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Experimental Investigation of the Flow Characteristics Near the Aperture of a Model Hybrid Solar Receiver Combustor

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Abstract

Presented in this paper is an experimental investigation of the flow structure near the aperture of a scaled down laboratory model of a Hybrid Solar Receiver Combustor (HSRC). The aim of the work is to evaluate the flow characteristics in the vicinity of the cavity aperture as function of the external flow velocity, simulating wind, and the flow patterns within the cavity induced by four jets simulating the burners. This interaction is expected under the mixed mode of utilizing both solar and combustion energy. Under this mode, ingress/egress into and from the solar cavity receiver due to the pressure difference between the inside of the cavity and the ambient, leads to convection losses, particularly under high wind velocities. In the current study, a simplified and scaled down HSRC geometry is used. It includes a cylindrical cavity of diameter 74 mm and length 225 mm. The configuration includes four jets with a diameter of 3.5 mm to model burners with different inclination angles of α_{jet}=25° and 50° and different azimuth angles of γ_{jet}=0°, 5°and 15°. The tests were conducted in the water channel using Particle Image Velocimetry (PIV) technique to measure the flow field. The conducted experiments aimed to investigate the influence of jet inclination and azimuth angle on the flow patterns through the aperture of the cavity. Furthermore, the influence of external flow changes on the flow pattern inside the cavity is investigated by adjusting the water channel stream velocity to 0.0, 0.08, 0.16 and 0.24 m/s. The results show that the flow behavior through the aperture strongly depends on two main factors. Firstly the flow fields induced by the variation of the inclination angle of the jets and secondly the external stream velocity. These results point to a complex interaction of the external and internal flows and highlight the need for the development of a fluidic barrier to de-couple them.

Introduction

Renewable energy is being deployed in order to mitigate climate change, cater for the increase in energy demand and as a clean energy source to support the de-carbonization of industrial processes. Solar energy, as a form of renewable energy, has been utilized for electricity generation using Photovoltaic (PV) and thermal energy using Concentrating Solar Thermal (CST) technologies [1]. However, due to the intermittent nature of the solar resource new approaches are being developed to increase solar share and guarantee firm supply. CST systems can greatly benefit from hybridisation and thermal storage as methods to overcome the problems with the intermittency of solar energy [2, 3]. To address the intermittent nature of CST, backup system where an auxiliary fossil based energy device is maintained for the time when solar energy is not enough is being used. Hybrid concepts such as solar with combustion of biomass or fossil fuels and wind energy are some of the proposed combination and it is believed to be a promising combination. Integration of CST into a conventional fossil fuel power plant has been suggested to solve the problems of the continuous dispatch of power or thermal energy [2]. The newly developed, hybrid solar receiver combustor (HSRC) concept provides a unique and cost effective solution for the aforementioned problem by providing a firm supply and reduced infrastructure costs as compared to stand alone systems [4, 5]. The distinctive geometry of HSRC features a single cavity which acts both as a combustion chamber and a solar receiver, where multiple burners and a heat exchanger are found within the cavity (Figure 1). The integrated combustion energy source into the cavity receiver opens the way for a mixed mode of operation, combustion and CST. This system avoids start-up and shut-down losses related to application of conventional hybrid systems [6].

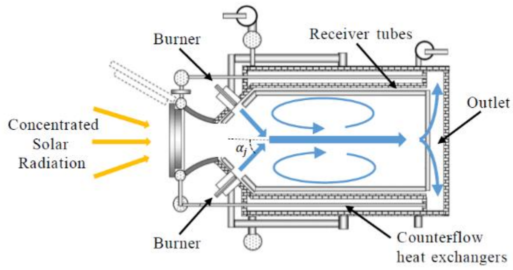

Figure 1- Schematic diagram of Hybrid Solar Receiver Combustor

The unique configuration of HSRC makes it necessary to study the flow field inside the cavity in order to optimize the flow behavior induced by the multiple jets inside a confined cavity and its interaction with the outside flow through the aperture.

Many studies in the literature have targeted the investigation of the flow field induced by multiple jets including parallel jets, opposed jets and inclined jets. Gao et al. [7] investigated the flow characteristics in confined impinging jet reactors by using PIV. They studied the effect of various geometric parameters and operating condition on the normalized mean velocity, turbulent kinetic energy and stagnation point offset from the center of the cavity. They found that in Reynolds number range of 10,620 to 21,210, the effect of Reynolds number on the normalized velocity is negligible. The normalized stagnation point is very sensitive to the jet velocity ratio. They emphasized that an equal volumetric ratio of the jets is essential to locate the stagnation point in the center of the cavity. Long et al. [8] used numerical modelling to investigate the effect of the jet inclination angle (α_{jet}) in a cylindrical cavity, similar to the HSRC configuration, equipped with four jets and using water as working fluid. They studied the configuration with a closed aperture and a throat, using CFD code ANSYS CFX in their modelling. Their work has identified four flow regimes within the cavity. The regimes have a strong inward annular recirculation for $0\ ° \leq \alpha_{jet} < 10°$, outward recirculation dominant flow for $10\ ° \leq \alpha_{jet} < 40°$, outward recirculation with back flow for $40\ ° \leq \alpha_{jet} < 60°$ and jet impinging flow $60\ ° \leq \alpha_{jet} < 90°$. The results show that configuration of the jets not only changes the flow pattern inside the cavity but it also affects the backflow through the throat. Long et al. [9] have also investigated flow structure within a cylindrical chamber generated by planar-symmetric isothermal jets using water as the working fluid. In their joint systematic experimental and numerical study, they evaluated the cases with two and four jets for the inclination angles (α_{jet}) over the range of 0 to 90. Their results show that the mean flow field strongly depends on the inclination angle and the number of the jets. Their research reveals that, the extent of the backflow inside the cavity through the throat, the turbulent intensity, the flow stability and the dominant recirculation zone depend on the inclination angle of the jets, as expected. However, the number of jets has a secondary influence on the turbulence intensity, the flow stability and the transition between different flow regimes.

To the best of the authors' knowledge, the interactions of the flows inside and outside a cavity with injected jets has not been investigated in the literature and requires further research. In this paper, we investigate the flow behaviour through the aperture induced by the jets inside the cavity and the external flows. To characterise the flow behaviour and identify the effect of the key controlling parameters on the velocity field, extensive experimental investigations were conducted in the University of Adelaide water channel. The findings and interpretations are presented in this paper.

Methodology

To determine the effect of internal flow pattern change on the flow through the aperture, several prototype models of a cylindrical cavity, with an open aperture, were designed and built. These prototypes aremade of Acrylic material and include different internal jet configurations. The transparent prototypes have a similar refractive index as water which allows it to be used with water as the working fluid and lend itself to the application of laser-based techniques such as PIV.

Figure 2 and Table 1 illustrate the key geometric features of the experimental configurations. The experimental setup is designed so that the different jet configurations, as shown in Table 2, can be investigated while using the same cavity. The cylindrical model has 74mm of internal diameter and is 225mm in length with an annular gap as the outlet of the cavity. The cavity inlet is configured with a straight desk which has an aperture of 24.6mm diameter. Four equi-spaced jets are included on the aperture side to model the combustion burners. Previous investigation, using similar geometries [9], has shown that the mass flow rates through the aperture will increase significantly when the flow pattern within the cavity changes due to the change in the inclination angle of the jets. The two configurations considered give a flow pattern which is classified as 'outward recirculation' when the inclination angle of 25° (α_j =25°) or 'outward recirculation with back flow' when the inclination angle is 50° (α_j =50°). Therefore, these two inclination angles of jets are considered for the current project. The cases of the jets with 50° inclination angle has three different azimuth angles of γ_{jet}=0°, 5°and 15° while the case with 25° inclination angle has azimuth angle of 15°.

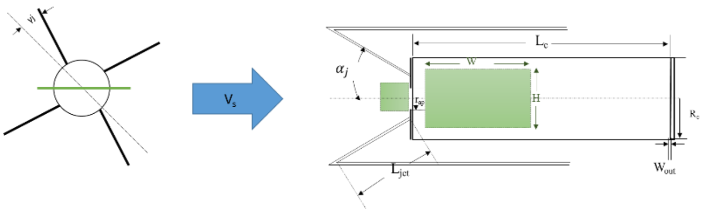

Figure 2- Schematic of the experimental model showing key geometric features of the configuration

Table 1- Values of the geometric parameters of the experimental configuration

Geometric Parameter	Value	Description	Geometric Parameter	Value	Description
L_c	225 mm	The length of the cylinder	D_{jet}	3.35 mm	The diameter of the nozzle
R_c	37 mm	The Radius of the cylinder	R_{ap}	24.6 mm	The radius of the aperture
L_{jet}	150 mm	The length of the jet supply pipe	α_j	50°, 25°	Jet inclination angle
W_{out}	3 mm	The width of the outlet for the exhaust	γ_j	0°,5°, 15°	Jet azimuthal angle

The tests were conducted in a recirculating water channel with a maximum speed of 0.3 m/s. The rectangular test section is 2.0 m long with a cross-section of 0.5m × 0.5 m. The device is submerged in the water and held there using a specially designed holder. The blockage ratio of the test section is 7.2% which is small enough to prevent wall effects. The volume flow rate of the jets were set at 1.4 l/min, resulting in a jet inlet velocity of 2.8 m/s and a Reynolds number of 10,500.

Table 2- Cases notation for the configurations investigated experimentally in the present study

Cases	Jet inclination angle, α_j	Jet azimuthal angle, γ_j	Stream velocity of the water channel (m/s)
25-15-(B-0-0.08-0.16-0.24)	25°	15°	Blocked aperture, 0.0, 0.08,0.16,0.24
50-15-(B-0-0.08-0.16-0.24)	50°	15°	Blocked aperture, 0.0, 0.08,0.16,0.24
50-5-(B-0-0.08-0.16-0.24)	50°	5°	Blocked aperture, 0.0, 0.08,0.16,0.24
50-0-(B-0-0.08-0.16-0.24)	50°	0°	Blocked aperture, 0.0, 0.08,0.16,0.24

The PIV technique was used to measure the instantaneous velocity field in the vicinity of cavity aperture and inside the cavity. The flow is seeded with polyamide seeding particles with a mean diameter of 50 µm and the density of 1.03 g/cm^3. The water within the channel is circulated back into a reservoir creating a closed loop operation. Seeds are added to the reservoir at the start of the test campaign, in order to provide a continuous seeding of the flow. The seeded particles were illuminated using an Nd-YAG double-Pulsed laser (Quantel Evergreen 200-200 mJ) operating on the second harmonic mode, giving two laser pulses at 532nm. The pulses were formed, using suitable optical components, to give horizontal laser sheets with a thickness of ~2 mm. PIV images are recorded by the sCMOS camera (Andor Zyla 5.5) with 5.5 megapixel resolution, capturing a region of interest with 2000×2000 pixels. The Andor SOLIS image capturing software is used for image collection. The laser and camera are connected to a pulse generator (Berkeley Nucleonics, Model 565) and a timer box to synchronize the data collection. Images were recorded from the bottom view of the cavity.

The images were acquired at a rate of 15 Hz with delay time of 4ms and 0.15ms for outside and inside measurement, respectively. A total of 500 image pairs were captured for each case. The post processing of the captured images was conducted using the PIVlab toolbox of MATLAB. The instantaneous velocity vectors were measured for an area of 24.6×24.6 mm^2 upstream region of the aperture inlet and 50×90 mm^2 inside the cavity. The images were processed using an interrogation window size of 64×64 pixels with an overlap of 50%.

Results and discussions

Figure 3 depicts the measured streamline patterns and the velocity contours within the cavity for the case with inclination angle of 50° and azimuth angle of 15° for the blocked aperture, stream velocity of 0.0 m/s, 0.08 m/s, 0.16 m/s and 0.24 m/s.

As could be seen, opening the aperture changes the flow pattern inside the cavity and expands the recirculation zones further downstream inside the cavity. Such changes show that the external flow changes the flow characteristics inside the cavity. Figure 4 shows the evolution of the mean axial velocity along the centreline of the cavity normalized by the jet inlet velocity.

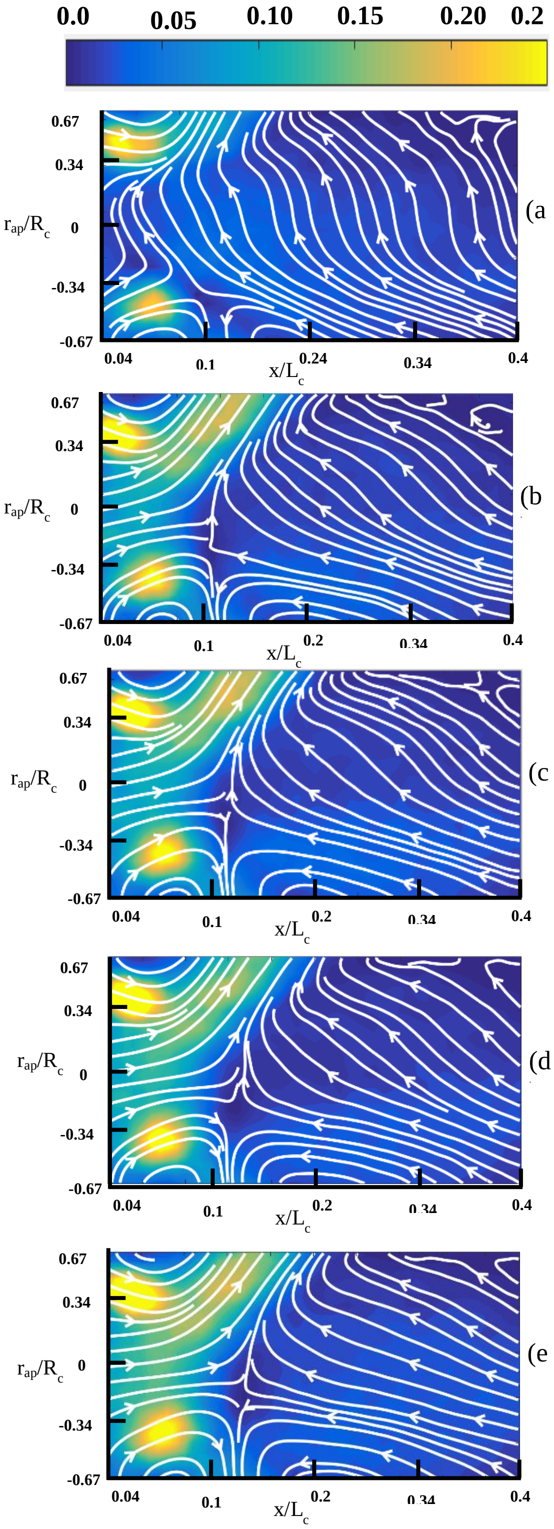

Figure 3- Velocity contour and streamlines inside the cavity for the case with α_j = 50° and γ_j=15°, a) Blocked aperture (50-15-B), b) V_s=0.0 m/s (50-15-0), c) V_s= of 0.08m/s (50-15-0.08), c) V_s= 0.16m/s (50-15-0.16), and d) V_s=0.24m/s (50-15-0.24).

As can be seen for the all cases the stagnation point, (the point that axial component of the velocity (V_x) to the velocity of the jet (V_{jet}) equals to 0.0) is located on the axis. The stagnation point transfers from x/L_c=0.15 to x/L_c=0.18 by changing the external velocity which shows expansion of the vortices in the vicinity of the aperture. Furthermore, opening the aperture affects the flow field in the vicinity of the aperture, and moves the highest velocity zone further downstream.

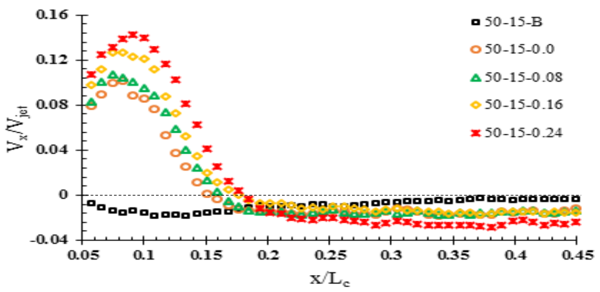

Figure 4- Spatial variation of the mean axial velocity (V_x/V_{jet}) along the centerline of the cylindrical chamber normalized by the inlet velocity as function of chamber length for α_j = 50° and γ_j=15°. Cases plotted are Blocked aperture (50-15-B), V_s=0.0 m/s (50-15-0), V_s= 0.08m/s (50-15-0.08), V_s=0.16m/s (50-15-0.16), and V_s=0.24m/s (50-15-0.24).

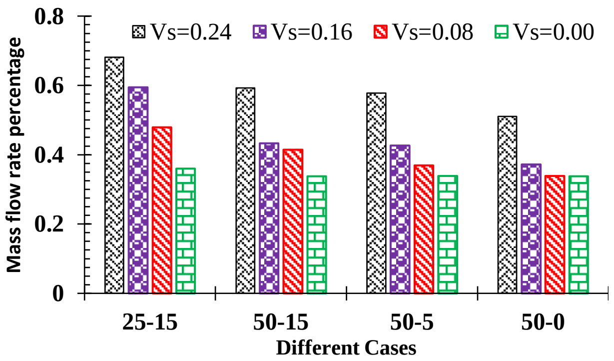

Figure 5-Percentage of the mass flow through the aperture to total mas flow from the jets, for different cases with inclination angles of 25° and 50° and azimuth angles of 15° ,5° and 0° in different stream velocities of 0.24, 0.16, 0.08 and 0.0 m/s.

Figure 5 shows the effects of the jets configuration and external stream velocity on the percentage of normalized mass flow rate through the aperture. As can be seen even for the stream velocity of 0.0 m/s, the ratio of mass flow through the aperture to the mass flow through four jets is 30% which shows that opening the aperture even in no wind condition causes a significant air ingress to the cavity. In addition, the measured normalized mass flow rates show that increasing the inclination angle from 25° to 50°, decreases mass flow rate by 10% for the stream velocity of 0.24 m/s while for cases with zero velocity of water channel stream, changing the inclination angle from 25° to 50° makes only 2% changes in normalized mass flow rate. This result is reasonable when observing the different flow patterns induced by the inclination angles of 25° and 50°. For the inclination angle of the 25°, the recirculation zones are closer to the centerline creating negative pressure that induce more flow through the aperture. While for the inclination angle of 50° the center of the recirculation zones are closer to the wall and have less effect on the flow behavior through the aperture. Furthermore, for the same inclination angle of 50°, by decreasing the jet azimuth angle from 15° to 0°, the mass flow rate through the aperture decreases markedly. It is quite clear that in higher stream velocities (V_s=0.24 m/s), the inclination angle has more effect on the variations of mass flow rate through the aperture than the azimuth angle of the jets.

Conclusions

A combined experimental study was conducted to investigate the flow field inside and in the inlet of a cylindrical cavity with four jets inclined at two different angles of 25° and 50° and for different azimuth angles of 0°, 5° and 15° degrees. It was found that there is strong interaction of the flow field inside the cavity and the flow behavior through the aperture. Opening the aperture of the cavity for operation in mixed mode, causes more than 30% of dimensionless mass flow rate into the cavity even for no wind condition. These results point to a complex interaction of the external and internal flows and highlight the need for the development of a fluidic barrier to de-couple these two flows.

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