



Numerical Investigation of Merged and Non-merged Flame of a Twin Cavity Annular Trapped Vortex Combustor

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Abstract: The present work is focused to characterize numerically the merged and non-merged flame emanating from the cavities in downstream of twin cavity Annular Trapped Vortex Combustor (ATVC). The isotherm corresponding to the auto-ignition temperature is used to locate the merging point of the flame in the mainstream region along the combustor length. In present study, the cavity flame is said to be merged only if this isotherm corresponding to self-ignition temperature of methane is located within 20 percentage of the combustor length from aft wall of cavities. It is interesting to note that on increasing the power loading parameter (PLP) in mainstream for a constant power loading parameter ratio (outer to inner cavity), the merging point gets shifted towards the cavity aft-wall. This leads to the reduction of combustor length and subsequent reduction in overall weight of the gas turbine engine.

Keywords: Merged Flame, Trapped vortex combustor and Power loading parameter

1 Introduction: Conventional swirl combustors are used usually among the modern gas turbine engines. These combustors have some limitations like flame stability, higher emission level, and higher flame length. Its performance gets deteriorated under off-design conditions. In recent times, it is envisaged that Trapped Vortex Combustor (TVC) can improve its performance further. Trapped vortex combustor is a cavity-based combustor in which a vortex is trapped within the cavity [1], in this recirculation (low velocity) region where fuel and air are mixed well and burnt to establish self-sustained combustion [2]. The main advantage of TVC is its flame stability over a wide range of operating conditions. Besides this, TVC provides higher combustion efficiency, high fuel residence time as well as low pollutant emission [2].

Several TVC geometries have been investigated by various research groups [1-13]. Hsu et al 1995 in USA which was a can type configuration [1] and called first generation TVC (Trapped Vortex combustor) to meet the modern gas turbine combustor requirements. Mishra et al. [9] studied a 2D dimensional trapped vortex combustor, which have two cavities with two injection strategies. An extensive review of literature reveals that very limited work is done on annular TVC. Due to having several advantages over can configuration, in the present work the annular configuration is considered which has two cavity namely inner and outer cavities.

In the present combustor, two flames emanating from outer and inner cavities can help to ignite the mainstream air-fuel mixture in the nearer to the cavity. The present combustor should be designed and operated such that mainstream air-fuel mixture ignites closer to the cavity so that flame length gets reduced

2. Numerical Methods

2.1 Geometrical description of the combustor: The geometrical description of newly designed TVC combustor is shown in Fig.2. This combustor has two annular cavity namely inner and outer cavities. Inner cavity has 16 holes for each fuel and air in inline pattern besides this, outer cavity has 64 holes for each fuel and air inlets in similar pattern as inner cavity. Cut-way section of designed combustor with its inlets for inner cavity and outer cavity is shown in Figure (1a, b).

Computational domain is divided into three zones namely upstream zone, cavity zone and downstream zone; cavity zone has significant importance as it can influence combustor performance. It can be noted that quarter of 3D computational domain is considered as shown in Figure 1(c) using symmetry boundary conditions to reduce the computational cost. No slip wall and adiabatic in nature conditions are specified at all wall of the combustor. The results are analyzed at plane 45° inclined from XY-plane

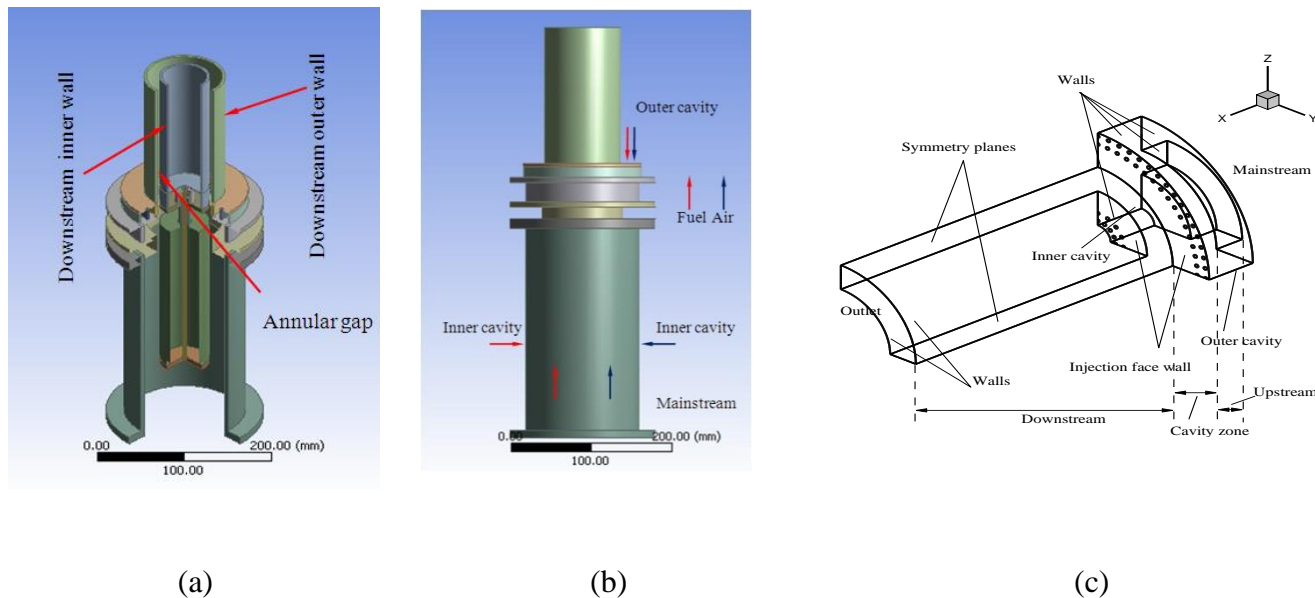


Figure (1)

in anticlockwise direction.

2.2 Numerical Model: Numerical simulations are carried out using Ansys Fluent software (version 13). Steady RANS simulations are carried out and equations are discretized using third order accurate QUICK scheme. Besides this, SST $k-\omega$ model is used to model the turbulence developed by Menter [4]. Two steps reaction chemistry is used with EDC combustion model [4].

2.3 Validation: The normalized total pressure drop across the combustor obtained from numerical simulation is compared with experiments as shown in Figure (2). It can be noted that total pressure drop is increasing with mainstream Reynolds number experimentally; similar trend is reflected in numerical results, which predicts the flow features within the acceptable error. Hsu et al. and Xing et al. [1, 12] also observed similar trend as that of the present study.

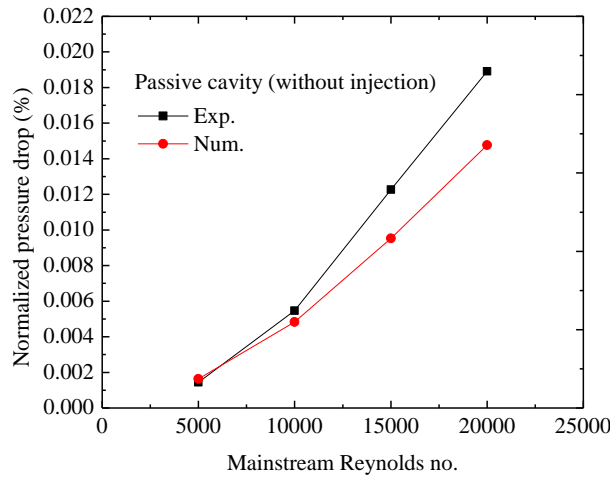


Figure (2): Normalized pressure drop vs Re_{ms}

3 Result and Discussions: Cavity plays an important role to stabilize the flame in the combustor and has significant impact on reduction of pollutant emission by mean of stage fuelling within the cavities. The present combustor has two cavities namely (i) inner cavity and (ii) outer cavity.

Besides this, major portion of total fuel is injected into the mainstream. The newly design annular TVC combustor has been investigated for flow conditions; inner and outer cavity are operated at $V_p = 50\text{ m/s}$ and 80 m/s respectively for all considered six cases, as given in the Table (3.1). In the present investigation, power loading parameter is defined which indicates how much power being generated due to burning of fuel in the combustor per unit volume. The power loading parameter is essential to normalise the cavity power as both the cavities are have different volumes given below;

$$PL = \frac{\dot{m}_f \Delta H_c}{\forall} \quad (3.1)$$

where, PL = power loading (W/m^3), \dot{m}_f = fuel mass flow rate (kg/s), ΔH_c = lower heating value of the fuel (J/kg) and \forall = volume to the combustor (m^3). This term, the power loading is defined separately for each combustor regions, namely (i) inner cavity, (ii) outer cavity, and (iii) mainstream as given below;

$$PL_{ms} = \frac{\dot{m}_{f_{ms}} \Delta H_c}{\forall_{ms}} \quad (3.2)$$

$$PL_{oc} = \frac{\dot{m}_{f_{oc}} \Delta H_c}{\forall_{oc}} \quad (3.3)$$

$$PL_{ic} = \frac{\dot{m}_{f_{ic}} \Delta H_c}{\forall_{ic}} \quad (3.4)$$

where, PL_{ic} = power loading for inner cavity (W/m^3), PL_{oc} = power loading for outer cavity (W/m^3), and PL_{ms} = power loading for mainstream (W/m^3). Note that the power loading ratio (outer to inner cavity) is kept constant while outer cavity operates at higher power loading as compared to inner cavity as shown in Table (3.1).

Table (3.1): Summary of flow conditions

Reynolds no.	ϕ_{ms}	ϕ_{cav}	PL_{ms} MW/m ³	PL_{ic} MW/m ³	PL_{oc} MW/m ³	$R = \frac{PL_{oc}}{PL_{ic}}$
10000	0.5	1.0	12.15	222.67	185.60	0.8
20000	0.5	1.0	23.67	222.67	185.60	0.8
20000	0.5	1.5	23.67	333.44	278.57	0.8
20000	0.5	2.0	23.67	445.02	372.01	0.8
20000	0.6	1.5	28.40	333.44	278.57	0.8
20000	0.6	2.0	28.40	445.02	371.20	0.8

3.1 Characterization of Merged and Non-Merged Flames: The present combustor has three region through which fuel has to be fed into the combustor namely (i) mainstream region (premixed), (ii) outer cavity region (non-premixed) and (iii) inner cavity region(non-premixed). In the present combustor, cavities are used to provide the pilot flame, which ignites the mainstream fuel-air mixture which will not be only dictating the flame length but also influencing the complete combustion of main stream fuel-air mixture. In the present work, an attempt has been made to reduce the flame length. For this propose, operating parameters namely mainstream Reynolds number, mainstream and cavity equivalence ratios are varied for a fixed cavity power loading ratio.

In this study, the merging of both cavities flame is essential for complete the combustion of mainstream fuel-air mixture. In order to estimate the merging location of cavity flames qualitatively, an effort has been made to locate the merging point of cavity flames in the mainstream region that influence the igniting of mainstream flow. The aim is to choose a proper criterion for identifying the merged and non-merged flames. Before venturing in the technical aspect, it is need to understand the concept of merged flame and non- merged flame.

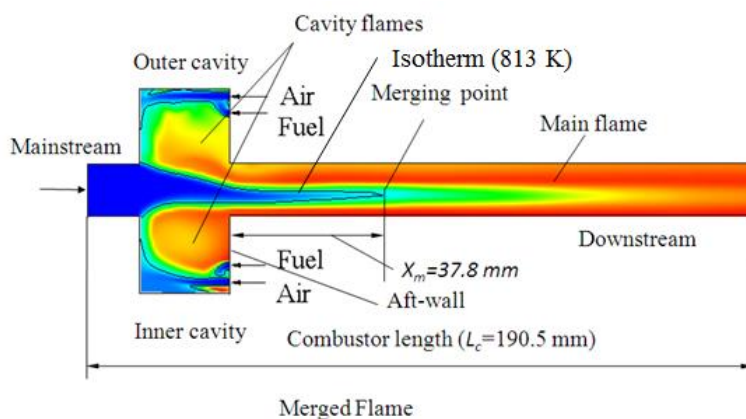


Figure 3: Merged flame for the case $Re_{ms}=20000$,
 $\phi_{ms} = 0.6$ and $\phi_c = 2.0$

Main flame is said to be merged only when flames from both the cavities approach together and are igniting the mainstream fuel-air mixture, consequently a single flame can be observed in the downstream of the cavity (see Figure 3). It is essential that the flame should be merged within an

acceptable length limit of combustor. For this purpose, the isotherm corresponding to the auto-ignition temperature of methane is used to locate the merging point in mainstream region along combustor length. In this criterion, the cavity flame is said to be merged only if this isotherm is located less than or equal to 20% of the combustor length at distance downstream of cavity. However, the merging point estimated from numerical results is located $X_m=37.8\text{mm}$ from the aft wall of the cavity as shown in the Figure 3, whereas X_m is the merging length measured from the aft wall. Note that auto ignition temperature (813 K) for methane is considered to trace the isotherm line in the present computation of merged-flame point (Lefebvre).

In order to study the effects of various operating conditions on establishing merged and non-merged flames qualitatively, a comparative study is carried out. For the different flow conditions as illustrated in the Table (3.1), temperature contours are analyzed at the 45° plane of the combustor domain.

3.1.1 Effect of Mainstream Reynolds Number: The temperature contours for $Re_{ms}=10000$ and 20000 at $\phi_{ms} = 0.5$ and $\phi_e = 1.0$ are shown in Fig.4. It can be observed from Figure 4 (a) that for $Re_{ms}=10000$ case that the cavity flames get merged at the distance $X_m = 0.0245\text{ m}$ from the aft-walls of the cavities. This merging point length happens to be 12.86 % of the combustor length (L_c) and hence can be considered as a merged flame according to merging point criterion chosen in this work. It can be noted that the power loading values namely $PL_{ic} = 222.67\text{ (MW/m}^3\text{)}$ and $PL_{oc} = 185.60\text{ (MW/m}^3\text{)}$ and at $12.15\text{ (MW/m}^3\text{)}$ are used for inner cavity, outer cavity and mainstream respectively (see Table 3.1).

In this case, cavity flames can manage to ignite the mainstream fuel-air mixture and thus likely to result in better combustion, which is a desirable condition for successful operation of TVC. Furthermore, for the case $Re_{ms}=20000$, $\phi_{ms} = 0.5$ and $\phi_e = 1.0$, as shown in Figure (4b), this merging point gets shifted far away from the aft-walls of the cavities in the downstream zone. Note that the merging point X_m is estimated about 0.0965 m from the aft-walls and it is 50.65 % of L_c . Hence this case can be considered as a non-merged flame. It is caused due to non-ignition of mainstream flow up to $X_m=0.0965\text{ m}$, as the mainstream flow with higher momentum flux quenches the emerging flames from the cavities although they are loaded at same power loading as in case of $Re_{ms}=10000$ case. The present study indicates that cavity flame merging point moves downstream with mainstream Reynolds number.

3.1.2 Effect of Mainstream Equivalence Ratio: An effort has been made to understand the effect of mainstream equivalence ratio on the merging of cavity flame. For this study, cases $\phi_{ms} = 0.5$ and $\phi_{ms} = 0.6$ at $Re_{ms}=20000$ and $\phi_e = 1.5$ are considered and the corresponding temperature contours are shown in Figure 5 (a) and Figure 5 (b) respectively.

For the case $\phi_{ms} = 0.5$ at $Re_{ms}=20000$ and $\phi_e = 1.5$ as shown in Figure 5 (a) the merging point is estimated at $X_m = 0.0605\text{ m}$ from the aft-walls of the cavities, that is 31.75 % of combustor length (L_c), which is non-merged flame according to choose criterion. It can be noted that the cavities are loaded at $PL_{ic} = 333.44\text{ (MW/m}^3\text{)}$ and $PL_{oc} = 278.57\text{ (MW/m}^3\text{)}$ and power loading $12.15\text{ (MW/m}^3\text{)}$ as illustrated in Table 3.1 for inner, outer cavity and mainstream respectively. However, for $Re_{ms}=20000$ and $\phi_e = 1.5$, when slightly increasing the mainstream equivalence ratio to 0.6, the merging point come closer to aft-walls and X_m is estimated to 0.039 m , which is 20.47 % of the combustor length.

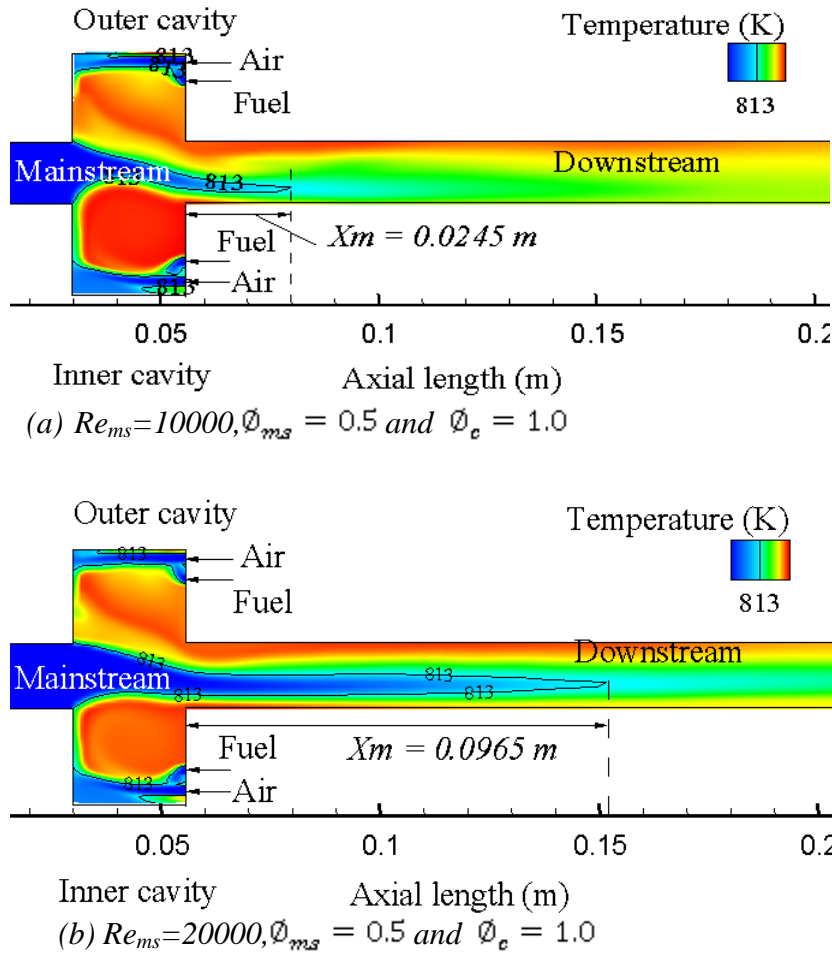


Figure 4: Temperature contours for $Re_{ms}=10000$ and 20000 at $\phi_{ms} = 0.5$ and $\phi_e = 1.0$

This value is very close to criteria chosen, for the merged flames and can say it is a merged flame. It can be concluded that cavity flame merging point length shifts to upstream location with increase the mainstream equivalence ratio.

3.1.3 Effect of Cavity Equivalence Ratio: As discussed in the previous sections, mainstream Reynolds number and mainstream equivalence ratio have the significant effect on merging point. However, in the present section, effect of cavity equivalence ratio on merged flame is investigated for three cases namely $\phi_e = 1.0, \phi_e = 1.5$, and $\phi_e = 2.0$ at $Re_{ms}=20000$ and $\phi_{ms} = 0.5$, whose temperature contours are shown as shown in Figure 6 (a), Figure 6 (b) and Figure 6 (c) respectively. For the case, $\phi_e = 1.0$ at $\phi_{ms} = 0.5$ and $Re_{ms}=20000$. It can be noted that the flame merging point is located at the distance $X_m = 0.0965 m$ from the aft-wall of the cavities in the downstream of cavity, which happens to be 50.65 % of the combustor length (L_c), which is essentially, a non-merged flame. It can be noted that the cavities and mainstream are loaded at $PL_{te} = 222.47 (MW/m^3), PL_{ce} = 185.60 (MW/m^3)$ and $23.67 (MW/m^3)$ for inner, outer and mainstream respectively. However, for the case $\phi_e = 1.5$ at $\phi_{ms} = 0.5$ and $Re_{ms}=20000$, as shown in Fig.6 (b) the merging point is estimated at the distance $X_m = 0.0605 m$ from the aft-wall of the cavities in the downstream, which is 31.75 % of the combustor length (L_c). It can be noted that for $\phi_e = 2.0$ and $Re_{ms}=20000$, flame merged point happens

to be 30.70 %, from the aft-wall of cavities, which is non-merged flame as shown in Figure 6 (c). This study reveals that the flame merging point gets reduced and comes closer to cavity aft-wall with increase in cavity equivalence ratio

4 Comparison of Merged and Non-Merged Reacting Flow: Based on criteria discussed in the above sections, two cases are considered for further analysis at merged and non-merged flame conditions. An attempt has also been made to compare the characteristics of temperature for both non-merged and merged flame cases.

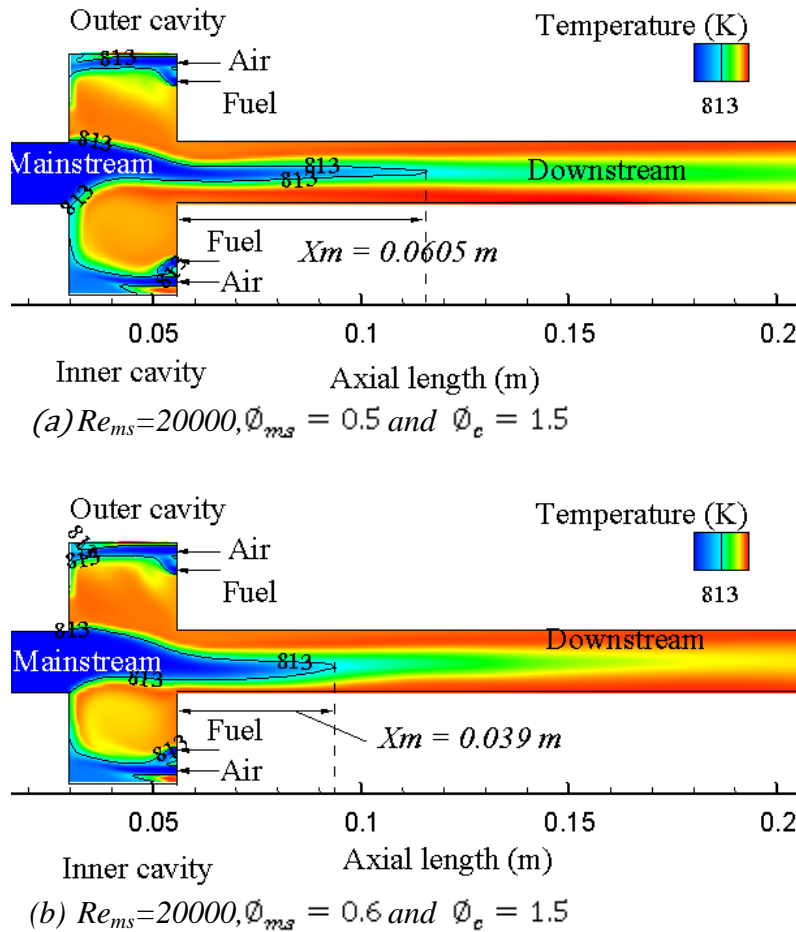


Figure 5: Temperature distribution at 45° plane from y direction

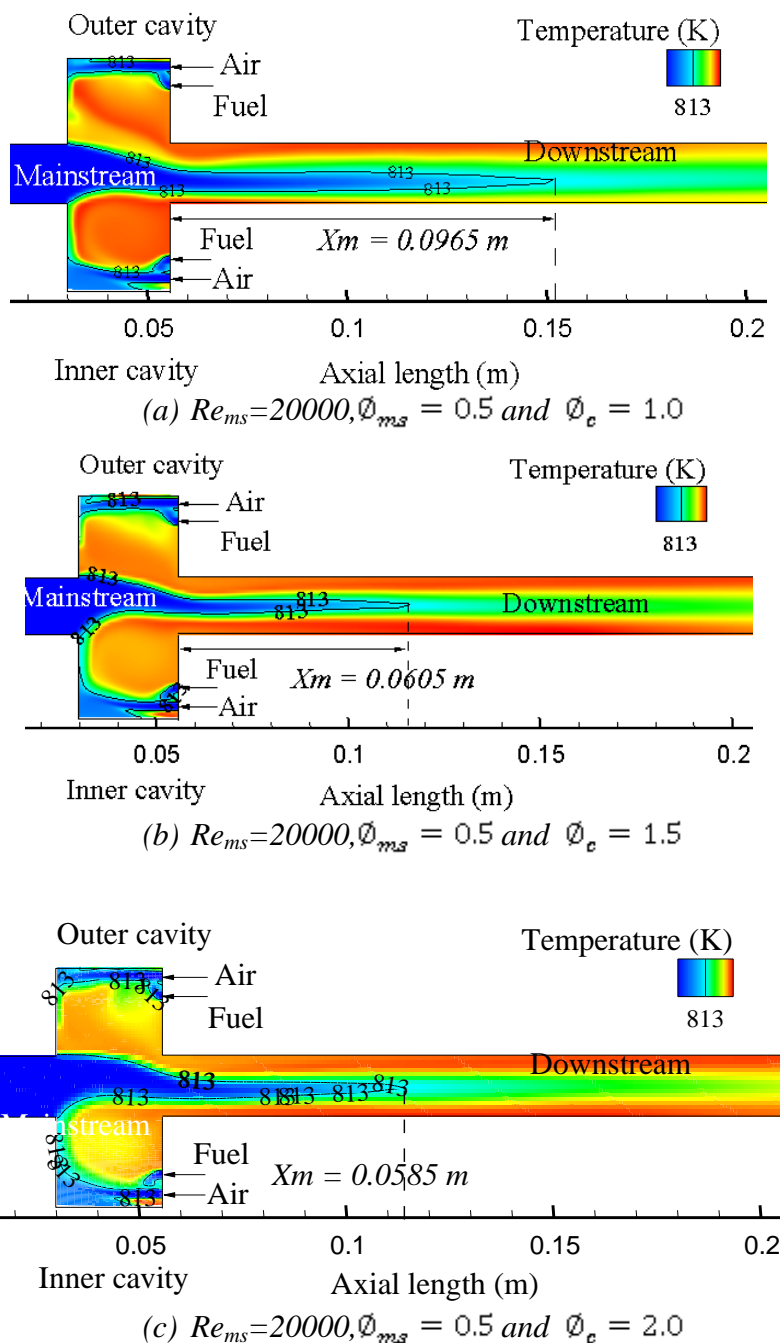


Figure 6: Temperature contours for cases $\phi_c = 1.0, \phi_c = 1.5$, and $\phi_c = 2.0$ at $Re_{ms}=20000$ and $\phi_{ms} = 0.5$

4.1 Temperature Distribution across the Combustor: Flame temperature is considered to be the prime factor as it controls the chemical reaction rate. In the present section, temperature distribution at different downstream and mid cavity sections of the combustor for two cases namely (i) merged flame and (ii) non-merged flame are shown in Figure 7 (a) and Figure 7 (b)

respectively. It can be noted that in merged flame case as shown in Figure 7 (a), the temperature in the cavity due to higher power loading, gets reduced due to incomplete combustion in the cavity region, as the cavity is fuel rich. It is evident that heat release gets reduced and caused the lower temperature. Besides this, in the injection region of the cavity, temperature value ranges from 1400 to 2000 K, but it increases at the shear layer formed by the mainstream and cavity interactions. The visible appearance indicates that higher temperature prevails in the downstream of cavity and results in ignition of mainstream fuel due to interactions of cavity flames and mainstream fuel-air mixture. It can also be observed at the exit of combustor very high temperature appears due to the ignition of mainstream fuel-air mixture. However, in case of non-merged flame as shown in Figure 7 (b) cavities have the higher temperature as compared to the merged flame that causes due to better combustion of fuel-air mixture when the cavities are operated at equivalence ratio closer to stoichiometric, where peak temperature attains due to the higher heat release. Besides this, in the injection region of the cavity, temperature ranges from 1500 to 2200 K, but it increases at the shear layer formed by the mainstream and cavity flow. However, in downstream of the cavity temperature gets reduced because of mainstream flow quenches the cavities flame as mainstream remains unburnt in case of non-merged flame. Besides this, for the non-merged case, mainstream is operated at less fuel as compared to merged case, which results in inefficient combustion at the mainstream region.

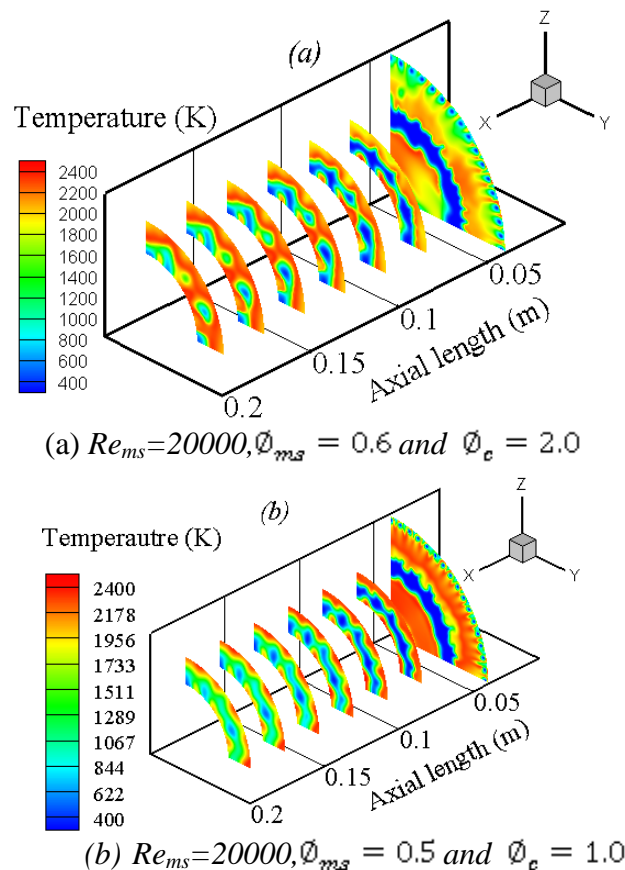


Figure 7: Temperature distribution for merged and non-merged flame

4.2 Temperature Distribution at Centreline: In order to analyze it further, temperature profile at centreline of the plane 45° from the Y-direction are compared for both cases namely (i) merged and (ii) Non-merged flame as shown in Fig.8. It can be noted that up to mid of the cavity, mainstream fuel-air mixture remains unburnt as its temperature is below auto ignition temperature of the methane-air mixture. At downstream of the cavities, flames emanating from cavities interact with mainstream fuel-air mixture and ignite it in case of merged case and caused the temperature increase at the centreline as shown in Figure 8. However, in case of non-merged flame case, the mainstream mixture remains unburnt as both the cavities and the mainstream are operated at lower power loading. It can also be noted that the temperature increases but the magnitude is lower as compared to the merged flame case. This study reveals that cavity power loading affects the heat release in the cavity as lower temperature is observed in merged flame as it operates in fuel rich zone beside this, higher temperature is observed in non-merged case as it operates near to stoichiometric condition. It also affects the heat release in mainstream flow as in case of merge flame

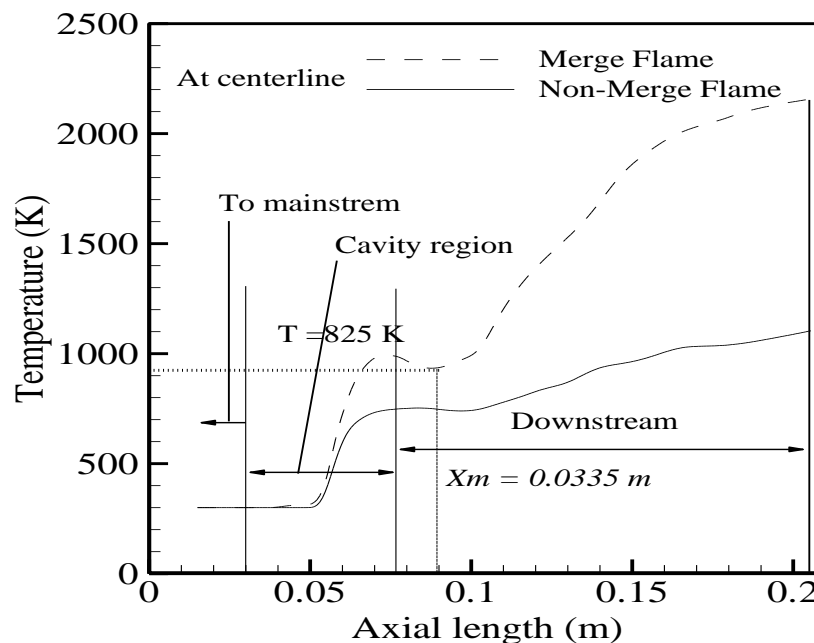


Figure 8: Temperature at centreline for merged and non- merged

5 Conclusions: In the present work, an attempt has been made to study the effects of main stream Reynolds number, cavity and mainstream equivalence ratio on the merging point of two flames emanating from outer and inner cavity for twin cavity annular trapped vortex combustor (ATVC). For the present study, merged flame is located $X_m = 37.8 \text{ mm}$ from the aft wall of the cavity in extreme $Re_{ms} = 20000$ case. Furthermore, cavity flame merging point moves towards downstream with mainstream Reynolds number. With increase in the mainstream equivalence ratio, the merging point shifts to upstream location of the combustor and it also gets reduced coming closer to cavity aft-wall with an increase in the cavity equivalence ratio. Besides this, the cavity power loading affects the heat release rate in the cavity as lower temperature is observed in the cavity for merged flame case due to prevailing fuelrich zone in both cavities. However, in non-merged flame case, higher temperature prevails in the

cavities. The cavity power loading parameter also affects the heat release rate in mainstream flow for merge flame case. However, for non-merge flame case, heat release rate in the main stream becomes lower due to incomplete combustion.

Acknowledgement

The present work is sponsored by Science and Engineering Research Board (SERB), New Delhi, India.

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