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The effect of inlet velocity and temperature on the strength of the swirling induced by a spilt channel: A CFD approach

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Abstract

Due to the increase of energy cost, natural heat resources and industrial waste heat have been considered as potential energy resources and has been the centre of attraction among many researchers in recent years. Limitations of the use of these freely available energy resources arise primarily from the engineering cost/efficiency challenges. Some researchers have focused on improving the efficiency of existing techniques to utilize these energy resources. Some other researchers have focused on finding new techniques of extracting energy from these heat resources. The ratio of the cost/efficiency index can be reduced not only by increasing the efficiency, but also by reducing the engineering cost. This research deals with an innovative low-cost technique to produce swirling flow by industrial wasted hot air which is already in use to induce fire-whirl by burning fuel in the laboratory. The configuration consists of two identical half cylinders which are placed off-centre. Previous studies show such a simple configuration is able to induce a swirling flow within the chamber when a hot air inlet is used instead of a fire. In this computational work, a configuration with nearly arbitrary geometries is modelled and the effect of the inlet temperature and velocity on the swirling strength is assessed. The computational results show reasonable agreement with the existing experimental data.

Introduction

Recent increases in fossil fuel cost is paving the way for new technology to harness and convert waste heat into a useful form of energy. Researchers are exploring how low grade natural heat source and industrial waste heat could provide a greener energy supply. Three main hurdles are low conversion efficiency, high initial investment, and possible adverse effect on the primary system. This work deals with a low-cost configuration to reduce the ratio of the cost/efficiency. The configuration is already utilised to induce fire whirl in laboratory. The configuration is a vertical channel with vertical slots along its height. A fire at the bottom of the split channel provides natural convection and inflow air from side slots which generates swirling flow. Replacing fire with hot air extends the possible application of the configuration to be integrated in harnessing exhaust hot air from industries and use of geothermal and solar energy.

A recent research shows the ability of the split channels to induce swirling flow using buoyant jet instead of fire, without any adverse impact on the performance of the primary system [1, 7]. In addition, the configuration is simple, does not require a high initial cost, and nearly maintenance-free operation as there is no mobile parts. The configuration simply converts thermal energy to kinetic energy. There are sufficient previous works which identify characteristics of the produced swirling fire, unlike with that for hot inlet gas. There is no previous work which shows the characteristic of the swirling flow generated in the case of hot inlet gas.

The cross-section of the split channels could have different shapes such as square, circular and hexagonal and the number of lateral gaps could be two, four or six. In this work, a cylindrical split channel with two lateral gaps is considered as most exhaust gases from industries are discharged from circular chimneys. The configuration consists of two identical half cylinders which are placed off-centre. The hot air enters to the configuration through a circular inlet at the base of the channel. The velocity distribution obtained in the case of hot air inlet is compared with two experimental works. The first experimental work [4] provides extensive results for radial and tangential velocity at different height of channel. The second experimental work [5] presents extensive results for axial velocity at different heights. The effect of inlet temperature and pressure on the velocity profile and the strength of generated swirling flow are also investigated. The velocity curl at Y direction which is the same as vorticity [2] can estimate the swirl strength. According to Fox [3], the relationship between the velocity and vorticity can be written as following:

$$\vec{\xi} = curl\,\vec{V} = \nabla \times \vec{V} \qquad (1)$$

Where $\vec{\xi}$ is vorticity and $\vec{V}$ is velocity vector.

The industrial waste and the geothermal heat energy sources are available with different outlet conditions which may affect the possibility to produce swirl flow within the spilt channel. As result, this study has assessed the generation of swirl flow using a variety of inlet temperatures and total inlet pressures.

Previous works [4, 5] show that the computational modelling is capable to estimate the velocity distribution within the channel in case of fire. A few recent works also show the computational work is able to reasonably predict the characteristics of flow within the channel.

Modelling

In this study, two cylindrical split channels with different geometrical parameters are modelled. The geometry of the first channel is similar with the work reported by [4] and the second channel is similar to the work of [5]. The channels are made up of two identical half cylinders which are located off-centres “see figure 1.” The geometrical parameters are presented in table 1. The top of the fuel pan is placed at the ground level in Kuwana’s work but it is 0.02 m above the ground level in Hassan’s work. The inlet hot air temperature and total pressure varied from 100°C to 1300°C and from 0 Pa to 5 Pa, respectively. The ambient wind speed is assumed to be zero for both cases.

The total number of meshes differs due to different domain sizes. The number of resolved meshes for simulating the first configuration is 2525044 tetrahedral elements and 1744 wedged elements. However, for the second configuration, the total number of tetrahedral element is 2,468,769 for all simulations.

The hot air has been treated as ideal gas and its thermodynamic properties vary with temperature which taken from the solver. The walls and the domain bottom had no slip boundary conditions which are assumed to be smooth and adiabatic. Thermal radiation is not modelled. The ambient temperature is assumed to be constant (25°C) ,but hydrostatic pressure changes by the following equation [6];

$$p = p_o \exp(-gy/RT) \quad (2)$$

Where p represents static pressure (Pa), p_o is the reference pressure (101325 Pa), y is height with respect to the reference point (m), R is air constant (287.1 J/kg/K) and T is the reference temperature (298.15K). The pressure is assumed known but the velocity value and direction are assumed to be unknown at the domain boundaries. The specified pressure is taken to be static pressure for the outflows but it is treated as total pressure for the inflows. The gravity is in the negative Y direction.

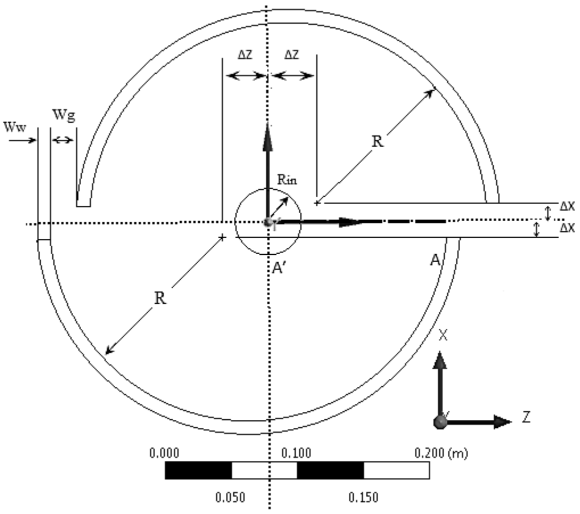

Figure 1.Top view of spilt channels.

Governing equations included in the simulations are the continuity, momentum, and thermal energy equations. The fully buoyancy model has utilised because of large temperature differences between the inlet temperature and ambient temperature (25˚C) through the fluid flow field. The shear stress transport turbulent model (SST) has been selected in the present study as recommended by [8]; and the initial turbulent intensity in the domain is 5%.

The high order discretisation schemes are used and the convergence criteria are set to 1×10^{-4} for all variables based on RMS residuals. In order to assess the robustness of the CFD results, the number of elements is increased by 50% and 36% for Hassan et al.'s configuration and Kuwana et al.'s configuration, respectively. The different simulation results show that the change of velocity profiles is less than 5%.

Configuration	Hassan et.al.[4]	Kuwana et.al.[5]
ΔZ (m)	0.015	0.015
ΔX (m)	0.025	0
R_{in} (m)	0.025	0.015
R (m)	0.15	0.1
W_g (m)	0.02	0.02
W_w (m)	0.01	0.01
Height (m)	2	1

Table 1. The dimentions of the configurations modelled

Results

Figure 2 presents the results of modelling at the height of Y/H= 0.05, using Hassan et al.'s configuration on the line A'-A "see "Figure 1". Where H is the channel height, and Y is axial distance in y direction. Hassan et al. [4] used 1-propanol as fuel and reported a maximum flame temperature of 1545˚C.

Figure 2a shows the axial velocity of the hot air at the centre of the channel with temperature of 1545˚C is 4.87 m/s, which is much higher than that of the fire whirls (0.45 m/s). This figure also shows a warm air with an inlet temperature of 30 ˚C to 50 ˚C is able to produce the same axial velocity of the fire-whirl. The axial velocity reduces at distances away from the centre in the all cases modelled but the rate of decrease is slower for the fire-whirl. At a distance of Z/R_{in}=3.2, the axial velocity in the all hot air inlet cases reduces to zero but this value is about 0.19 m/s in the case of the fire-whirl.

All the cases exhibit the same trend for the tangential velocity (see Fig. 2b). The tangential velocity is zero at the centre of the channel and reaches to a maximum value and then decreases as distance from the centre increases further to the zero value. The maximum tangential velocity of the fire-whirl is 0.7385 m/s which occurs at Z/R_{in}=1.393. In the cases of hot air, the maximum tangential velocities occur at a larger radii which are as follows: Z/R_{in}=2.48 at Tin=30˚C; Z/R_{in}=2.64 at Tin=50˚C; Z/R_{in}=2.56 at Tin=100˚C; and Z/R_{in}=2.4 at Tin=1545˚C and their values are 0.146 m/s; 0.249 m/s; 0.462m/s; 1.163m/s respectively.

Figure 2c shows the radial velocity profiles are quite different between the two cases. In the case of the fire whirl, the radial velocity remains negative at all distances from the centre. The magnitude of the radial velocity reaches to a minimum of -0.34 m/s at Z/R_{in}=1.396. On contrary, in the case of hot air, the radial velocity is positive and indicates a maximum at Z/R_{in}= 0.984, 0.862, and0.738 for Tin=30°C, 50°C, and 100°C respectively but declines at further distances to negative values.

Figure 3 present the results of computational work using Kuwana's configuration [5]. Figure 3a indicates the axial velocity distribution at the height of Y/H=0.05. The results are similar with those presented earlier. The central axial velocity at temperatures of 800°C and 1300°C is 2.402 m/s and 3.12 m/s respectively which are greater than that for the fire-whirl "2.31 m/s".

Figure 3b indicates changes in axial velocity with the channel height. In the case of fire-whirl, the axial velocity is 2.311 m/s at the height of Y/H=0.05 and increases to 4.874m/s at the height of Y/H=0.4. On the contrary, the axial velocity of hot swirling air decreases with height. The axial velocity at the height of Y/H=0.05 is 0.67m/s, 2.402 m/s, and 3.118 m at the inlet temperatures of 100˚C, 800˚C , and 1300˚C , respectively. These values decrease to 0.4955 m/s, 1.331 m/s, 1.5889 m/s, respectively at the height of Y/H=0.4.

Figure 4 shows the effect of the inlet temperature and pressure (velocity) on the radial and tangential velocities at the height of Y/H=0.05 at Kuwana's channel. The radial velocity at the centre of the channel is zero at all temperatures but reaches to a maximum values of 0.037 m/s, 0.088 m/s, 0.123 m/s and 0.1387 m/s at Z/R_{in}=0.81 for the inlet temperatures of 100°C, 500°C, 1300°C respectively "see Fig. 4a".

The radial velocity decreases at further distances and becomes zero at Z/R_{in}=5.667 for all the modelled inlet temperatures. The tangential velocities are also zero at the centre of channel but reaches to a maximum value at Z/R_{in}=3.267. The maximum tangential velocity in the negative direction is 0.340 m/s, 0.751 m/s, 0.912 m/s, and 0.966 m/s at temperatures of 100˚C, 500˚C, 1000 ˚C, and 1300˚C, respectively. The tangential velocity is again zero at Z/Ri_n=5.667 for all the temperatures.

Figure 4b shows the effect of inlet velocity (or inlet total pressure) on the radial and tangential velocities at the height of Y/H=0.05. The effect of increasing inlet velocity is very similar to the effect of increasing temperature. In this case, the radial and tangential velocities are a maximum at Z/R_{in}=0.809 and Z/R_{in}=3.238 respectively at all the pressures.

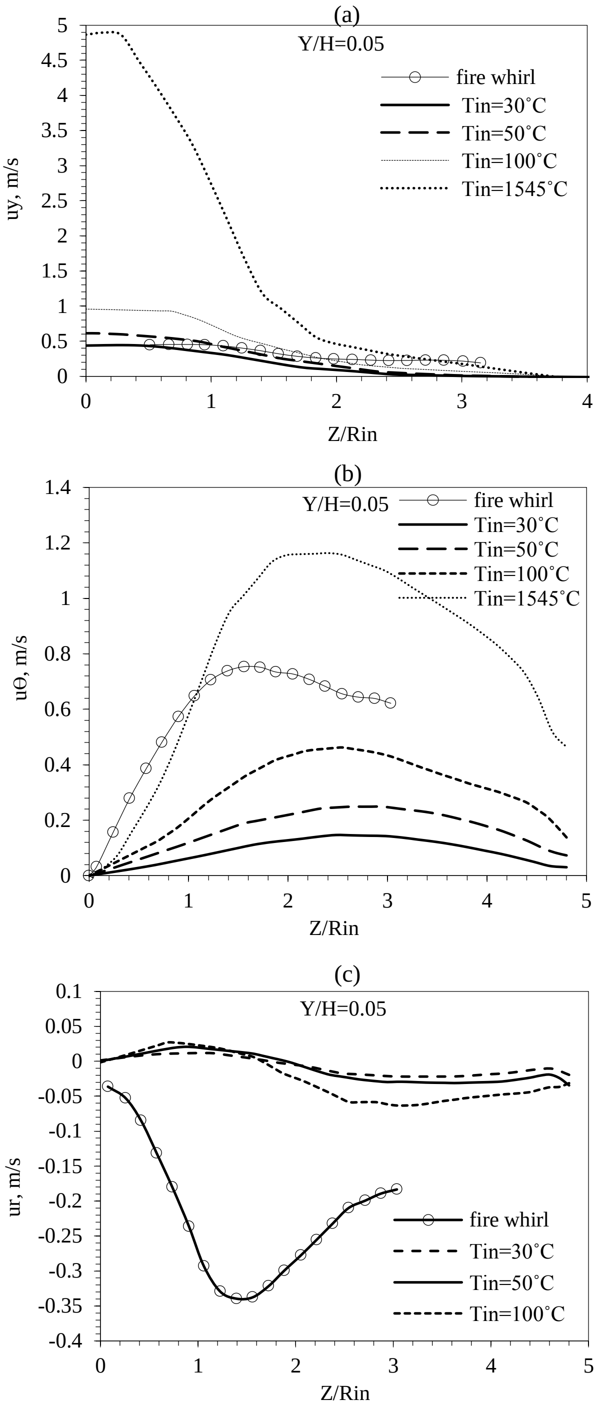

Figure 2. Comparison between the velocity components using Hassan's configuration for both generating fire whirl and swirling hot air at Y/H=0.05 on the line A-A′ (see fig. 1).(a) axial velocity; (b) tangential velocity;(c) radial velocity.

Figure 5 presents the effect of inlet temperature and pressure on the vorticity respect with the Y-axis at different heights. The vorticity exists at the base of the channel but rapidly reaches to a maximum value at Y=0.05m (Y/H=0.05) for all the cases. In the case of zero inlet pressure, the maximum vorticity is 0.875s^{-1}, 2.443 s^{-1}, 3.171 s^{-1}, and 3.449 s^{-1} at temperatures of 100˚C, 500˚C, 1000˚C, and 1300˚C respectively. The vorticity decreases as height increases and at Y/H=0.15 is about 0.765 s^{-1}, 1.788s^{-1}, and 2.633 s^{-1}, 2.874 s^{-1} at temperatures of 100 ˚C, 500˚C, 1000 ˚C, and 1300˚C, respectively. With further increase of the height, the vorticity increases and reaches its second maximum at Y/H=0.6, and then decreases to a minimum value at the top of the channel. The effect of the inlet pressure on the vorticity respect to the central axis of the channel at temperature of 100 ˚C is in figure 5.

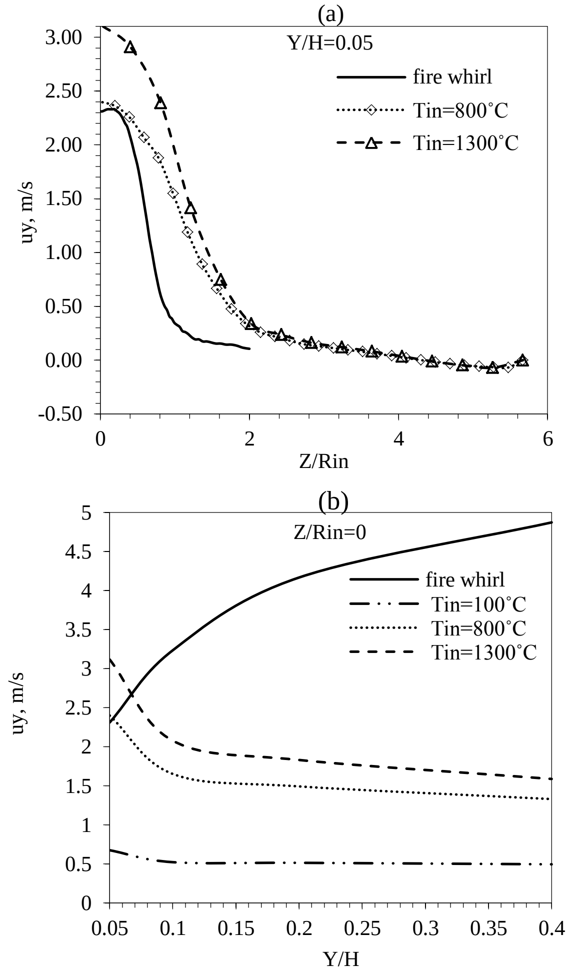

Figure 3. Comparison between the velocity components on the line A-A′ (see fig. 1) using Kuwana's configuration for both fire whirl and swirl hot air. (a) Axial velocity profile at Y/H=0.05 with different temperature; (b) the centreline axial velocity against height.

The vorticity exists for all the inlet pressures at the base of the channel. It becomes maximum at around Y=0.05 m (Y/H=0.05). The maximum vorticity is 0.875s^{-1}, 1.686 s^{-1}, and 2.516 s^{-1} at inlet pressures of 0 Pa, 2 Pa, and 5 Pa, respectively. The vorticity decreases at greater heights and reaches to a value of 0.294 s^{-1}, 0.625 s^{-1}, and 2.516 s^{-1} at Y/H=1 for total pressures of 0 Pa, 2 Pa, 5 Pa, respectively. On contrary to the effects of increasing temperature, the axial vorticity doesn't show a second maximum.

Discussion

The swirling flow generated by split channels presents a velocity profile which differs from that for a fire-whirl. The centreline axial velocity of the swirling flow at the base of the channel is greater than the axial velocity of the fire-whirl but the axial velocity decreases as height increases.

In the absence of a fire, it is expected that the temperature of hot inlet air decreases faster than fire-whirl case due to the lack of

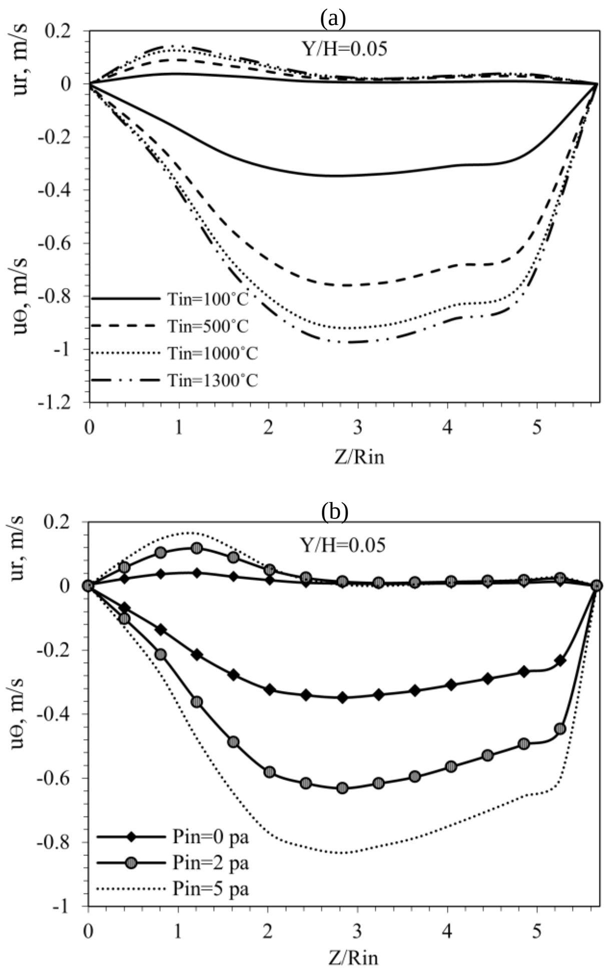

Figure 4. The effect entry conditions on radial and tangential velocity at Y/H=0.05. (a) Inlet temperature; (b) inlet total pressure (velocity).

combustion and the mixing with the entrained air which lowers the buoyancy force and consequently the axial velocity.

In addition, the positive and negative values of radial velocity along the radius of channel indicates that the upward moving air going out from the central plume "ur positive" to some point and then again shifting its direction forwards the central plume "ur negative" because of mixing with entrained radial inflow air from lateral gaps "see figures 2c ". On the contrary, in the case of fire, the air moving in due to the suction generated by the fire "negative radial velocity, see figure 2c". The tangential velocity of the swirling flow is less than that for the fire-whirl but the trends are similar in both the cases "see Fig.2b". In the case of the fire-whirl, the maximum tangential velocity occurs closer to the centreline of the channel "see Fig. 2b". A higher tangential velocity at a shorter radius shows a stronger rotation of the flow. The radial velocity of the flow within the channel is much smaller than that for the fire-whirl and has a different profile.

It was also found that all components of the velocity increases as inlet temperature or total pressure "velocity" increases "see Fig. 4". Increasing the inlet temperature increases the maximum vorticity with respect to the central axis at lower heights of the channel. This was expected as rising air loses its temperature and consequently its momentum as height increases. Increasing inlet velocity "or pressure" has a similar effect and increases the vorticity. The interesting result is that the height of the maximum vorticity is virtually independent of the inlet pressure or temperature at Kuwana's channel.

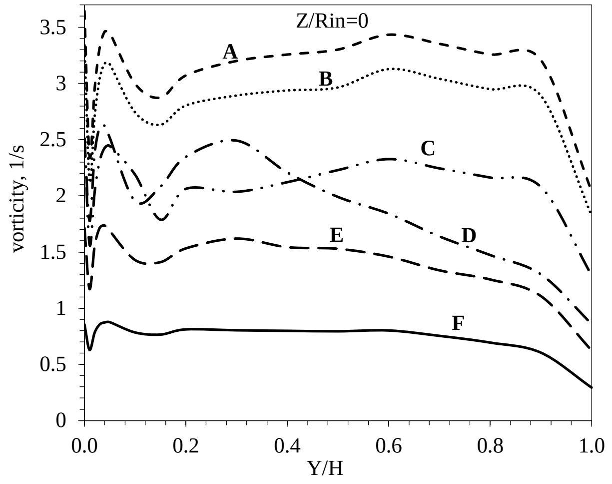

Figure 5. The effect of the inlet temperature and total pressure on vorticity with respect Y-axis. **A**: Pin=0 Pa &Tin=1300°C; **B**: Pin=0 Pa &Tin=1000°C; **C**: Pin=0 Pa & Tin=500°C; **D**: Pin=5 Pa &Tin=100°C; **E**: Pin=2 Pa &Tin=100°C; **F**: Pin=0 Pa &Tin=100°C

Conclusions

In this study two spilt channels has been modelled and the results showed that swirling flows could be produced by using hot air instead of burning fuel, no matter of the temperature and pressure of the hot air. The swirling strength of the flow is increased with the increasing in the inlet temperature and pressure of hot air. The axial velocity of the swirling flow decreases along the height of the channel in hot air case whereas it increases for fire-whirl case. In the case of swirling flow, the entrained velocity is less than that for the case of fire-whirl.

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