TECHNICAL NOTE

Enhanced vortex stability in trapped vortex combustor

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ABSTRACT

The Trapped Vortex Combustor (TVC) is a new design concept in which cavities are designed to trap a vortex flow structure established through the use of driver air jets located along the cavity walls. TVC offers many advantages when compared to conventional swirl-stabilised combustors. In the present work, numerical investigation of cold flow (non-reacting) through the two-cavity trapped vortex combustor is performed. The numerical simulation involves passive flow through the two-cavity TVC to obtain an optimum cavity size to trap stable vortices inside the second cavity and to observe the characteristics of the two cavity TVC. From the flow attributes, it is inferred that vortex stability is achieved by circulation and the vortex is trapped inside when a second afterbody is added.

1.0 INTRODUCTION

TVC is a relatively new concept for potential use in gas turbine engines addressing ever increasing demands of high efficiency, low emissions, low pressure drop, and improved pattern factor. This concept holds promise for future because of its inherent advantages over conventional swirl-stabilised combustors. The main difference between TVC and a conventional gas turbine combustor is in the way the combustion is stabilised. In conventional combustors, the flame is stabilised because of formation of toroidal flow pattern in the primary zone due to interaction between incoming swirling air and fuel flow. On the other hand, in TVC, there is a physical cavity in the wall of combustor with continuous injection of air and fuel leading to stable and sustained combustion.

A brief review of the literature on the experimental work and the numerical simulation of trapped vortex combustor are given below. Little and Whipkey[2] explored the drag and flow characteristics of locked vortex afterbody shapes formed by thin discs spaced along a central spindle. Their accentuation was to develop drag reduction concepts for conventional aircraft afterbodies. They demonstrated that the minimum drag corresponds to the aspect ratio where the recirculation zone is stable.

Hsu and Roquemore[1] revealed that when the cavity length is 0·59m of the forebody diameter, a vortex is trapped in the cavity. Peak combustion efficiency can be improved by increasing primary airflow rate and when a second trapped vortex is added to the combustor via a second afterbody downstream to the first afterbody.

Selvaganesh and Vengadesan[4] studied the characteristics of the trapped vortex combustor under cold flow (non-reacting) condition using k-ω family of turbulence models. From the entrainment characteristics, it is inferred that the primary air needs to be injected to accommodate the decrease in oxidiser inside the cavity to obtain better performance from the TVC.

Nandakumar and Vengadesan[3] investigated the vortex dynamics of the cavity into which the fuel/air is directly injected through jets. The chemical kinetics is modeled with the eddy dissipation model along with the turbulence models. It was observed that the modified k-ω turbulence model predicts temperature distribution better than those by other turbulence models.

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Viswanath[5] presented a review of the developments on the use of passive techniques or devices for axisymmetric base and net afterbody reduction in the absence of jet flow in the base.

It is well reported that the performance of TVC is strongly influenced by the stability of vortex. It has been conjectured that the addition of second cavity improves the constancy of trapped vortex. However, the detailed fluid dynamic changes inside the combustor due to the addition of second cavity and how it contributes to the vortex stability is much less understood. In this work, we study in detail the influence of second cavity on the performance of TVC under cold flow conditions.

2.0 OBJECTIVE

The objective is to study the vortex stability in the trapped vortex combustor when a second afterbody is placed under cold flow condition. From previous studies carried out by the same research group (Selvaganesh and Vengadesan[4], Nandakumar and Vengadesan[3]) on single cavity TVC respectively (the cold and the reacting flow), it is concluded that modified k-ω model predicts flow field better than those by other models. Hence in this work we use modified k-ω turbulence model.

3.0 METHODOLOGY

The geometry chosen for the study is the same used by Viswanath[5] for experimental studies. The two-cavity TVC geometry consists of 70mm diameter flat cylindrical forebody (D_0) surrounded by a cylinder of inner diameter 80mm (outer body). The fore-body spans a length of 30mm. It is concluded from Selvaganesh and Vengadesan[4] that a cavity with aspect ratio of 0·6 is optimum with regard to minimum change in mean drag coefficient ($\Delta\overline{C_D}$) we maintain the same aspect ratio. The coefficient of drag $C_D = D/(0{\cdot}5\rho U_0^2 A_p)$, where ρ is density of air, U_0 is the free stream velocity, and A_p is the projected area. Hence at 40mm downstream of the forebody, first afterbody of diameter (D_1) 50·8mm and width 20mm is placed and a second afterbody (D_2) of 40·95mm diameter and width 20mm is placed 9·975mm (G) downstream from the first afterbody. The optimum cavity size for the second cavity size is explained later. The fore-body and the two afterbodies are connected through a 9mm diameter cylindrical pipe.

Incompressible turbulent flow through the above explained TVC geometry is considered. Governing equations and numerical details are given in Selvaganesh and Vengadesan[4] for cold flow analysis of TVC. Unsteady Fluent code has been used and the termination of the program is based on convergence of drag coefficient to a constant value with flow time.

3.1 Boundary conditions

A flat velocity profile of 40ms^{-1} is applied at the inlet. The Reynolds number based on hydraulic diameter (Re_{Hd}) for the incoming velocity and the forebody diameter (D_0) is $1{\cdot}916 \times 10^5$. The turbulent intensity (I) of 4·5% based on the formula $I = 0{\cdot}16 \times Re_{Hd}$ for fully developed pipe flow and a length scale of inlet duct height (h = 5mm) are used as the boundary condition at the inlet. Neumann condition ($\partial\phi/\partial x = 0$) is prescribed at the outlet and axis boundary condition along the centre line is applied. The usual no slip is applied at the walls along the forebody-spindle-afterbody combination and the outer tube.

3.2 Grid independence study

A grid independent study has been done for two-cavity TVC using ten different grid size and $\Delta\overline{C_D}$ obtained is compared. 2D grid with axisymmetric boundary condition is used due to symmetry of the geometry. The grid independent study is carried out on the optimum cavity size for the second cavity which is explained later. The grid details and the ΔC_D obtained are summarised in the Table 1.

In this number of grids in x and y direction were varied separately and systematically as shown in the Table 1. It is seen from the table that for mesh size of 350 × 90, the ΔC_D shows negligible deviation when compared to those obtained by other grids. We have maintained the same grid parameters and arrived about mesh size of 270 × 90 for single cavity. Corresponding ΔC_D is given in the Table 1.

Table 1
Grid independent study

For two cavity TVC

Grid	Cells	Average C_D
350 × 95	49,653	0·0098
400 × 95	55,088	0·0103
500 × 95	60,742	0·0139
350 × 90	48,174	0·0105
350 × 80	44,704	0·0099
350 × 105	53,367	0·0105

For single cavity TVC

Grid	Cells	Average C_D
270 × 90	35,904	0·0188

4.0 RESULTS AND DISCUSSIONS

4.1 Optimum cavity size

In order to obtain a stable vortex inside the cavity, an afterbody needs to be placed at an appropriate position. Before carrying out detailed study on the second cavity, it is first necessary to arrive at the optimum cavity size for the second cavity (location of second cavity from the first cavity). For this, we have considered one diameter ratio D_2/D_0 = 0·585 (Viswanath[5]) and varied the position of second cavity. For every case we determined $\Delta\overline{C_D}$. $\Delta\overline{C_D}$ is obtained by subtracting the base drag coefficient without second cavity (i.e. with single cavity alone) and is plotted in Fig. 2.

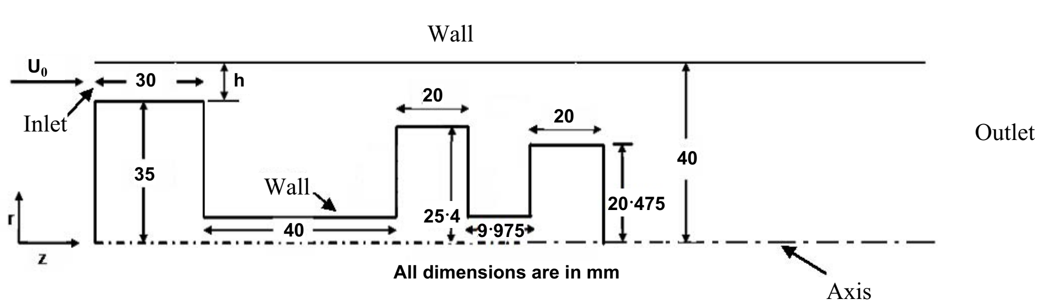

Figure 1. Geometry of trapped vortex combustor for numerical study.

The drag coefficient decreases initially with increase in separation distance (G/D_0) between the first afterbody and the second afterbody, reaches minimum and then increases for large separation. The results show that, the drag reduction is high when the second body is placed at $0{\cdot}585D_0$ downstream of the first afterbody.

4.2 Minimum pressure drop

One of the main objectives of any combustor is to maintain the minimum pressure drop .The pressure drop is strongly influenced by the fluid dynamics and geometry of the cavity (aspect ratio, blockage ratio, and length). The pressure coefficient for the two-cavity TVC is 16·87 and for a single cavity TVC is 19·02 (for the optimum grid size), there is 11% decrease of pressure drop for a two-cavity TVC with respect to the single cavity TVC.

4.3 Flow patterns

The cold flow inside the combustor can be described by the total pressure, stream lines and vorticity magnitude throughout the flow field. Respective quantities are shown in Figs 3 and 5. It is observed that, presence of a secondary vortex due to the second cavity stabilises the first vortex (called primary or main vortex). One can observe from the pressure plots (Fig. 3) that low pressure region inside the cavity is due to flow separation which results in vortex formation. We can observe from the streamlines plots (Fig. 4) that the flow is in clockwise direction. The wall after the first afterbody of single cavity and second afterbody of a two-cavity TVC behaves like a backward facing step (BFS). The recirculation region behind the afterbody is defined as the streamwise distance between the point of separation and the corresponding point of reattachment. We see that the recirculation length created behind the second after body is small when compared to that of single cavity TVC as it is 0·04m for single cavity TVC and 0·01m for the two-cavity TVC (Fig. 4). This could be due to the existence of second cavity. Due to the smaller recirculation region the drag experienced by the flow is less. The rate of rotation (circulation) is measured by the vorticity magnitude. This is high in two-cavity TVC when compared to that in the single cavity TVC. In the two-cavity TVC the overall circulation is predominant which leads to better mixing, when compared with the single cavity (Fig. 4). Mean vorticity magnitude were collected at different axial locations. For a two-cavity TVC the vorticity magnitude at x = 0·12m is 3,537·87s^{-1}, x = 0·09m is 4,952·63s^{-1} and at x = 0·05m is 5,522·74s^{-1} (Fig. 5) and for a single cavity the vorticity magnitude at x = 0·05m is 5,514·9s^{-1} and at x = 0·104 m is 1,394·16s^{-1}. From these values one can say that the vorticity magnitude is high in case of the two-cavity TVC. In Fig. 5 we notice that primary vortex is being shed in the single cavity and the vortex is trapped inside double cavity. From this it can be concluded that the vortex stability can been achieved when a second afterbody is placed.

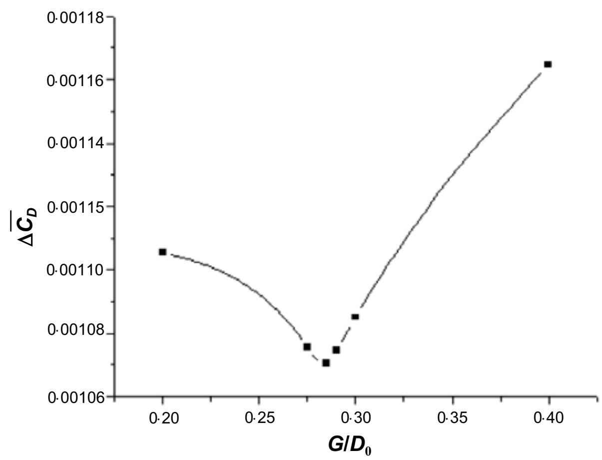

Figure 2. Change in drag coefficient due to the second cavity.

4.4 Residence time characteristics

The complete and effective burning of fuel can be achieved (1) by high rate of mixing fuel and air; or (2) increasing the fuel-in-combustor residence time. The residence time is time dependent and

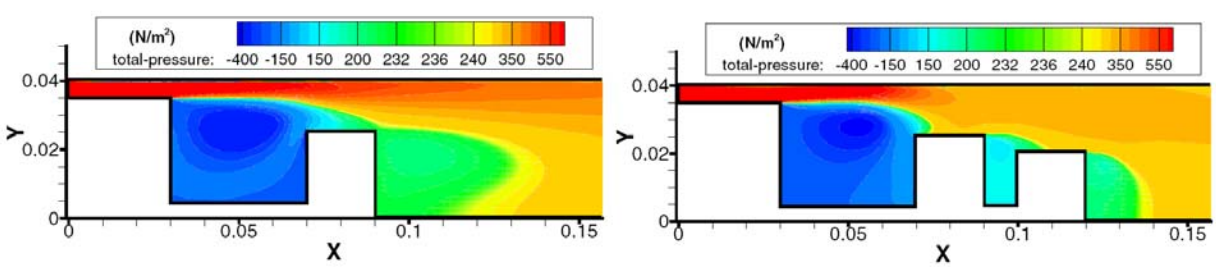

Figure 3. Mean total pressure plots for single and double cavity TVC.

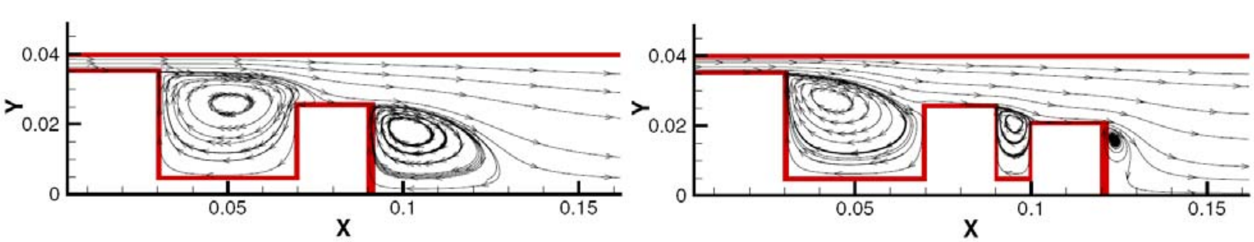

Figure 4. Mean streamline plots for single and double cavity TVC.

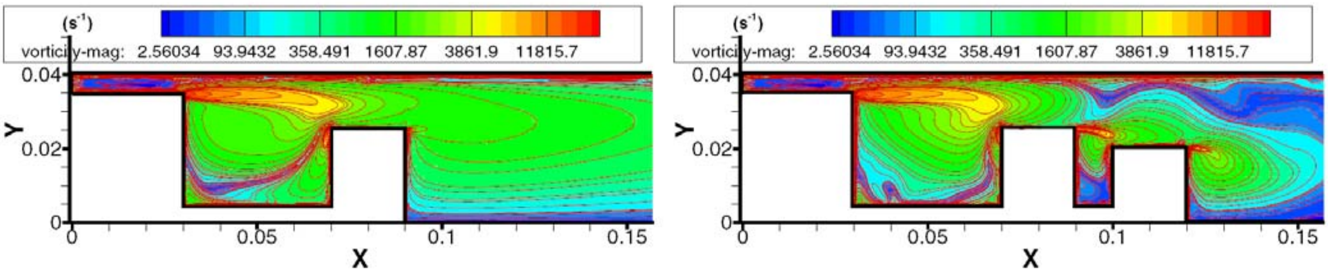

Figure 5. Mean vorticity plots for single and double cavity TVC.

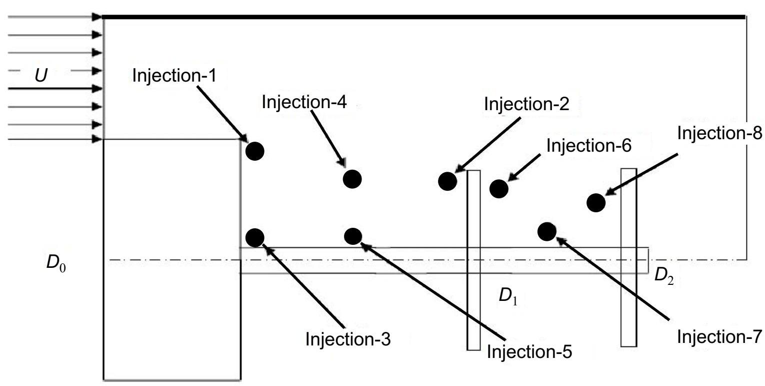

Figure 6. Locations of particle injections inside the cavity.

is calculated by injecting massless particles at different locations inside the cavity between the forebody and afterbody. The particles are injected into the upper and lower halves of the vortex that are formed inside the cavity. The different locations where the particles are injected are non-dimensionalised with the forebody diameter (D_0) shown in the Table. 2. Corresponding injection details are shown in the Fig. 6.

Table 2
Co-ordinate information for different injection points inside the cavities

Inside the first afterbody:

	z co-ordinate (m)	*r* co-ordinate (m)
Injection-1	$0{\cdot}52D_0$	$0{\cdot}45D_0$
Injection-2	$0{\cdot}05D_0$ before the disk	$0{\cdot}37D_0$
Injection-3	$0{\cdot}52D_0$	$0{\cdot}15D_0$
Injection-4	Centre of cavity ($X_c/2$)	$0{\cdot}2D_0$
Injection-5	Centre of cavity ($X_c/2$)	$0{\cdot}36D_0$

Inside the second afterbody:

	z co-ordinate (m)	*r* co-ordinate (m)
Injection-6	$0{\cdot}52D_1$	$0{\cdot}45D_1$
Injection-7	Centre of cavity ($X_c/2$)	$0{\cdot}36D_1$
Injection-8	$0{\cdot}05D_1$ before the disk	$0{\cdot}37D_1$

Residence time is inversely proportional to the decay time. The time taken by the particles to remain inside the cavity as a function of time taken to reach the complete domain (outlet) by that particle for both single and double cavity are given in the Table 3.

Table 3
Residence time of injected particles inside the cavity

	Time taken to remain inside the cavity as a percentage of time taken to reach the outlet	
	Single cavity	**Double cavity**
Injection-1	100	100
Injection-2	22·4	54·5
Injection-3	100	100
Injection-4	100	100
Injection-5	40·49	45·13
Injection-6	–	100
Injection-7	–	100
Injection-8	–	100

The observations made from the residence time characteristics are as follows:

When the particle is injected at the injection-2 location, the particle takes less time to remain inside the single cavity whereas in the case of double cavity it remains for higher time. Interestingly, the particles which are injected inside the second cavity (injection-6, injection-7, and injection-8) remain inside the cavity for all the time. From Table 3, we observe that the residence time for the particles is higher in the double cavity when compared to that in the single cavity. The higher residence time implies that the proper mixing of fuel and air in the cavity takes place and thereby higher combustion effiency can be achieved. Thus the vortex created in the second cavity entraps the particles and ensures stability of flame better and thus higher combustion.

5.0 CONCLUSIONS

In the present work, numerical investigation on the influence due to second cavity on the performance of TVC is carried out. At present a detailed cold flow analysis is carried out. Initially optimum cavity size for the second cavity is determined. Pressure drop and observations of flow patterns indicate that the presence of second vortex stabilises the primary vortex. Vortex stability has been achieved by the circulation of the fluid in both the cavities. With higher residence time due to the two-cavity TVC proper mixture of fuel and air takes place. The study reveals that the second cavity plays a role in stabilising the vortex and an actual reacting flow analysis is required to understand the improvements in combustion efficiency, mixing efficiency and reduction in NO_X emissions.

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