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Full Length Article

Combustion characteristics of a non-premixed methane flame in a generated burner under distributed combustion conditions: A numerical study

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ABSTRACT

Distributed combustion is a novel technique in providing of thermal field uniformity over the entire of the combustor and in reducing of pollutant emissions. This study concentrates on combustion characteristic of a non-premixed methane flame for the newly generated burner under conventional and distributed combustion conditions. The non-premixed methane flame has been modelled by using a computational fluid dynamics commerce code. In the modellings, standard k-Ɛ turbulence model, the non-premixed modeling with and assumed-shape that is β -function Probability Density Function and P-1 radiation model have been used. The predicted temperature distributions have been compared with the experimental data under conventional combustion conditions and it has been determined that the predicted results are in good agreement with the measured temperature values. The predicted results show that distributed combustion enables more uniform thermal field under distributed combustion conditions in the combustor. In particular, it has been demonstrated that the temperature of the methane flame has been reduced significantly. When the effect of distributed combustion on pollutant emissions is evaluated, it has been concluded that NO_X and CO emissions have been reduced down to nearly zero emissions while CO_2 emission levels have been increased slightly at the combustor outlet under distributed combustion conditions.

1. Introduction

Energy demand is continuously rising all over the World due to the increase in heating, electricity and etc. requirements. Energy requirements can be met by different energy resources such as fossil fuels, renewable energy, nuclear energy, biomass and etc. However, more than 85% of energy demand is still provided by fossil fuels. Fossil fuels can be classified as solid, liquid and gas in terms of their phases. Natural gas is a well-known type of gaseous fuels while coal and crude oil are types of solid and liquid fossil fuels. In terms of burning technologies, burning gaseous fuel is easier than that of liquid and especially solid fuels. It is also known that gaseous fuel combustion is more appropriate due to pollutant limitations. So, natural gas as a gaseous fuel remains the most important resource. Nowadays, environmental limitations are more strict. This situation compels the scientists to develop novel combustion techniques such as MILD (moderate or intense low oxygen distribution), HiTAC (high temperature air combustion) or distributed combustion (colorless distributed combustion). Among these techniques, distributed combustion has become prominent in reducing of NO and CO emissions along with more stable and less noise combustion as well as it also enables combustion stability [1–4].

Distributed combustion can be defined as reduction of oxygen concentration in oxidizer. This reduction can be achieved by recirculating of hot combustion products in which the fuel flow rate or thermal load is kept constant. The most important step in achieving of distributed combustion is that recirculation prior to ignition occurs. Therefore, combustion takes place by a lower reaction rate and as a result of this the combustion products propogate into the combustor uniformly. In other words, reaction takes place over the entire combustor under distributed combustion conditions. Thus, distributed combustion enables to alleviate high NO_X levels arising from thermal NO_X mechanism [5].

Distributed combustion technique is commonly used in providing of thermal uniformity and mitigating of emission levels. Khalil and Gupta [5], for instance, have performed an experimental study that is directly related to distributed combustion. In that study, thermal field and emission levels were investigated under conventional and distributed combustion conditions. They have concluded that reducing oxygen concentration is principal factor in achieving of thermal field uniformity. In their other studies, they have also investigated highly intensity distributed combustion conditions [6], flame fluctuations for oxy-CO_2-methane mixtures [7], the role of CO_2 as a diluent on oxy-colorless distributed combustion [8], highly intensity distributed combustion for more combustion conditions such as mixture temperature,

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Nomenclature

S	Swirl number
d_h	Generator hub diameter
d	The outer swirl generator diameter
β	Exit angle of the swirl vanes
Φ	The dependent variables
Γ	The transport coefficient
S_Φ	The source term of the transport equation
f	The mixture fraction
Z_i	The elemental mass fraction for element, i
$\overline{f}$	The Favre mean (density-averaged) mixture fraction
k	Laminar thermal conductivity of the mixture
c_p	Specific heat of the mixture
σ_t	Prandtl number
μ_t	Turbulent viscosity
$\overline{f'^2}$	The mixture fraction variance

oxygen concentration, equivalance ratio and heat load [9], acoustic and heat release signatures [10], flame-front interaction [11], the effects of fuel property that are methane, propane and hydrogen enriched methane on distributed combustion [12], colorless distributed combustion regime [13], JP-8 and ethanol under distributed combustion conditions [14]. Moreover, some additional studies are available regarding distributed, flameless or colorless combustion technique in the literature [15–20].

There are some studies related to distributed or colorless combustion technique in the literature as mentioned above. In the present study, the non-premixed methane flame for the newly generated burner has been modelled by using Ansys Fluent CFD (computational fluid dynamics) code under distributed combustion conditions. The present study is aimed at investigating usage of the newly generated non-premixed burner under distributed combustion conditions as there is few studies related to the generated burner under the conditions. Thus, the burner can be easily integrated to this combustion conditions enabling more uniform thermal field and less emissions, which means that distributed combustion can be used in more any combustion application and integrated to environmental limitations. Distributed combustion has been achieved by simulating recirculation of hot product gases and thermal field and emissions have been determined over the entire combustor and at the combustor outlet. Therefore, thermal field uniformity, less NO_X and CO emissions for the newly generated burner have been provided with the success of distributed combustion, which means that distributed combustion being a novel combustion technique can be used in gas turbine and further combustion applications actively.

2. Description of the burner and the combustor

The burner used in the present study is the non-premixed burner being the newly generated. Some combustion characteristics of the non-premixed methane flame for the burner were experimentally investigated under conventional combustion conditions [21]. The cross-sectional view of the burner is shown in Fig. 1. The burner involves two stream regions coaxially, one of which is the air stream and the other is fuel stream. When the air stream reaches to the air inlets in the burner, it encounters types of two inlets. The annular inlet is of diameter of 2 mm. The hub and outer diameters of the swirl generator representing the angular inlet are also of d_h: 28 mm and d: 40 mm, respectively. Moreover, the burner has a swirling angle of β: 15°, in which case the geometrical swirl number is of about 0.23 (Eq. (1)). The fuel inlet is also different as the air inlets. If the direction of the fuel stream is accepted as axial direction, the fuel inlet' direction can be defined as radial direction and its diameter is of 4.75 mm.

$$S = \frac{2}{3}\left(\frac{1-(d_h/d)^3}{1-(d_h/d)^2}\right)tan\beta \tag{1}$$

In the present study, the combustor that was also used in the experimental study [21] has been used in order to determine thermal field of the non-premixed methane flame under conventional and distributed combustion conditions. The details of the combustor are presented in Fig. 2. The length and the diameter of the combustor are of 100 cm (excluding inclined exit) and 40 mm (including wall thickness), respectively. The combustor involves five measuring ports where thermal field can be determined inside the combustor and the outlet where pollutant emissions can be measured. Measuring ports were placed to be 20 cm apart from each other. Temperature values of the non-premixed methane flame were measured inside the combustor by the ceramic coated R-type thermocouples, each of which can be withstood up to 1700 °C.

3. Details of the modelling

The mathematical modelling described for diffusion methane flame is based on some assumptions, which the flow is steady-state and three-dimensional continuity. Computational fluid dynamics (CFD) code solves momentum, energy and species equations. The general form of transport equation is expressed by Eq. (2):

$$\frac{\partial(\rho\Phi)}{\partial x} + div(\rho\Phi u) = div(\Gamma grad\Phi) + S_\Phi \tag{2}$$

where Φ represents the dependent variables. Γ expresses the transport coefficient for variable Φ. S_Φ also represents the source term of the transport equation for Φ.

3.1. Combustion modelling

The solution of transport equations for one or two conserved scalars (the mixture fractions) is involved in non-premixed modelling. Equations for individual species are not solved. Instead, species concentrations are derived from the predicted mixture fraction fields. Turbulence-chemistry interaction is accounted for with an assumed-shape being the β-function Probability Density Function (PDF) [22].

The origin of the non-premixed modelling approach is that under a certain set of simplifying assumptions, the instantaneous thermochemical state of the fluid is related to a conserved scalar quantity known as the mixture fraction, f. The mixture fraction can be expressed in terms of the atomic mass fraction as below [23]:

$$f = \frac{Z_i - Z_{i,ox}}{Z_{i,fuel} - Z_{i,ox}} \tag{3}$$

where Z_i is the elemental mass fraction for element, i. The subscript ox

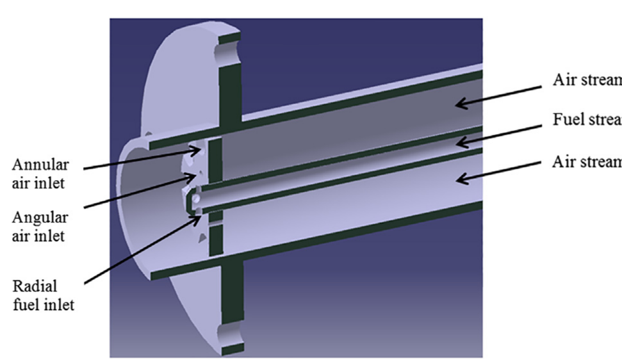

Fig. 1. The cross-sectional view of the burner.