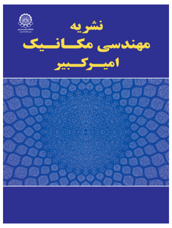

Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 52(4) (2020) 211-214
DOI: 10.22060/mej.2018.14433.5859

Investigation of the Effect of Spray Fuel Injection Pattern on Evaporation of Droplets in the Gas Turbine Pre-mixer

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ABSTRACT: In a liquefied gas turbine combustor, due to the limited length of the premix tube, the evaporation process of fuel droplets is not completely carried out inside the tube, and the droplets enter the combustion chamber. The presence of droplets in the combustor causes the reactions to occur in the non-premix mode and the emission of NOx increases as a result. To avoid the emission of this pollutant, it is necessary that the droplets are evaporated completely in a limited space. Herein, a mechanism is proposed for spraying the droplets, in which, fuel droplets are injected to form a hollow-cone spray pattern in the opposite of the gas flow direction. In this type of injection, due to the relative velocity of droplets and subsequent enhancement of the droplet break-up and evaporation processes, it is possible to achieve this goal. To verify this matter, various patterns of injected n-heptane droplets into nitrogen gas passing through a premix tube have been simulated at the temperature of 800 K and the pressure of 20 bar using the Eulerian-Lagrangian approach. The validation of heat and mass transfer models, as well as the influence of gas molecules penetration into fuel droplets, has been evaluated. The results showed that using this type of injection, in addition to full evaporation of droplets in the limited space, the distribution of the temperature and the fuel vapor mass fraction in the tube outlet are more evenly distributed

Review History:

Received: 12 May 2018
Revised: 15 July 2018
Accepted: 17 July 2018
Available Online: 23 July 2018

Keywords:

Premix tube
Droplet evaporation
High pressure
Fuel injection
Gas turbine.

1. Introduction

In recent decades, the use of the Lean premixed system has been developed to reduce the nitrogen oxides emissions in gas turbines. However, in liquefied gas turbines, the premixing of fuel droplets with air does not help in reducing these emissions. Therefore, it is essential that the spray droplets should be evaporated and mixed completely with the air before entering into a combustor. Besides, due to the limitations, the premix tube should have a compact length. In this regard, several researchers have investigated the effect of various patterns of injection in the premix tube including co-flow and cross-flow [1-4]. The results showed that with these kinds of injection patterns, the complete evaporation of spray droplets is not possible in a compact tube. In the direction of increasing the evaporation rate, on the one hand, to attain the most relative velocity of the droplets, the spray should be injected in the opposite direction. On the other hand, in order to use more space in the tube, the droplets should be sprayed from a point on the tube centerline symmetrically. Therefore, in this study, the effect of this pattern of injection is investigated by simulating of the n-heptane droplets sprayed in a premix tube.

2. Methodology

2.1. Governing equations

The Lagrangian-Eulerian approach is used to account for the variation in mass, momentum, energy, and mass of each species exchanges between gas and liquid phases. The governing equations for the gas phase can be written as [5]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = S_m \tag{1}$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{uu}) = -\nabla P + \nabla \cdot \{2(\mu + \mu_t) [\boldsymbol{S} - \frac{1}{3}(\nabla \cdot \mathbf{u})\mathbf{I}] - \frac{2}{3}\rho k \mathbf{I})\} + \rho \mathbf{g} + \mathbf{S_u} \tag{2}$$

$$\frac{\partial \rho h}{\partial t} + \nabla \cdot (\rho \mathbf{u} h) = \frac{\mathrm{D}P}{\mathrm{D}t} + \nabla \cdot [(\alpha + \alpha_t)\nabla h] + S_h \tag{3}$$

$$\frac{\partial \rho Y_i}{\partial t} + \nabla \cdot (\rho \mathbf{u} Y_i) = \nabla \cdot [(\mu + \mu_t)\nabla Y_i] + S_{Y_i} \tag{4}$$

The turbulent viscosity μ_t is estimated from Launder-Sharma turbulence model, a low Reynolds k-ε model [6]. The governing equations for each droplet's position, $\mathbf{r}_d$, velocity, $\mathbf{u}_d$, mass, m_d, and temperature T_d are set by Ref. [5]:

$$\boldsymbol{u}_d = \frac{d\boldsymbol{r}_d}{dt} \tag{5}$$

$$\frac{d\boldsymbol{u}_d}{dt} = \frac{\boldsymbol{u} - \boldsymbol{u}_d}{\tau_u} + \boldsymbol{g} \tag{6}$$

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$$\dot{m}_d = -2\pi\rho d D_{diff}(Y_s - Y_\infty)Sh \tag{7}$$

$$\frac{dT_d}{dt} = \frac{T - T_d}{\tau_h} f - \frac{h_{fg}}{C_{p,d}\tau_e} \tag{8}$$

Also, the effect of the gas solubility at the droplet surface and the real gas behavior in the gas phase is examined by considering the Peng-Robinson equation and the Van der Waals mixing rule in the governing equations [7].

2.2. Numerical method

The governing equations are solved numerically using SprayFoam solver in OpenFOAM CFD Package [8]. The effect of the gas solubility at the droplet surface is applied in this code to simulate the spray evaporation correctly in high-pressure environments.

3. Results and Discussion

To validate the heat and mass transfer models, the evaporation history of one n-heptane droplet is simulated in the nitrogen gas with the pressure of 20 bar and the temperature of 748 K. The result is in agreement with Nomura experimental data [9].

Before injecting the fuel droplets, the gas flow in a tube with a diameter of 18 mm, the length of 44 mm and the inlet velocity of 15 m/s is simulated. The gas in the tube is nitrogen with 20 bar pressure and 800 K temperature. By injecting a fully atomized spray in different patterns, as specified in Table 1, the two-phase flow is performed in the tube. In each case, the droplets are injected from a point on the tube centerline, 20 mm far from the inlet section. The density function of the droplets is the Rosin-Rammler with Sauter Mean Diameter (SMD) of 0.075 mm. The mass flow rate and initial velocity of the droplets are 0.0066 kg/s and 100 m/s respectively.

Table 1. Different patterns of the fuel injection in the pre-mixer

Cases	Injection direction	Spray angle (°)
1	Counter-Flow	30-80
2	Counter-Flow	0-80
3	Co-Flow	30-80
4	Co-Flow	0-80

Fig. 1 shows the flow field in the longitudinal section of the tube for all cases. By comparing these results, it could be realized that by the injecting of the fuel droplets in the opposite direction, the droplets are evaporated completely.

In these conditions, when the droplets are injected with a hollow-cone spray in the interval of 30 to 80 degrees, the evaporation process occurs in a compact space. Moreover, in Fig. 2, the profile of the fuel vapor mass fraction at the outlet is indicated for all cases. In this figure as shown, the mass fraction distribution of the vaporized liquid fuel is almost uniform at the outflow in the counter-flow cases.

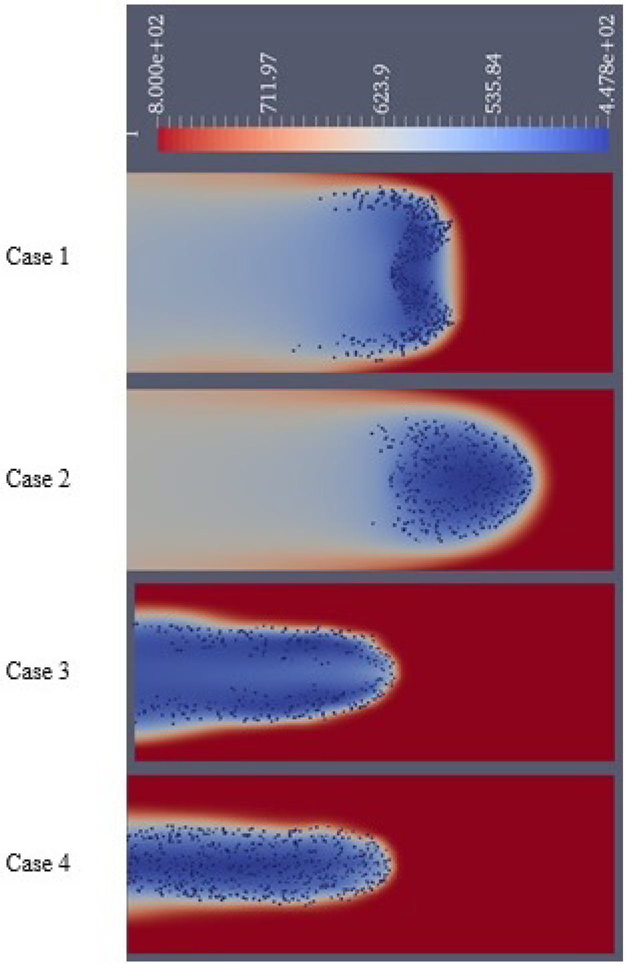

Fig. 1. The longitudinal section of the flow field in the pre-mixer for different spray patterns

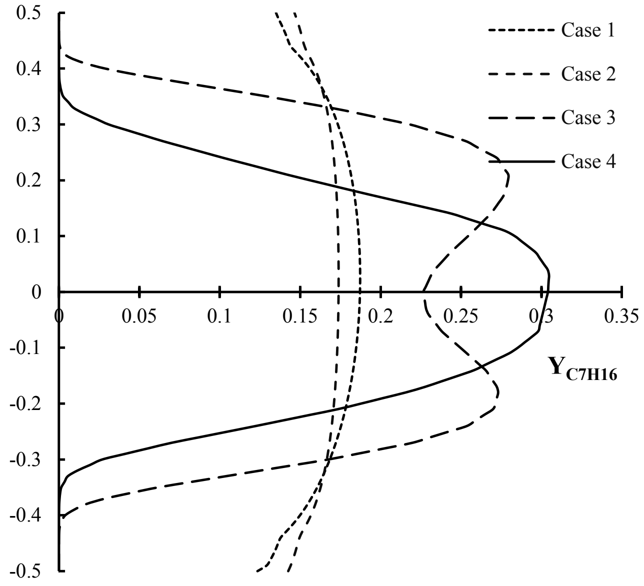

Fig. 2. The distribution of the fuel vapor mass fraction at the outlet for different spray patterns

4. Conclusions

In this study, to evaporate the fuel droplets in a compact premix tube, an injection pattern is presented, in which the fuel droplets are injected in the opposite direction of the gas flow. The results showed that by injecting the fuel droplets in the opposite direction, full evaporation of the droplets within the tube is provided due to the increase of relative velocity of droplets and subsequent acceleration in break-up processes. In order to reduce the length of the spray penetration and limit the length of the pre-mixer, the spray pattern of the hollow cone with internal and external angles of 30 and 80 degrees is provided. In this pattern, in addition to full evaporation of the droplets in a limited space, the uniform distribution of the gas temperature and the fraction of the fuel vapor at the tube outlet can be obtained.

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