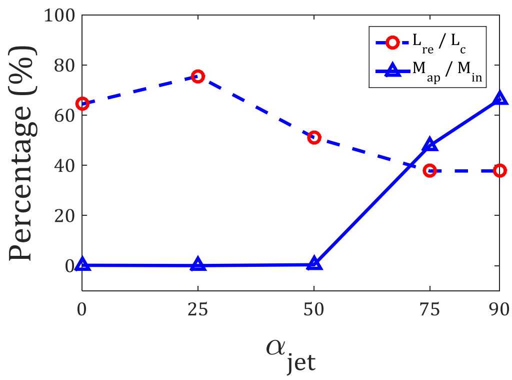

Figure 10. Calculated recirculation length normalised by chamber length, and calculated mass flow rate through the secondary concentrator normalised by inlet mass flow rate as a function of the inclination angle

Conclusions

A CFD study was conducted to better understand the flow patterns inside a cylindrical geometry equipped with four annular jets inclined at several different angles (α_{jet}). This iso-thermal study aimed at emulating the flow regimes for 'combustion only mode' of the Hybrid Solar Receiver Combustor (HSRC). The key outcomes are as follows:

- Significant back-flow through the secondary concentrator is likely to be identified in $\alpha_{jet} \geq 50^{\circ}$.
- About 0.3% of the injected flow would enter the secondary concentrator when $\alpha_{jet} < 50^{\circ}$. This indicates that the angle range $\alpha_{jet} < 50^{\circ}$ may limit the decrease of reactor efficiency.
- The α_{jet} could significantly influence the flow field within the HSRC with smaller α_{jet} ($0^{\circ} \leq \alpha_{jet} < 10^{\circ}$) leading to an inward annular recirculation while larger α_{jet} ($10^{\circ} \leq \alpha_{jet} < 90^{\circ}$) generates an outward annular recirculation with a back-flow ($\alpha_{jet} \geq 50^{\circ}$) through the aperture plane.
- The 'inward recirculation dominant flow' ($0^{\circ} \leq \alpha_{jet} < 10^{\circ}$) and 'outward recirculation dominant flow' ($10^{\circ} \leq \alpha_{jet} < 40^{\circ}$) are deduced to be the preferred classes of flow for the 'combustion only mode' HSRC because a long recirculation and a small backflow occur in these two flow regimes.

Acknowledgements

The authors will acknowledge the financial support from the Australian Research Council.

References

[1] Boushaki, T., et al., Effects of inclined jets on turbulent oxy-flame characteristics in a triple jet burner. *Exp. Therm. Fluid Sci.*, **32**, 2008, 1363-1370.

[2] Boushaki, T., et al., The behaviour of lifted oxy-fuel flames in burners with separated jets. *Int. Commun. Heat Mass*, **34**, 2007, 8-18.

[3] Boushaki, T. & Sautet, J.C., Characteristics of flow from an oxy-fuel burner with separated jets: influence of jet injection angle. *Exp. Fluids*, **48**, 2010, 1095-1108.

[4] Chammem, T., Vauquelin, O., & Mhiri, H., Performance evaluation of alternative tunnel longitudinal ventilation systems using two inclined jets. *Tunn. Undergr. Sp. Tech.*, **41**, 2014, 53-61.

[5] Chammem, T., Mhiri, H. & Vauquelin, O., Dominant Flow Features of Two Inclined Impinging Jets Confined in Large Enclosure. in *Proceedings of World Academy of Science, Engineering and Technology*. 2013.

[6] Chammem, T., Mhiri, H. & Vauquelin, O., Experimental and computational investigation of Reynolds number effect on the longitudinal ventilation in large enclosure of twin inclined jets. *Build. Environ.*, **67**, 2013, 87-96.

[7] Desideri, U. & Campana, P.E., Analysis and comparison between a concentrating solar and a photovoltaic power plant. *Appl. Energ.*, **113**, 2014, 422-433.

[8] Long, S., et al., CFD Modelling of Isothermal Multiple Jets in A Combustor, in *International Conference on CFD in the Minerals and Process Industries (11th: 2015: Melbourne, Australia)*, 2015.

[9] Mehos, M.S., et al., Combustion system for hybrid solar fossil fuel receiver, Midwest Research Institute, 2004.

[10] Moore, J. & Apt, J., Can hybrid solar-fossil power plants mitigate CO2 at lower cost than PV or CSP? *Environ. Sci. Tech.*, **47**, 2013, 2487-2493.

[11] Nathan, G., et al., A hybrid receiver-combustor. 2013, *Provisional Patent Application No. 2012/901258.*, Adelaide Research and Innovation Pty. Ltd, 2012.

[12] Ordorica-Garcia, G., Delgado, A.V. & Garcia, A.F., Novel integration options of concentrating solar thermal technology with fossil-fuelled and CO 2 capture processes. *Energy Procedia*, **4**, 2011, 809-816.