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Influence of Microjets Flow Condition on a Dump Combustor Reacting Flow Characteristics

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1 Introduction

Lean premixed (LP) combustion in gas turbines has a great potential to achieve higher operating efficiency and lower emissions and hence draws an immense interest from both the research and the industrial community. Due to the nature of the flame in an LP combustion mode, the turbulent eddies alter the flame structure thereby enhancing the mixing of the reactants and the products. The transport of scalar quantities is augmented due to the turbulence. Lean nature of the fuel-air mixture results in a lower overall temperature thereby reducing the potential for NOx generation. The design constraints involved in achieving these objectives are challenging. LP combustion requires the fuel-air mixture to be as lean as possible to attain lower equivalence ratio, stable combustion dynamics at all operating conditions and sufficient residence time.

There are different types of combustor used in gas turbines. Some common ones are can, can-annular and annular combustors. Dump combustor is a viable design for LP combustion due to their ability to force mixing of the burnt and fresh mixture at the dump plane. A recirculation zone is formed near the dump plane which acts as a flame holding mechanism in the combustor. The size, location and structure of the recirculation zone dictates the ability to control the mixing process and hence the flame shape and location. Different groups have investigated the enhancement of reacting flow performance in a dump combustor.

Active flow control is an area of research to enrich the combustor performance. One method used to manipulate the various zones within a combustor is the use of microjets. Previous studies indicate that the addition of microjets tend to increase mixing in the shear layer. Earlier efforts include a limited scale parametric study of microjets in a dump combustor [1]. The study included the effect of the number of microjets and inlet flow velocity on the mixing characteristics, the amount of unburnt fuel at the exit. Microjets with higher momentum lead to non-uniform turbulence increasing the mixing attribute and three-dimensionality of the flow. Microjets were found to increase the flame speed due to the higher amount of turbulent kinetic energy generated by them in the flow. Flame surface area was also enlarged due to the action of microjets. The recirculation caused by the microjets in the flow enabled better mixing of the hot products and cold reactants.

The ability of microjets to strengthen the quality of a methane-air flame was investigated by Chouaieb et.al [2]. The effect of microjets velocity and diameters on mixing of reactants and products and the production of soot because of the combustion reaction were studied. Microjets with high speed increased the mixing and reduced the soot in the exhaust [2]. The flow characteristics improved even at lower microjet speeds. With a constant mass flow rate of the methane-air mixture, the diameter of the microjet was also found to affect the performance.

Ganguly et.al [3] observed that introduction of microjets in a coaxial burner reduces the length of the flame. The amount of soot production was lower with the microjets configuration resulting in a reduction of overall luminosity. The difference in flame structure and shortening of the flame length was noticed also by Cao et.al [4]. The presence of microjets tends to reduce the instability characteristics in a flow. Different instability modes had varied response to the injection of the microjets. Equivalence ratio of the flow was found to be an influencing factor for the performance of the combustor with microjets [5]. Flame anchoring in a combustor due to swirl flows has been studied extensively. The development of a recirculation region and enhanced mixing of the reactants and the products are primarily caused by swirl flows in a combustor [6]. Swirl flows also increase the flame speed of the mixture and the turbulence in the flow. In an earlier study, the higher number of microjets increased the average temperature at the outlet of the combustor. A 13% gain in velocity was achieved at the outlet with increase in the microjets [7].

To better understand the effect of microjets in the dump combustor, the current study investigates the effect of the number of microjets on the flow of an axisymmetric combustor using high fidelity numerical simulation. This paper is organized into the following sections; section two describes the combustor geometry and numerical model used in the simulation while the results are presented and discussed in section three. Preliminary conclusions are presented in section four.

2 Combustor Geometry and Numerical Setup

2.1 Computational Domain

In the current study, we used an axisymmetric dump combustor geometry with a total length of 0.597 m. Premixed propane-air mixture enters the combustor through an axial inlet located at the geometry centerline with a diameter of 0.076 m. There is a 5:1 contraction section before the combustor inlet, with an entry diameter of 0.170 m. The combustor inlet is identified as the expansion step downstream of the contraction section which brings the diameter of the combustor to 0.076m. Microjets with a diameter of 0.0001 m are located at the face of the expansion step on the same cross section plane of the propane-air inlet. They are equally distributed across a circumference with a radius equally divides step height.

The current study involves different configurations; a baseline configuration with no microjets and two microjets evenly distributed over the circumference of the injection plane with different swirl ratio.

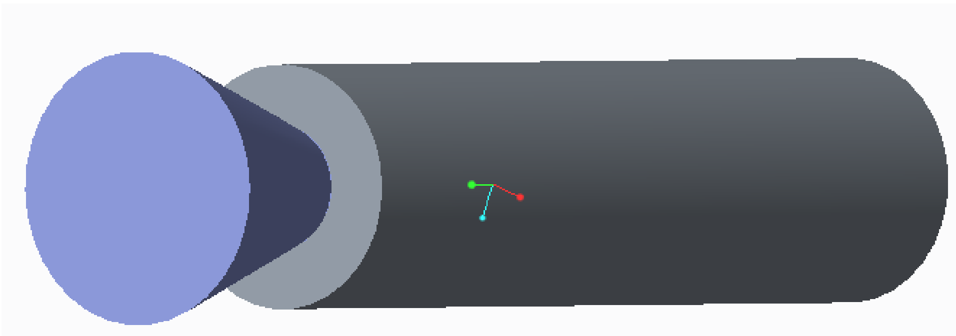


Figure 1. Axisymmetric dump combustor configuration for the baseline configuration

The baseline configuration has no microjets on the surface of the combustor wall. A geometry was created for each configuration, and a corresponding mesh was generated using uniform sizes to maintain the same total number of cells in both configurations used. Mesh was created using the CutCell mesh generation approach in ANSYS Mesher and Hexahedral meshes were created for all configurations under investigation. Figure 1 shows the combustor geometry setup for the baseline configuration with no microjets. A total number of cells around 10 million is maintained for the both cases. Local mesh refinement around the microjets was carried out to sufficiently resolve the flow features around the small jet diameter.

2.2 Boundary Conditions

Premixed propane-air enters at the upstream of the contraction section with a velocity of 4.6 m/s normal to the boundary of the flow. Specifying the fuel velocity at the inlet of the contraction section maintains the centerline velocity and temperature of the fuel at the combustor inlet as 21.5 m/s and 298K respectively. Microjets of pure air are injected at the combustor inlet axially and parallel to the fuel with a velocity of 91 m/s. The initial temperature of the domain is 298 K. Outlet boundary is set as a pressure outlet condition, and all other faces are treated as an adiabatic wall boundary condition. Default values were used for all the reference values. To maintain a fuel equivalence ratio of 0.5 for all cases investigated, the mass fraction of the species was recalculated to account for the addition of the pure air through the microjets. A constant 300 K temperature was kept for all adiabatic walls.

2.3 Numerical Model

Numerical simulations were carried out using the commercial solver ANSYS Fluent. ANSYS Fluent is a finite volume solver and contains models to simulate flow, heat transfer, turbulence, and reactions. The flow in this study is incompressible, and the mixture is treated with an ideal gas density. The combustible mixture is propane-air with an equivalence ratio of 0.5. Pressure-velocity coupling was calculated using the SIMPLEC scheme in ANSYS Fluent. Spatial discretization was second-order for pressure, species, momentum, energy, and turbulent quantities. A multigrid solver with V-cycle for pressure with the default settings was chosen. A CFD simulation model was developed for the baseline axisymmetric dump combustor configuration as shown in Figure 1. Turbulence was computed using the Large Eddy Simulation (LES) model whereas the Flamelet-Generated Manifold (FGM) model was used for turbulent combustion. GRI 3.0 mechanism is imported into ANSYS Fluent for flamelet generation. Flamelets with 101 points for both mixture fraction and reaction progress variable was constructed based on this global mechanism. A Probability Density Function (PDF) was generated for a global equivalence ratio of 0.5. The mixture fraction and progress variable variance points were kept at 32 for the PDF generation.

3 Results

The combustor geometry with no microjets is considered as the baseline geometry. A new geometry with two microjets was created and simulated. The results from both configurations are analyzed in this section. The details of the cases are summarized in table 1.

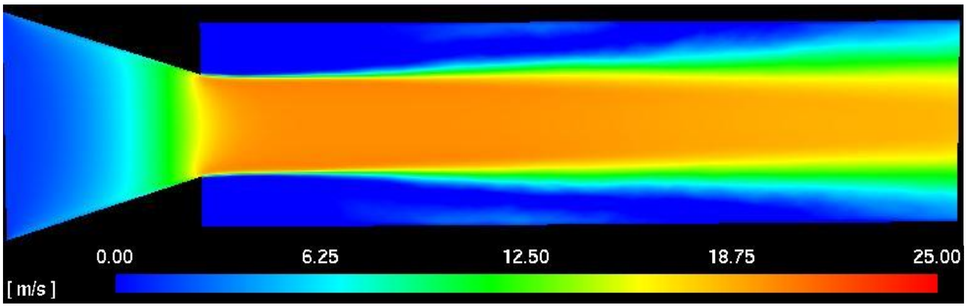
Name	Microjets (Y/N)	Main Fuel Velocity (m/s)	Microjets Velocity (m/s)	Global Equivalence Ratio
Baseline	N	3.5		0.5
Two Microjets	Y - Two	3.5	91	0.5

Table1: Summary of geometry and flow parameters for the studied configurations.

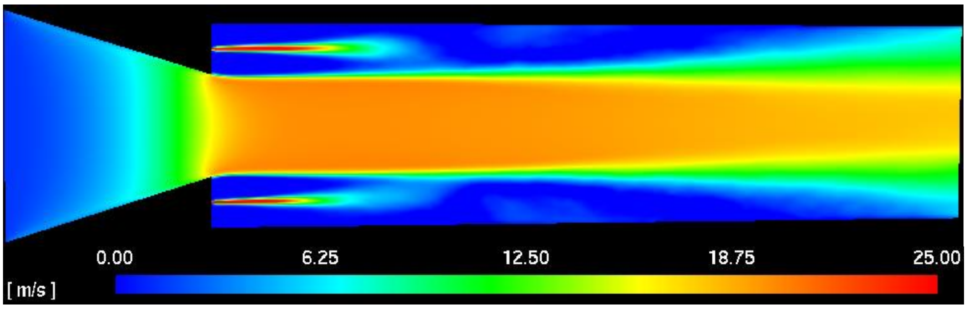
3.1 Velocity

The introduction of microjets into the combustor affects the structure of the fuel mixture stream as shown in Figure 2. The high-speed jet in case two mixes with the low velocity region in the step base area as in Figure 2(b). Although downstream, the microjet flow loses momentum and diffuses into the main fuel mixture stream, its mixing earlier in the upstream flow carries an effect on overall flow by opening the main fuel region laterally towards the combustor outlet as shown in Figure 2(b).

This behavior makes the outer boundaries of the main fuel stream wider in the case with microjets and it is also slower. The inner core of the main premixed mixture is thinner at the outlet with microjets.

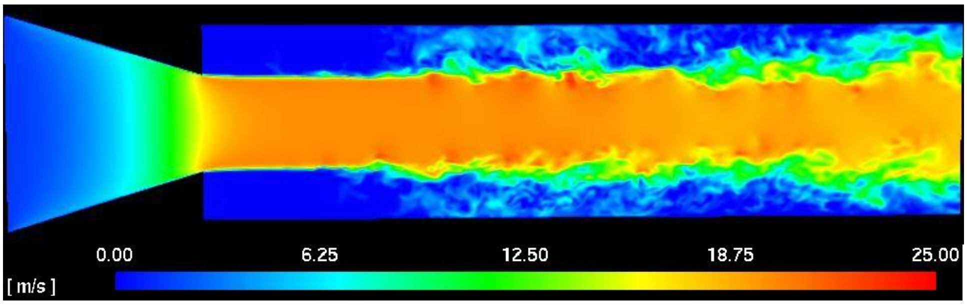


a) Baseline case

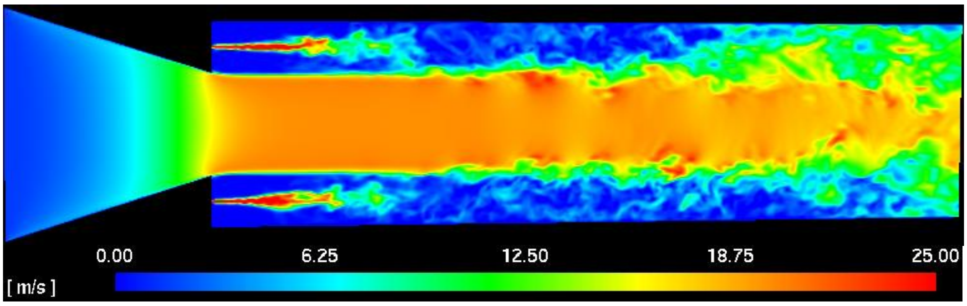


b) Case with two microjets

Figure 2. Time- Averaged Velocity contour of an axial plane along the combustor centerline.



a) Baseline case



b) Case with two microjets

Figure 3. Instantaneous Velocity contour at t=0.3 s of an axial plane along the combustor

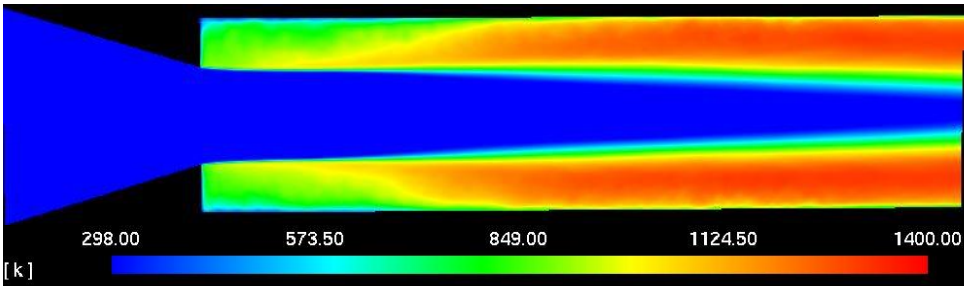
Starting from the middle section of the combustor, two distinct regions can be seen in case two, where the higher velocity premixed mixture converges towards the outlet, whereas the outer core with slower velocity diverges. This process is initiated after the diffusion of the microjets in to the premixed fuel-air mixture stream.

The instantaneous velocity distribution comparing both cases is shown in Figure 3, which provides similar observation with respect to the changes introduced in the flow field due to the injection of microjets.

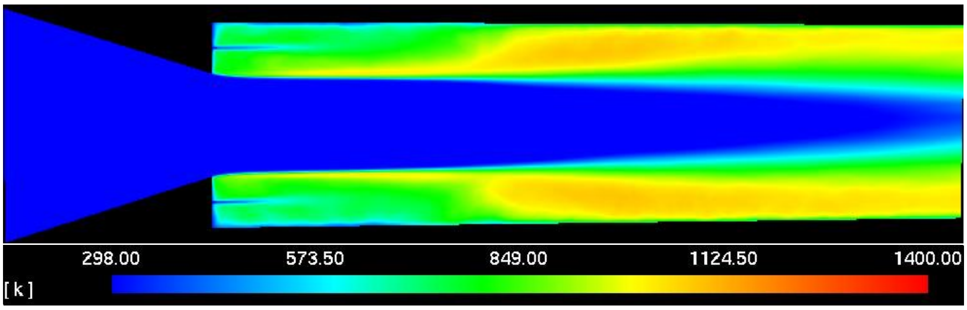
The vortices formed from the high speed microjets break down closer to the inlet section of the combustor. The smaller eddies diffuses into the premixed fuel air stream. The main stream with a higher velocity reduces in size towards the outlet in case two. The exit pattern of the flow field is also altered in case with microjets. The velocity of the exiting combustible mixture is lower when compared to that of case without micorjets.

3.2 Temperature

Microjets, when introduced in the flow, reduce the overall temperature within the combustor significantly as seen in Figure 4. The effect of injecting pure air microjets is to dilute the flow thereby reducing average temperatures within the combustor and affecting the shape of the flame front.



a) Baseline case



b) Case with two microjets

Figure 4. Time-Averaged Temperature contour of an axial plane along the combustor

The flame front in case two is more smeared towards the outlet of the combustor when compared to case one. The shear layer between the microjets and main premixed mixture stream entraps hot products from the combustion.

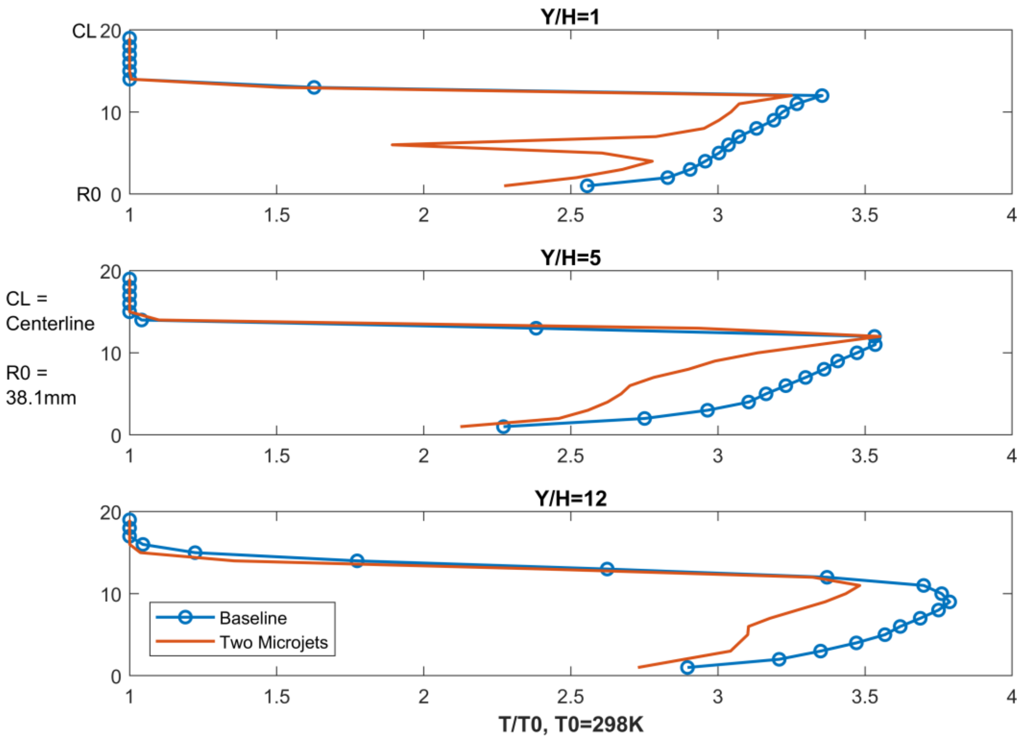
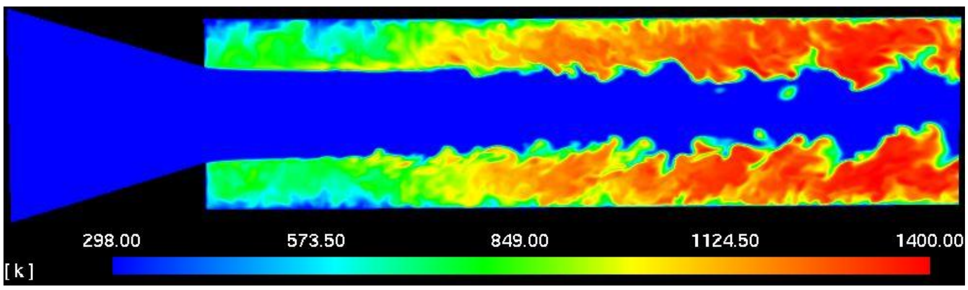


Figure 5. Mean Static Temperature along the radial axis at different axial sections of the combustor at t=0.3 s, T0=298K

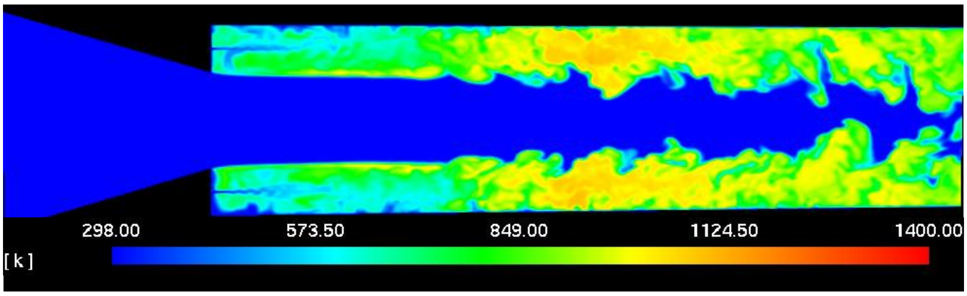
The average temperature of the combustible mixture is lower in case two when compared to the baseline case. The formation of high temperature products is pushed downstream in case two due to the presence of the microjets. At the outlet the peak temperature values are reduced significantly due to the microjets in the flow field. The reduction in peak temperature in a lean premixed combustion system can help in reducing the production of the undesirable pollutants like N R0

The reduction in the combustion temperature throughout the combustor due to the microjets is evident from Figure 5. The distribution of the mean static temperature along the radial direction at three different axial stations; close to the inlet, midsection of the domain and close to the outlet, shows the lower temperature in the flame front in the case with microjets.

Similarly, in Figure 6 the instantaneous temperature contour shows the difference between the two geometries downstream of the combustor. The cold premixed fuel stream collapses near the outlet of the combustor in the case with the microjets.



a) Baseline case



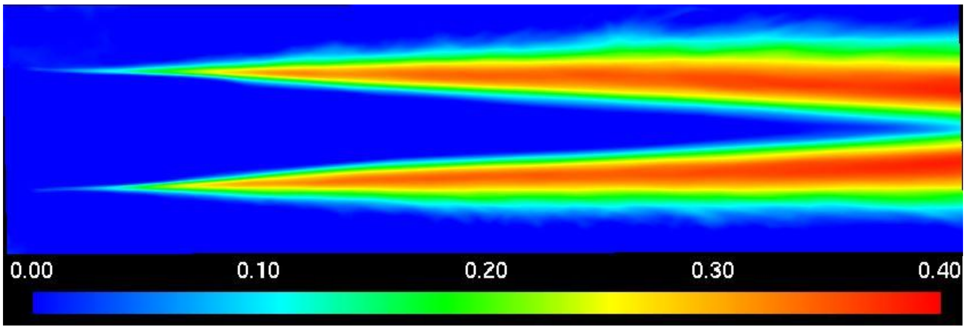
b) Case with two microjets

Figure 6. Instantaneous Temperature contour at t=0.3 s of an axial plane along the combustor

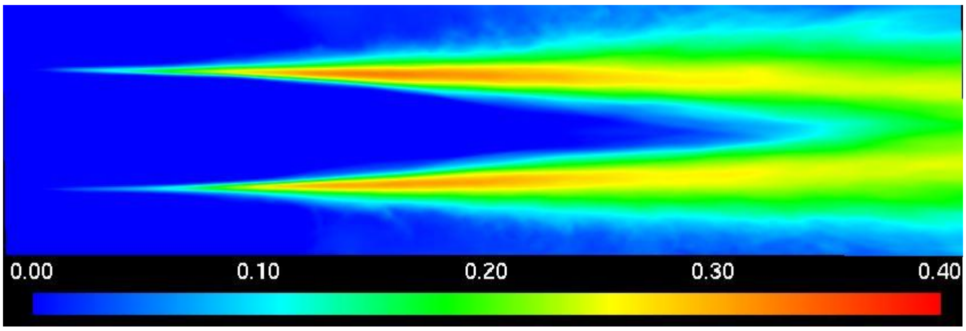
3.3 Reaction Progress

In a combustion system, the flame front propagates downstream creating a region of burnt and unburnt products. The flame front propagation denotes the progression of the reaction. By modeling the reaction progress the flame propagation can be calculated. The reaction progress variable is modeled through a scalar quantity c. A transport equation is solved for this scalar. The progress variable is defined as a normalized sum of the product species mass fractions with respect to chemical equilibrium [8].

The reaction progress variable is defined as a boundary condition at all the inlets. A value of c=0 denotes an unburnt mixture and c = 1 denotes a burnt mixture. The microjets changes the mixing pattern in the combustor by diffusing into the main flow. As shown in Figure 7, the reaction progress is more distributed across the combustor cross section due to this diffusive nature of the flow which results in a larger volume of reaction progress variable. The combustion process is widely spread downstream of the combustor in the case of the microjets, shown by the reaction progress values in Figure 7. The flame front towards the outlet is wider in the case with the microjets.



a) Baseline case

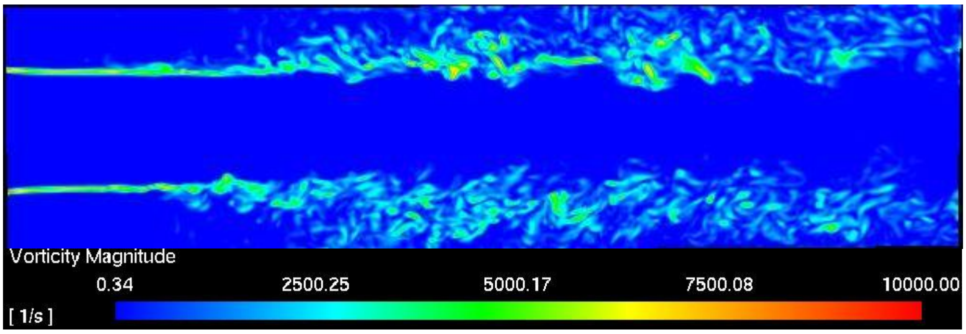


a) Case with two microjets

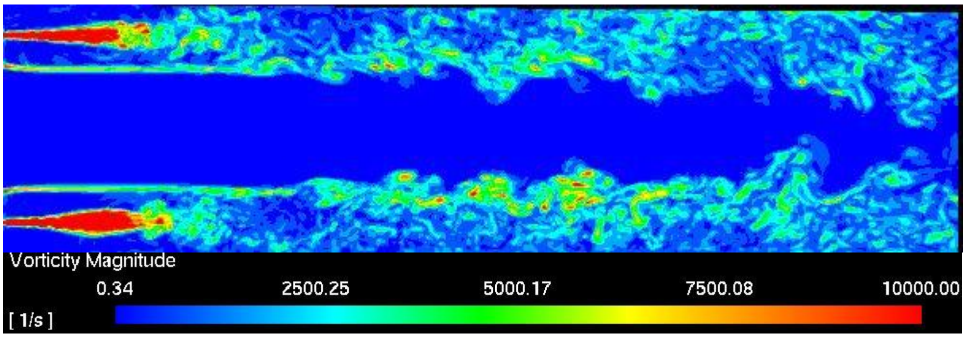
Figure 7. Mean Reaction Progress Variable contour of an axial plane along the combustor

3.4 Vorticity

The changes in the combustion profile due to the presence of the microjets can be explained with the help of the vorticity in the domain. In Figure 8, the vorticity magnitude of both configuration is shown. The high speed jet mixes with the main fuel stream downstream of the combustor inlet causing vortices to form. The formed vortices disintegrate and mix with the main fuel stream close of the middle of the combustor leaving an overall stronger vorticity compared to case one without microjets.



a) Baseline case with no microjets



b) Case with two microjets

Figure 8. Vorticity magnitude of an axial plane along the combustor

3.5 Species Concentration

Combustion of the fuel and oxidizer generates products such as CO_2, H_2O and other intermediate radicals like the OH. Incomplete combustion of the hydrocarbon results in generation of CO in the products mixture.

To maintain a constant equivalence ratio of 0.5 while injecting pure air through the microjets, the mass fractions of the fuel and air components of the premixed propane-air mixture at the main inlet are re-adjusted. Therefore, the mass fraction of propane is higher while that of air is lower at the premixed inlet in the microjets case. The reduction in the amount of air at the inlet is compensated by the mass of air injected through the microjets.

By comparing the outlet values of the mass fractions of the fuel, oxidizer and products, we see less unburnt fuel, less oxygen and higher CO2 and H2O in the microjet case which suggests a better combustion with microjets.

The radicals of CO and OH do show a slight increase which is attributed to the fact that there is less residence time in the combustor. May be having more microjets will cause more lateral diffusion providing the required residence time. This and other methods can be part for any future work.

	C3H8		O2		H2O	
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
Baseline	3.11E-02	1.94E-02	2.26E-01	1.83E-01	0.00E+00	1.91E-02
Two Microjets	3.30E-02	1.76E-02	2.25E-01	1.71E-01	0.00E+00	2.42E-02

	C3H8		O2		H2O	
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
Baseline	3.11E-02	1.94E-02	2.26E-01	1.83E-01	0.00E+00	1.91E-02
Two Microjets	3.30E-02	1.76E-02	2.25E-01	1.71E-01	0.00E+00	2.42E-02

Table2: Mass Weighted Average of Mass Fraction of Species.

4 Conclusions

This study has presented results comparing the effect of microjets on the flow of a premixed dump combustor. The concept of microjets was introduced in the geometry to observe the changes in the mixing and combustion pattern due to the presence of the high-speed jets. A global equivalence air of 0.5 and propane-air as the fuel mixture was used in the study. Turbulence was modeled using the Large Eddy Simulation (LES) model and the combustion was modeled using the Flamelet Generated Manifold (FGM) approach.

By comparing the outlet species values from Table 2, we observe better combustion characteristics with the microjet case. The microjets change the mixing pattern in the combustor by diffusing into the main flow. This, in turn, causes a more uniform and wider reaction space thus lowering the peak temperature for the same or slightly more amount of heat generation. This may help in reducing the NOx levels

The velocity of the combustible mixture and the products are also lowered due to the microjets. The microjets when introduced create additional vortices in the flows. These vortices tend to increase the mixing of the reactants and thereby improving the combustion. The vortices also affects the turbulent levels in the flow.

In order to further understand and quantify the effect of the microjets, more thorough parametric and optimization studies need to be carried out. Future studies to be carried out will include different number of microjets at the combustor inlet, swirl levels of the microjets, microjets flow angle and the velocity of the microjets. With a complete investigation of such effect, microjets can then be recommended as a viable tool to enhance lean combustion systems.

References

[1] Kanchi, H., Russell, K., Anderson, M.J., Beard, S.P., Strykowski, P.J., Mashayek, F., "Fluidic control with microjets in dump combustors", International Journal of Heat and Mass Transfer, Volume 54, Issue 25-26, 2011, PP 5395-5405

[2] Chouaieb, S., Kriaa, W., Mhiri, H., Bournot, P.,"A parametric study of microjet assisted methane/air turbulent flames",Energy Conversion and Management, Volume 140, 2017, PP 121-132

[3] Ganguly, R., Puri, I.K.,"Nonpremixed flame control with microjets", Experiments in Fluids, Volume 36, Issue 4, 2004, PP. 635-641

[4] Cao, Y., Wu, J., Mi, J., Zhou, Y, " Flame Structure of a Jet Flame with Penetration of Side Micro-jets", Chinese Journal of Chemical Engineering, Volume 16, Issue 6, 2008, PP. 861-866

[5] LaBry, Z.A., Shanbhogue, S.J., Speth, R.L., Ghoniem, A.F., "Flow structures in a lean-premixed swirl-stabilized combustor with microjet air injection", Proceedings of the Combustion Institute, Volume 33, Issue 1, 2011, PP. 1575-1581

[6] Driscoll, J. and Temme, J.,"Role of Swirl in Flame Stabilization", 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, 2011, Orlando, FL.

[7] Vellakal, M, Taha, A, Lu, Q, "Large Eddy Simulation for effect of number of microjets on flow in an axisymmetric dump combustor", 53rd AIAA/SAE/ASEE Joint Propulsion Conference, 2017, Atlanta, GA.

[8] ANSYS Fluent Theory Guide