Editorial

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Three Exergy Zones of a Typical Non-Premixed Methane-Air Jet Flame

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Abstract

Three exergy zones are observed in this study by investigating the local percentages of kinetic exergy, chemical exergy, and thermal exergy of a typical non-premixed methane-air jet flame, the Sandia flame D. It is observed that the flame domain can be divided into three zones as (1) zone I, the fuel zone where methane sprays and spreads, (2) zone II, the air zone where air sprays and spreads, and (3) zone III, the left area besides zone I and zone II in the flame domain, and this is the place where combustion occurs and flame spreads. Results show that zone I and zone II have higher local percentages of kinetic exergy and chemical exergy whereas zone III has higher local percentages of thermal exergy.

Keywords: Exergy zones; Non-premixed methane-air jet flame; Local percentage; Kinetic exergy; Chemical exergy; Thermal exergy

Introduction

Methane is the simplest hydrocarbon in the alkane family and the principal component of natural gas. Compared with the other hydrocarbon fuels, methane produces more heat for each unit of consumed mass whereas yields less carbon dioxide for each unit of released heat, it is therefore widely used as an important and typical fuel source in our daily life for practical applications in cooking, heating, vehicle cylinders, turbine combustors etc.

The common characteristic of the practical applications of methane in cooking, heating, vehicle cylinders and turbine combustors is the turbulent combustion of non-premixed methane-air, which is characterized by non-premixed methane-air jet flames. Among the non-premixed methane-air jet flames, the Sandia flame D is the most typical and popular one and is therefore comprehensively investigated [1]. The objective of this study is to investigate the exergy characteristics of a typical non-premixed methane-air jet flame by studying the local percentages of kinetic exergy, chemical exergy, and thermal exergy of the Sandia flame D.

Research Methods

Geometry

Figure 1 shows the computational domain used for the Sandia flame D. The geometry of the Sandia flame D is simplified as a 2 D axis symmetrical structure, and the computational domain is 80 d in axial direction and 20 d in radial direction. The main jet inner diameter d is 7.2 mm and the annulus pilot inner diameter dp is 18.2 mm [2].

Exergy theory

The specific exergy of a closed control volume is defined as follows [3]:

$$a = k + \phi + u + P_0 v - T_0 s - \sum_s \mu_{s,0} y_{s,0} \tag{1}$$

where a, k, ϕ, u, v, and s are the specific exergy, kinetic exergy, potential exergy, internal energy, specific volume, and specific entropy of the closed control volume, respectively. $\mu_{s,0}$ and $y_{s,0}$ are the standard chemical potential and standard mass fraction of component s in the environment, respectively.

The specific enthalpy of a control volume is given:

$$h = u + Pv \tag{2}$$

$$h_0 = T_0 s_0 + \sum_s \left(\mu_s \right)_{T_0,P_0} y_s \tag{3}$$

where p and h are the pressure and specific enthalpy of gas in the closed control volume, respectively. h_0 and s_0 are the specific enthalpy and entropy of gas at environmental state, respectively.

Equation (1) then gives:

$$a = k + \phi + (h - h_0) - T_0 \left(s - s_0 \right) + (\sum_s \mu_s y_s - \sum_s \mu_{s,0} y_{s,0})_{T_0,P_0} \tag{4}$$

When the potential exergy is neglected [4, 5], equation (1) furthers to give:

$$a = k + (h - h_0) - T_0 \left(s - s_0 \right) + (\sum_s \mu_s y_s - \sum_s \mu_{s,0} y_{s,0})_{T_0,P_0} \tag{5}$$

For the mixture of ideal gases in the control volume, we have:

$$s = \sum_s s_s y_s \tag{6}$$

$$h = \sum_s h_s y_s \tag{7}$$

$$k = \frac{1}{2} \sum_s y_s c^2 \tag{8}$$

where s_s and h_s are the specific entropy and enthalpy of component gas s in the control volume, respectively. c is the velocity of the control volume.
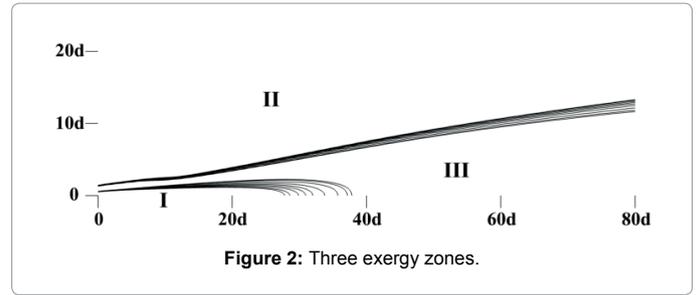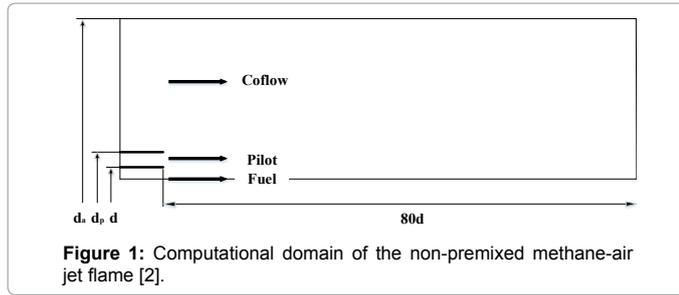
For ideal gases, we further to have:

Figure 1: Computational domain of the non-premixed methane-air jet flame [2].

Figure 2: Three exergy zones.

$$a = \frac{1}{2}\sum_s y_s c^2 + \sum_s y_s \left(\int_{T_0}^T C_{p,s}\, dT - T_0 \int_{T_0}^T C_{p,s} \frac{dT}{T} + \frac{R}{M_s} T_0 \ln \frac{P}{P_0} \right) + \left(\sum_s \mu_s y_s - \sum_s \mu_{s,0} y_{s,0} \right)_{T_0,P_0}$$

(9)

where $C_{p,s}$ and M_s are the specific heat capacity and molar mass of component gas s in the control volume, respectively. R is the universal gas constant (8.314472 kJ/kmol K).

The total exergy is defined in this study as the sum of kinetic, thermal, and chemical exergy as:

$$a = a_k + a_{th} + a_{ch}$$

(10)

Where,

$$a_k = \frac{1}{2}\sum_s y_s c^2$$

(11)

$$a_{th} = \sum_s y_s \left(\int_{T_0}^T C_{p,s}\, dT - T_0 \int_{T_0}^T C_{p,s} \frac{dT}{T} + \frac{R}{M_s} T_0 \ln \frac{p}{p_0} \right)$$

(12)

$$a_{ch} = \left(\sum_s \mu_s y_s - \sum_s \mu_{s,0} y_{s,0} \right)_{T_0,P_0}$$

(13)

The chemical exergy can also be expressed as [4,5]:

$$a_{ch} = \sum_s \frac{y_s}{M_s} \left(a_{ch,s}^0 + RT_0 \ln x_s \right)$$

(14)

where y_s and x_s are the mass fraction and volume fraction of component gas s in the gas mixture, respectively. $a_{ch,s}^0$ is the standard chemical exergy of component gas s.

Results and Discussion

Simulation procedure

Ansys Fluent was used to solve the above equations, and the velocity field and scalar field were further used to compute the local exergy. The pressure-velocity coupling scheme is based on the coupled method. The spatial discretization of the gradient is based on the least square cell method whereas the spatial discretization of pressure is based on the PRESTO method. The other spatial discretizations were based on the Second Order Upwind. When the residuals of continuity, energy and DO-intensity were less than 10^{-6} and the other residuals were less than 10^{-5}, the calculations were considered to be convergent.

Exergy zones

We analyzed the local percentages of kinetic exergy, chemical exergy, and thermal exergy for the whole computational domain, and observed something in common for the local percentages. The local percentages of kinetic exergy, chemical exergy, and thermal exergy are defined in this study as the ratios of local kinetic exergy, chemical exergy, and thermal exergy to local total exergy, respectively.

It was observed that the non-premixed methane-air jet flame can be divided into three zones and these three zones have similar shapes for the local percentages of kinetic exergy, chemical exergy, and thermal exergy. The three zones are labeled in Figure 2 and they are defined in this study as: (1) zone I, the fuel zone where methane sprays and spreads, (2) zone II, the air (environment) zone where air sprays and spreads, and (3) zone III, the left area besides zone I and zone II in the computational domain, and this is the place where combustion occurs and flame spreads. It was also observed that zone I and zone II have higher local percentages of kinetic exergy and chemical exergy whereas lower local percentages of thermal exergy. Zone III has lower local percentages of kinetic exergy and chemical exergy whereas higher local percentages of thermal exergy.

Conclusions

The non-premixed methane-air jet flame can be divided into three exergy zones and these three zones have similar shapes for the local percentages of kinetic exergy, chemical exergy, and thermal exergy.

Zone I and zone II have higher local percentages of kinetic exergy and chemical exergy whereas lower local percentages of thermal exergy. Zone III has lower local percentages of kinetic exergy and chemical exergy whereas higher local percentages of thermal exergy.

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