Numerical study on swirl flow analysis of a modified dump combustor for different vane angles

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Abstract. A numerical study has been carried out on flow characteristics for turbulent swirl flow in a modified dump combustor with central restriction of vertical ellipsoidal (VE) dome shape. Here, four different swirlers with different vane angle (15°, 30°, 45° and 60°) have been considered. In this study, the flow is considered to be highly turbulent and accordingly, the value of Reynolds number is chosen as 1.2x10^5. The governing realizable k-ε model and Reynolds stress model (RSM) have been used to solve the turbulent parameters for the considered cases. The relevant governing differential equations for the conservation of mass and momentum have been solved by using SIMPLE algorithm with the commercial CFD code ANSYS Fluent 16.0. From the study, it is observed that width and strength value of recirculating zone increase with the increase of vane angle of swirler up to a certain value. Variation of axial and tangential velocities with radial distance at different locations, have been studied in details for considered four swirlers. Under turbulent swirl flow condition, 45° vane angle swirler is suitable to create both primary re-circulation zone before the restriction and secondary recirculation zone after the restriction.

1. Introduction

The swirling motion disseminated to the flow in a modified dump combustor, either by a vane swirler or through a scroll, induces a pressure gradient along the radial direction and causes the pressure at the axis to fall. Adverse pressure gradient along the axis causes the formation of a central re-circulating zone as a result of the vortex breakdown. Swirling flows are often found in industrial flow applications when intense mixing between different streams is required. A typical example of an application is a swirl-stabilized flame, where the internal re-circulating zone acts as a flame holder. To mix air and fuel in a dump combustor for highly turbulent flow condition, swirler plays a big roll before the combustion and offers the chances of complete combustion with less emission. To improve the combustion efficiency, and to enhance mixing and burning of the air-fuel mixer better. Many researchers have reported many ascribes of the flow by experimental, numerical and analytical studies. Among them, Musa et al. [1] have performed both experimental and numerical investigation on effect of inlet parameters on reacting turbulent flow. They have done experiments for a ramjet engine, powered by solid fuel. They have reported that to enhance the regression rate for better turbulent mixing, swirling motion has an enormous effect on reaction strategies. They also study the effects of inlet parameters (temperature and mass flow rate) on the swirling reacting flow. Giorgi et al. [2] have investigated on the performance of a swirled combustor for different air-fuel mixing strategies. Numerically they have reproduced the typical combustor operations to understand the
relation between the injection conditions and the related flame structures. Tuncer et al. [3] have done their experiment on a swirl stabilized premixed combustor to study the flame stability into the re-circulation zone. They have used a 45° vane angle swirler which is constructed with eight numbers of blades. It is noted that up to a certain distance the vortex structures are similar for both cold and reacting flow. They have reported the flame structure, streamlines pattern of the combustion system for a low swirl number of 0.74. They also studied the effect of equivalence ratio on the noise formation and re-ignition phenomena under blowout condition. Majunder and mandal [4] have numerically investigated the turbulent fluid flow analysis by RANS-Method in an axis-symmetric sudden expansion dump combustor. They confirmed that two recirculation zones form in the throat by using modified k-ε model incorporating curvature correction. The variation of recirculation strength with change in dump size and Reynolds number has been observed. Zohir et al. [5] have experimentally investigated on swirl generator to enhance heat transfer through a sudden expansion pipe. For their investigation, they have considered Reynolds number ranging from 10,000 to 40,000. They have imported three different propeller fan of different swirl angles (θ=15°, 30°, 45°) at different positions throughout the pipe and reported that at an optimum value of swirl angle θ=45°, heat transfer rate increases up to 225%. Mak et al. [6] have carried out experiments to understand the field characteristics of swirl motion. They have done their experiments for three swirl numbers of 0, 0.17 and 0.65 for a Reynolds number of 10,000. They have observed that the jet spreads slightly faster, the separated flow reattaches earlier before the secondary recirculation zone disappears. After comprehensive study of literatures, it has famed that many researchers have done their experiments on swirl flow analysis to predict the flow pattern in a dump combustor for several time. There are very few literatures available based on modified dump combustor with a central restriction of vertical ellipsoidal (VE) dome shape and a swirler of different vane angles imported at the inlet of the dump.

2. Mathematical expression

2.1. Physical model for computation

Schematic diagram of the physical model for the flow through a modified dump combustor configuration with central restriction shape is shown in Figure 1. In the present work the shape and size of the combustor are taken from Ko and Sung [7]. The Inlet pipe length (L_i) and length of the casing (L_cas) are 0.08 m and 0.3 m respectively. The diameter of inlet duct (D_i) and outlet duct (D_o) are 0.04 m and 0.12 m respectively. The length (L_r) and diameter (D_r) of central restriction have been chosen as 0.06 m and 0.04 m respectively from Mandal and Chakarbarti [11].

![Figure 1. Schematic diagram of the modified dump combustor configuration with central restriction of vertical ellipsoidal dome shape.](image-url)
The radius ($R_t$) of the vertical ellipsoidal dome shape is taken as 0.02 m from Ghose et al. [8]. The ratio of major to minor axes for the vertical ellipsoidal dome is 1:1.8. A swirler is considered to be placed at the inlet duct to impart the required swirl flow. For simulation, inlet condition of flow is assumed to be same as the exit flow from the compressor. In order to vary the swirl intensity at the entry of the dump combustor, different vane angles of swirler is chosen.

2.2. Numerical model and design parameters of swirler

Four different vane angle swirlers have been considered. This considered swirler is not arbitrary. In fact, it has been clearly stated by Raj and Ganesan [9]. The standard turbulence $k-\varepsilon$ model has been used to estimate the low and medium swirl flows ($15^\circ$ and $30^\circ$ swirlers) and Reynolds stress model (RSM) is used to divine strong swirl flow as run into with $45^\circ$ and $60^\circ$ swirlers. While advancing the momentum equations, the turbulent viscosity ($\mu_t = c_{\mu}k^2/\varepsilon$) is calculated using the present values of $k$ and $\varepsilon$. At the inlet plane, uniform axial velocity has been contemplated, while the radial velocity is specified as zero. For computation of local tangential velocity the following equations are used as

$$V_{\theta in} = V_{x in} \tan \varphi$$

Where the vane angle $\varphi$ at any radius $r$ for such a swirler can be expressed as

$$\varphi = \tan^{-1}\left(\frac{r}{R_t} \tan \varphi_t\right)$$

Where, $R_t$ and $\varphi_t$ are the radius and vane angle at the tip of the swirler, respectively. Inlet distributions of $k$ and $\varepsilon$ have been considered as

$$K_{in} = 0.015(V_{x in})^2$$

$$\varepsilon_{in} = \left[\frac{(k_{in})^{1.5}}{0.005 \times (R_t - R_h)}\right]$$

These conform to a turbulent intensity of 10% of the inlet stream and an average turbulent length scale equal to 0.5% of the annulus height of the inlet duct reported in Mondal et al. [10]. The design details of a typical $15^\circ$ annular vane swirler are shown in Figure 2. The hub to tip ratio is considered as 2.5. The diameter of the hub is 16 mm. length of the hub is taken 46 mm at the inlet.

![Figure 2](image-url)
2.3. Grid test for mesh independent solution
In this analysis, wall static pressure along the upper wall of the considered modified dump combustor has been studied to illustrate grid independence. Figure 3, illustrates the comparison for different quadrilateral elements of wall static pressure at Re=$1.2\times10^5$, non dimensional dump gap (DG) =1 and central restriction (CR) =100 percent.

Figure 3. Comparison of upper wall static pressure for different quadrilateral elements at Re=$1.2\times10^5$ for considered modified dump combustor.

Here, the model with different quadrilateral elements has been simulated to show the grid independence. The quadrilateral elements are selected as 70420, 124060 and 154238 corresponding to grid spacing 0.08, 0.06 and 0.04 respectively for the said configuration. From Figure 3, it can be seen that the wall static pressure values for all the three cases are almost similar and follow a similar pattern. The model with 124060 quadrilateral elements exhibits minimum wall static pressure drop beyond the throat, whereas the peak value of wall static pressure remains almost same for all three considered quadrilateral elements. Hence, for the whole numerical study, the model with 124060 quadrilateral elements has been considered.

3. Results and discussion

3.1. Validation of computational results
For validation of the present numerical model, comparisons are made between our numerical results and the experimental data reported by Raj and Ganesan [9]. The experimental geometry used by Raj and Ganesan [9] is considered in the simulation. The computations have been carried out for inlet velocity of 20 m/s, turbulent intensity 1% and aspect ratio of 3. During validation, the said model has been chosen with a 45° vane angle swirler at the inlet. Axial locations of presented velocity profile in our considered model have been converted to the locations in accordance with the paper Raj and Ganesan [9], and accordingly the results have been placed in Figure 4(a) and 4(b) respectively.

Out of different considered locations in the paper Raj and Ganesan [9], we have considered two axial locations (X/D_c=0.093 and 0.467). It shows the variations of axial and tangential velocity profiles at considered locations throughout the dump, along with the experimental results of Raj and Ganesan [9]. As observed, the numerical results obtained by us are in good agreement with the experimental data.

3.2. Variation of wall pressure
The numerical predictions for 30° vane angle swirler are validated by comparing against the experimental data of Rahim et al. [12] for the same geometric and operating conditions. Accordingly, a swirl number (SN) = 0.38, inlet axial velocity ($U_i$) =32.37 m/s, tangential velocity ($U_\theta$) =18.68 m/s and a non-dimensional dump gap DG=1 with vertical ellipsoidal dome at the liner head have been
used in the present computation. The validation has been made by comparing the casing wall pressure in the dump plane and the results have been presented in Figure 5(a) and (b).

![Figure 4(a). Axial velocity profiles at different axial locations.](image)

![Figure 4(b). Tangential velocity profiles at different axial locations.](image)

![Figure 5. Variation of wall pressure along the casing wall for (a) non-swirling (no swirler) and (b) swirling flows (30° vane angle swirler).](image)
It is observed that the numerical predictions agree to the experiment quite closely, particularly within the dump for non-swirl flow (S=0) in Figure 5(a). Within the dump in Figure 5(b), some disagreement in the negative peak wall pressure is observed particularly just after the restriction due to restricted length of central restriction in present model, though the overall qualitative trend and the positive peak pressure remain same.

3.3. Variation of axial velocity at different positions throughout the length

Figure 6, depicts the measuring positions of the mean axial velocities along the radial distance throughout the dump. Two axial locations are chosen in between throat and front of the restriction (X/D=2.5 and 3.5), near the second contraction (X/D=4.5) and after the second expansion (X/D=5.5) for comparison, as flow parameters change more contiguously in these positions.

![Figure 6. Details of position of measuring locations indicated by vertical lines.](image)

![Figure 7. Variation of axial velocity for different swirlers at different positions.](image)
From Figure 7 (a), at X/D = 2.5, the axial velocities gradually decrease from the central axis to the dump wall with increase in the radial distance. Near the wall of the dump, the values of axial velocities are zero for all swirler. Due to this variation of the axial velocity, a re-circulating flow is visible near the wall of the dump. In Figure 7 (b), just entry of the second contraction and in the front of the central restriction, the axial velocities near the central region is less due to the presence of the restriction. As the flow area is decreased the axial velocities increase to a maximum value for every swirler shown in Figure 7 (c)

Axial velocity near the upper wall of the restriction is more for 45° swirler, whereas at the same line, near the wall of the dump, axial velocity is negative. This reversed negative velocity creates a adverse pressure gradient which is responsible to create the re-circulation flow near the wall region. Figure 7 (d) shows that after the second expansion, the value of axial velocity goes negative for two times along the same radial distance. One is just end of the central restriction and another is near the wall of the dump for the second time.

From the velocity profile, it has been seen that the fluctuation of axial velocity is more for 45° swirler and in this case, more reverse velocity is created near the wall. As the turbulence kinetic energy dissipation rate near the outer periphery of the dump is more for 45° swirler, it creates more re-circulation zone. It may be predicted that by incorporating a 45° swirler at inlet, the dump combustor may perform in a better efficiency with better mixing and less emission.

3.4. Variation of tangential velocity at different positions

In swirl flow, the component of tangential velocity has enormous effect to create re-circulation zone of high strength compared to component of radial velocity. As the swirl number (S) of the swirler is the ratio of axial flux of tangential momentum to the axial flux of axial momentum.

Figure 8. Variation of tangential velocity for different swirlers at different positions.
From Figure 8, shows the variation of tangential velocity at four considered positions for different swirlers. From Figure 8 (a), at the inlet casing of dump, the maximum tangential velocity is more for 45° swirler compared to others three swirlers. As the swirl number is more for the 45° swirler, the fluctuation of maximum tangential velocity is also more at any location. Tangential velocity just before the restriction, is more for 60° swirler near the axial region shown in Figure 8 (b), whereas along the same line tangential velocity is more for 45° swirler near the wall. In Figure 8 (c) and (d), when the velocity gradient is increased suddenly in the second expansion region, the turbulence kinetic energy is very less at the end of the restriction. The 30° swirler creates a recirculation zone at this position but 45° swirler creates two strong recirculation zones at both central and nearest to the dump wall. The area of recirculation mass flow is also more at the outlet casing. In a swirl flow dump combustor, a swirler of 45° vane angle creates more reverse flow that may be useful for uniform mixing and complete combustion.

3.5. Variation of axial velocity contour
Figure 9 (a), (b), (c) and (d) show that the distribution of axial velocity in the mid plane for 15°, 30°, 45° and 60° vane swirlers respectively.

![Figure 9(a), (b), (c) and (d). Axial velocity contour in mid plane for 15°, 30°, 45° and 60° annular vane swirler respectively.](image-url)
From Figure 9 (a), it is seen that maximum reverse velocity occurs in case of 15° swirler. As the turbulent kinetic energy dissipation rate over the upper wall of the central restriction is high, the generated reverse flow creates the re-circulating zone near the wall of the dump. Another re-circulating zone, also called as secondary re-circulating zone, is created just after the second expansion and behind the restriction.

In Figure 9 (b), when the vane angle of the swirler is 30°, the kinetic energy dissipation is quite less over the restriction’s wall. The re-circulating flow near the corner region of the throat and in the second expansion region is more. Figure 9 (c) shows, the area of reverse velocity contour for 45° swirler. From the figure, it is noted that the said area is more than others. Due to the high tangential velocity and comparatively low axial velocity near the wall, the strong swirl flow creates a cyclone near the throat. This cyclone flow spreads up to second contraction region and creates more re-circulating zone throughout the casing. The reverse mass flow rate in secondary re-circulating zone just after the central restriction is larger compared to others.

Figure 9 (d) shows a narrow and short width re-circulation zone just after the restriction due to more blockages of 60° vane the axial velocity is reduced. The region with reverse velocity is termed as central re-circulation zone, which is mainly responsible for flame stabilization. It can be seen from Figure 9 (c), the length of recirculation zone is large after the restriction. This recirculation zone is critical as far as the residence time for the reactant species and the heat transfer rate are concerned.

4. Concluding remarks

In this present numerical work, the flow characterization of fluid flowing through a modified dump combustor with a central restriction has been carried out for turbulent swirl flow. Four different swirlers (15°, 30°, 45° and 60°) are used at the inlet for swirl flow analysis. It leads to following initial observations.

- Fluctuation of axial velocity with the radial distance at different positions, creates a negative pressure gradient which is responsible to create re-circulation flow near wall region of the dump.
- Throughout the dump, magnitude of tangential velocity is more for 45° vane angle swirler compared to 60° vane angle swirler which creates more blockage area in the flow direction to withstand the flow.
- Under turbulent flow condition, swirler of different vane angle plays a big role to create the swirl motion. Among the considered four swirler (15°, 30°, 45° and 60°), 45° swirler is more efficient to create re-circulation zone. This swirler may be recommended to use for further swirl flow analysis.

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