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Investigating the effect of induced centrifugal force resulting from duct geometry on the propagation speed of premixed flame using OpenFOAM software

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Abstract

Increasing the propagation speed of the flame due to centrifugal force can leading to a reduction the length of the combustion chamber and increasing the ratio of thrust-to-weight in air gas turbine engines. The effect of centrifugal force on the propagation of the premixed flame has been investigated. For this purpose, the Large Eddy Simulation of premixed combustion of the air-propane mixture in two straight and curved ducts with a step in the outer wall as a flame holder was performed using OpenFOAM software and compared with the experimental data. The ducts have an inlet and outlet, and the average temperature and the wrinkling (which is defined as the ratio of laminar to turbulent flame speeds) were investigated for two different inlet velocities. It was observed that the curved duct inducing centrifugal force to the fuel and air mixture causes better mixing and increases wrinkling of the flame front, and as a result, the speed of flame propagation was improved. Also, the curved duct can withstand increasing the inlet velocity to higher values. To study the effect of fluid circulation, a new duct geometry for more mixture circulation was designed and analyzed. The comparison of temperature and wrinkling parameters in the outlet section for two initial curve ducts (C2) and the new one (C3) showed that the increase in the rotation due to the increase in centrifugal force improved the average temperature and wrinkling parameters in the outlet.

Keywords: Combustion, OpenFOAM, Premixed, Large Eddy Simulation, Centrifugal Force, Wrinkling, Temperature.

1. Introduction

Increasing efficiency has always been one of the main goals in the research and development of turbojet engines. To compact the combustion chamber, the flame length should be reduced. One of the ways to reduce the flame length is to use Riley-Taylor instability. Rayleigh-Taylor instability occurs at the boundary between two fluids with different densities, which in the combustion case, are reactants and products [1]. Turbulent mixing causes wrinkling in the flame front and increases the flame surface area. The increase in flame speed due to centrifugal force, which produces Riley-Taylor instability, was first noticed by Lewis [2]. Lewis filled a steel pipe with a mixture of fuel and air and rotated it on an axis perpendicular to the axis of the pipe with an electric motor. The rotation of the tube induces a centrifugal force on the fuel-air mixture [3, 4].

Lapsa [5, 6] investigated a stable flame in three duct shapes. The aim was to study the effects of centrifugal force in three states of zero, positive, and negative on flame propagation. In positive and negative centrifugal force cases, Riley-Taylor instability was induced due to the curvature of the duct, and in the straight duct case without curvature, the centrifugal force was zero. For all cases, increasing the inlet velocity, the propagation length became independent of the inlet velocity. Also, for inlet velocity higher than 45 m/s, the flame in the straight duct was extinguished. In the curved duct with a step located on the outer wall, the flame remained stable up to 70 m/s. The effect of Riley-Taylor instability on turbulent flame speed [7-10] and small gas turbine engines [11-16] were studied by numerous researchers. Investigating premixed combustion has also attracted the attention of many researchers [17-21].

Considering that the effect of Riley-Taylor instability is observed at the boundary between two fluids of different densities, in reactive flows, the boundary between reactants and products is the flame surface. The induction of centrifugal force causes Rayleigh-Taylor instability. Therefore, by examining the amount of wrinkling of the flame surface, the effect of Riley-Taylor instability can be better observed. This research aims to investigate the effect of curvature in the duct geometry and subsequently, the wrinkling of the flame surface and the temperature profile at the outlet. Therefore, first, for validation, the large-eddy simulation of the air-propane premixed combustion in two straight duct geometries (named C1) and curved geometry (duct C2). To study the effect of the curvature in duct geometry, a new duct (named C3) was designed, and wrinkling in different sections and the temperature profile at the outlet was investigated and compared with the C2 duct.

2. Methodology

The premixed combustion is considered unsteady, compressible, three-dimensional, and fully turbulent. The governing equations include continuity, momentum, turbulence, total enthalpy, and species transport [16]. Large-eddy simulation (LES) of the premixed combustion is used in this study. The one-equation eddy-viscosity model is chosen to close the subgrid-scale modeling [17, 18].

The effect of turbulence on the premixed combustion process is wrinkling and corrugation of the flame surface. The flame front propagation is considered by solving the transport equation for the density-weighted mean reaction regress variable [19, 20]:

$$\frac{\partial}{\partial t}(\rho b) + \nabla \cdot (\rho \vec{u} b) - \nabla \cdot \left(\frac{\mu_t}{Sc_t} \nabla b\right) = -\rho_u S_u \Xi |\Delta b| \quad (1)$$

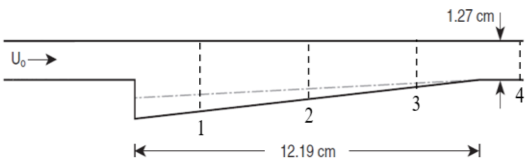
To consider the effects of stretch and curvature on laminar flame speed, a transport equation is used as follows [21, 22]:

$$\frac{\partial S_u}{\partial t} + \widehat{U_s} . \nabla S_u = -\sigma_s S_u + \sigma_s S_u^{\infty} \frac{(S_u^0 - S_u)}{S_u - S_u^{\infty}} \quad (2)$$

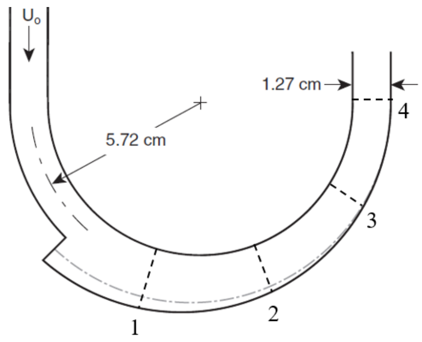
In the simulation of air-propane premixed combustion, the XiFoam solver is used. The numerical scheme for discretization temporal term is the second-order Backward Differencing Scheme. Gradient, divergence, and Laplacian terms are discretized with Gauss linear scheme (a second-order). The PIMPLE algorithm is used to solve the coupling of velocity and pressure fields [23-26].

3. Result and discussion

Three duct geometries have been considered to investigate the effect of Rayleigh-Taylor instability on the flame surface. First,b to validation the numerical solution method, two straight (C1 in Figure 1-a) and curved (C2 in Figure 1-b) duct geometries were investigated according to Lapsa's experiment [5].



1-a: C1 duct



1-b: C2 duct

Figure 1. Schematic of duct geometries in Lapsa's experiment

In air-propane premixed combustion, the thickness of the quiet flame is estimated to be around 1.4 mm [9]. Therefore, a uniform grid with a size of 0.2 mm has been used to grid the desired geometries so that the thickness of the quiet flame is covered by at least 5 cells. Also, to accurately consider the effects of the wall on the flow field, the grid of the boundary layer with 18 layers and the distance of the first layer of 0.001 mm was considered to ensure that YPlus becomes smaller than 1 in the entire field. Three types of inlet, outlet, and wall boundary conditions have been used for the geometries analyzed in this research. The combustion of air-propane premixed with a 1.1 stoichiometric ratio at two inlet velocities of 4 and 40 m/s for two ducts was compared with experimental data [5].

The results depicted that the place where the flame collides with the opposite wall has good agreement with experimental data.

To investigate the effect of curved geometry on the flame surface wrinkling and outlet temperature profile, the geometry of Figure 2 was designed and analyzed.

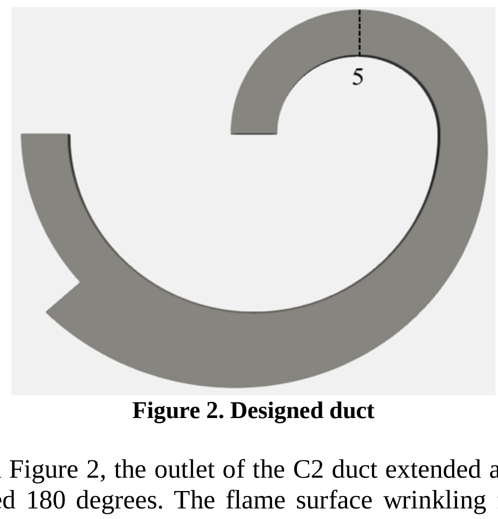


Figure 2. Designed duct

In Figure 2, the outlet of the C2 duct extended and rotated 180 degrees. The flame surface wrinkling for two inlet velocities of 4 and 40 m/s at the output section for C2 and C3 duct, are compared in Figure 3. The amount of wrinkling in Figure 3 has increased due to the increase in the induction of centrifugal force. The presence of the wall and curvature in the ducts generates vortices near the wall, which increases wrinkling in the desired section. Due to an increase in fluid circulation in the designed duct, C3, there was an increase in temperature at the outlet section, the temperature profile at the outlet was more uniform (Figure 4).

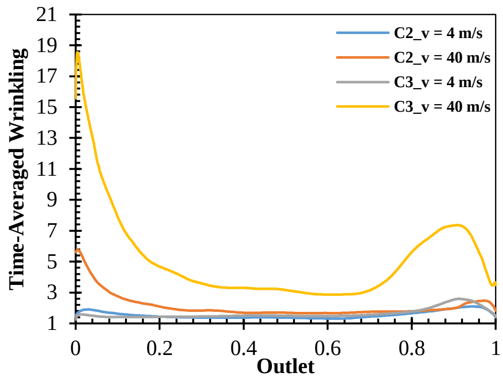


Figure 3. Time-averaged wrinkling at the outlet of the C2 and C3 ducts

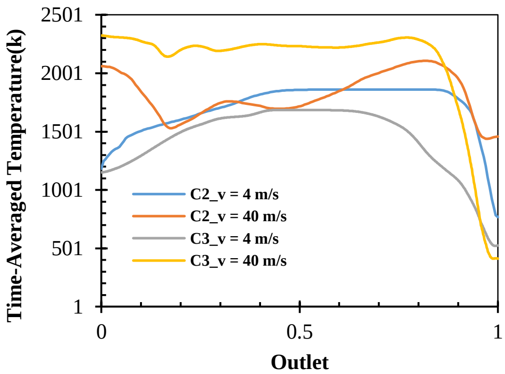


Figure 4. The time-averaged temperature at the outlet of the C2 and C3 ducts

All simulations were implemented using OpenFOAM software. The hardware was a server with Ubuntu operating system version 20.04.3 LTS and of 64-bit type with 24 cores and a frequency of 2.7 GHz and 32 GB.

4. Conclusion

The most important results of this simulation are summarized below:

1- Due to the lack of induction of centrifugal force in the straight duct (C1), the flame surface wrinkling was decreased. Increasing the inlet velocity, reduced the flame surface area.

2- In the curved duct (C2) due to the curvature and centrifugal force induction to the flow field, Rayleigh-Taylor instability increases, therefore flame surface area, wrinkling, and the temperature of the combustion products increase. As a result, the curvature of the duct causes the stability of the combustion flow. Increasing the inlet velocity does not decrease temperature and combustion characteristics (unlike the C1 duct).

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