Effects of turbulence intensity and length scale on the flame location of premixed turbulent combustion in a diffuser combustor

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Abstract

This study focused on the dependency of the flame location of a premixed propane–air flame on turbulence intensity and length scale. The flame location was investigated using a diffuser-type combustor to show the response of the flame location to varying turbulence intensities and length scales without changing the mixture velocity, i.e., the thermal power. Combustion simulations were conducted using a coherent flame model within the framework of Reynolds-averaged Navier–Stokes equations under unsteady state conditions. The flame generally moved toward the combustor inlet with increases in turbulence intensity and length scale. The combustion and inlet turbulence caused a flow separation mainly downstream of the flame front. Consequently, the secondary flow structures influenced the flame topology and location.

Keywords: Premixed flame, Flame location, Diffuser, Turbulence, Flow separation

1. Introduction

Turbulent combustion is an attractive process in many industrial devices, such as spark ignition engines and gas turbines. Understanding the interaction between flame and turbulence plays a role in increasing the performance and reliability and in reducing the pollutant emissions of combustion systems. Therefore, the interaction between premixed flame and turbulence has become an important research area and is considered a main problem in combustion analysis (Pope 1978, Peters 2004, and Poinsot & Veynante 2005). Many researchers, such as (Marble and Broadwell 1977, Borghi 1989, Veynante and Vervisch 2002, and Ahmed & Prosser 2016), studied the influence of turbulence on a premixed turbulent flame and proposed many models for modeling premixed turbulent combustion. Most of these studies dealt with solving the source term in the species equation. The coherent flame model (CFM) is a promising approach to employing the source in the transport species equation for premixed turbulent combustion. CFM depends on a modified flamelet model and is based on the solution of the source term in terms of flame area density and fuel mass fraction (Marble and Broadwell 1977).

Turbulence intensity and length scale represent the effect of turbulence on flame, which is wrinkles flame and dominates at high levels but is less sensitive to wrinkle the flame at low levels (Clavin and Joulin 1983, Aldredge and Williams 1991, Yuan et al. 2006, Fruv et al. 2011, Aspden et al. 2015, and Bagdanavicius et al. 2015). (Gülder and Smallwood 2007) studied the flame area density in a premixed turbulent flame at the vast level of turbulence intensities and found that turbulence affects the flame area density. In addition, the maximum flame surface density does not vary with the turbulence intensity.

Conclusions from previous studies, which are related to turbulent combustion interaction, indicate that turbulence has a significant effect on flame. In spite of the numerous studies that examine the effect of turbulence on flame, the flame front location has not yet been studied extensively. Therefore, the influence of turbulence on flame location should

be considered in an extensive investigation of a simple combustor, where sole effect of turbulence on flame can be tested. In this study, a diffuser-type combustor is used to investigate the response of flame location to various turbulence intensities and length scales without changing mixture velocity, i.e., thermal power and combustor geometry. The diffuser form is selected because the flow slows down along the flow direction such that the flame is expected to propagate toward the inlet when the flame speed increases.

This paper studies the location of a premixed turbulent flame that is exposed to varying turbulence intensities and length scales. This paper is organized into several sections, including flame combustion modeling, numerical simulation, and results. The combustion model is detailed in the section that discusses the modeling of combustion and flame. In the result section, the effect of turbulence on flame location is discussed and the influence of flow structure on the flame location is compared across different turbulence intensities and length scales.

Nomenclature

CFM	Coherent flame model	S_C	Schmidt number [-]
D	Diameter [m]	S_L	Laminar flame speed [m/sec]
FL	Flame location [m]	S_f	Source term in term fuel mass fraction
Ka	Karlovitz number [-]	TI	Turbulent intensity [-]
K_t	Flame ftrech [1/s]	u	Velocity [m/s]
L	Diffuser length [m]	x_k	Coordinate component [m]
S	Source term	Y	Axial direction a long diffuser

Greek symbol

$\tilde{c}$	Reaction Progress variable	β	Constant parameter of the CFM model
$\tilde{Y}_f$	the fuel mass fraction [%]	u'	Fluctuation velocity [m/sec]
$\widetilde{Y_{ft}}$	Residual of fuel mass fraction [%]	ε	Dissipation rate [m^2/s^3]
$\tilde{u}_k$	Favre velocity [m/sec]	λ	Air – fuel ratio actual to stoichiometric
ν_t	kinematic viscosity [m^2/s]	α	Constant parameter of the CFM model
ℓ	Turbulent length scale [m]	ℓ_f	Flame thickness [m]
ρ	Density [kg/m^3]	ρ_u	Density of the unturned gases [kg/m^3]
Γ_K	Parameter of stretch strain	Γ_p	Flame production due to the stretch
Γ_q	Flame quench due to the stretch	S_Σ	Source term in term flame area density
Σ	Flame area density per volume[-m]	σ	Flame area density per mass [m^2/kg]
Ka_δ	Second Karlovitz number [-]		

2. Modelling of the flame and combustion

A suitable and simple model of premixed turbulent combustion depends on the type of combustion process. CFM is a promising flame model for premixed turbulent combustion that deals with turbulent combustion interaction. CFM is based on solving the reacting term in the species transport equation in terms of flame area density and fuel mass fraction. Flame area density is used to represent the increase in the area of the flame front that results from wrinkling generated by turbulence. This study is about the impact of turbulence on combustion; therefore, CFM is selected as the most suitable model for this work.

The k-ε model is also used to involve the turbulent effect within the Reynolds-averaged Navier–Stokes (RANS)

framework (Tangermann et al. 2010, Ahmed and Prosser 2016, and Huang et al. 2016), which is a main approach used to simulate the premixed combustion and turbulence problem. Density varies during combustion. Thus, Favre averaging is used to represent all the combustion and flow quantities. The species equation in terms of Favre-averaged density is formulated as follows:

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{c}) + \frac{\partial}{\partial x_k}(\bar{\rho}\tilde{u}_k\tilde{c}) = \frac{\partial}{\partial x_k}\left(\bar{\rho}\frac{v_t}{S_C}\frac{\partial\tilde{c}}{\partial x_k}\right) + \bar{S} \tag{1}$$

CFM (Marble and Broadwell 1977) is based on solving fuel mass and flame area density in the source term. Therefore, a transport equation is formulated for the fuel mass fraction as follows:

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{Y}_f) + \frac{\partial}{\partial x_k}(\bar{\rho}\tilde{u}_k\tilde{Y}_f) = \frac{\partial}{\partial x_k}\left(\bar{\rho}\frac{v_t}{S_C}\frac{\partial\tilde{Y}_{ft}}{\partial\tilde{x}_k}\right) + \bar{S}_f \tag{2}$$

where $\tilde{Y}_f$ is the fuel mass fraction. The mean reaction in terms of the fuel mass fraction (S_f) in the source term can be described as

$$S_f = -(\rho_u S_f \Sigma)(Y_{ft} - Y_{res}) \tag{3}$$

In the CFM, flame area density (σ) is the flame area per unit mass; therefore, the transport species equation is expressed in this model in terms of the flame area density by (Meneveau and Poinsot 1991 and CD-adapco 2016).

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{\sigma}) + \frac{\partial}{\partial x_k}(\bar{\rho}\tilde{u}_k\tilde{\sigma}) = \frac{\partial}{\partial x_k}\left(\bar{\rho}\frac{v_t}{S_C}\frac{\partial\tilde{\sigma}}{\partial\tilde{x}_k}\right) + \bar{S}_\Sigma \tag{5}$$

The source term in the equation that includes flame area density Σ and flame is calculated by

$$S_\Sigma = \alpha K_t \ \Sigma - \beta \frac{\rho_u Y_{ft} S_L \left(1 + a\sqrt{k}\big/S_L\right)}{\rho \ Y_f} \Sigma^2 \tag{6}$$

The impacts of turbulence intensity and length scale are included within the flame area density in terms of flame stretch, turbulence kinetic energy (TKE) k, and turbulent dissipation rate ε (Meneveau and Poinsot 1991). Therefore, the flame stretch K_t in Eq. (6) can be calculated as

$$\Gamma_K = \frac{K_t}{\varepsilon/k} = f\left(\frac{\acute{u}}{S_L}, \frac{\ell}{\ell_f}\right) \tag{7}$$

where u' and ℓ are the rms of the velocity fluctuations and the turbulent length scale, respectively, which are obtained from the following equations (Pope 2000):

$$u' = \sqrt{\frac{2}{3} \ k} \tag{8}$$

and

$$\ell = \frac{k^{3/2}}{\varepsilon} \tag{9}$$

Γ_k is estimated by the following equation:

$$\Gamma_K = \Gamma_p - \ B\Gamma_q \tag{10}$$

where Γ_p and Γ_q are the flame production and quench due to stretch, respectively.

3. Settings for numerical simulation and test cases

In this study, the influence of turbulence on flame location is evaluated in a premixed diffuser combustor. The flame is exposed at the diffuser inlet to various turbulence intensities and length scales, which are listed in Table 1. Fuel and air are assumed to be the premixed upstream of a diffuser combustor. The air–fuel ratio is lean and premixed with λ = 1.7, and the mixture comprises 3.81% C_3H_8, 23.55% O_2, and 72.63% N_2 by mass. The propane–air mixture flows at an inlet

velocity of 0.3 m/s through the diffuser burner with an inner inlet diameter of 10 cm, outlet diameter of 20 cm, and a sufficient diffuser length of L = 95.53 cm.

Table. 1 Test cases of the simulation for different (TI) and (ℓ) at the diffuser inlet.

Test cases	ℓ [cm]	TI [-]	TI [-]	TI [-]	TI [-]	TI [-]	TI [-]	TI [-]
1	1	5 %	10 %	15 %	20%	25 %	30%	35%
2	5	5 %	10 %	15 %	20%	25 %	30%	35%
3	10	5 %	10 %	15 %	20%	25 %	30%	35%

This dimension is selected depending on the diffuser angle, which measures 3° from the inlet diameter to the upper downstream outlet diameter, to decrease flow separation and recirculation. The diffuser downstream, which measures 40 cm and has a constant diameter, is constructed. Fig. 1 shows the combustor–diffuser setup used in this work.
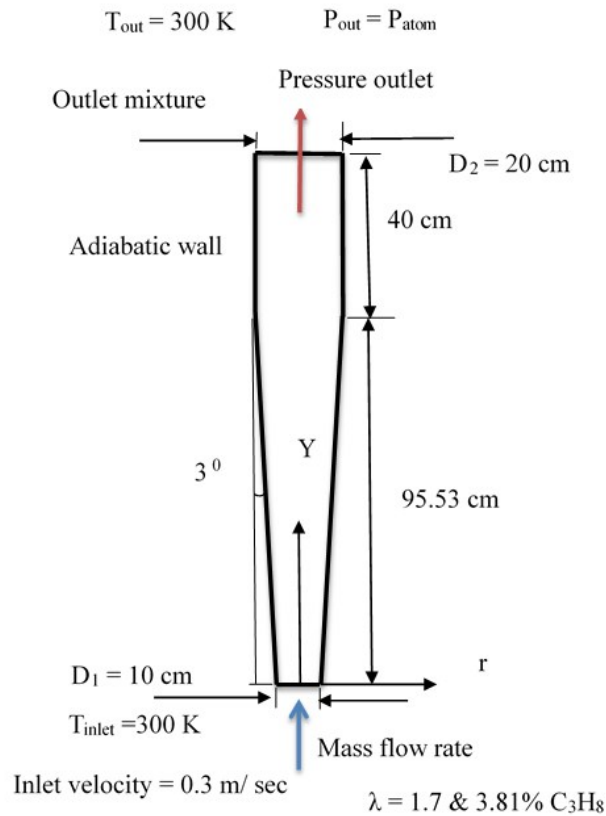

Fig. 1 The geometry of the diffuser combustor and the boundary conditions.

The implicit unsteady, three-dimensional CFM and the $k - \varepsilon$ model within the frame of the RANS equation are used to solve the premixed turbulent flame model. Unsteady combustion simulations are conducted numerically using the STAR CCM+ version 11.02.009-R8 until the flame is stabilized. The one-step global reaction is assumed in the combustion model as

$$C_3H_8 + 5(O_2 + 3.76N_2) \longrightarrow 3CO_2 + 4H_2O + 18.8 \ N_2 \tag{11}$$
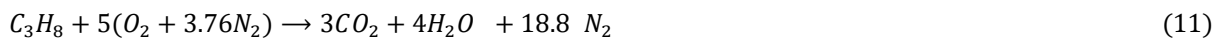
At the diffuser inlet, the ambient pressure and temperature are set as the inlet and outlet conditions, respectively, and

the burner wall is adiabatic. The simulations are performed under steady-state condition at TI = 5% and ℓ = 1 cm and are then taken as the initial conditions to the unsteady simulations. The inlet turbulence conditions in the unsteady simulations are changed stepwisely to the required levels of turbulence intensity and length scale. This approach augments the numerical convergence. The simulations are conducted for a sufficient amount of time to allow the flame location to stabilize with the new values of turbulence intensity and length scale.

4. Results and discussion

Flame behavior should be indicated within the regime map of the premixed turbulent combustion to understand the influences of turbulence intensity and length scale on flame location. (Borghi 1989, Peters 1989, and Abdel-Gayed et al. 1989) depended on velocity and turbulence scale ratios to establish the regimes of premixed turbulent combustion. Therefore, a change in turbulence intensity level and length scale causes a change in the type of combustion zone within the regimes of the premixed turbulent combustion as a result of the change in the physical process. The value of the laminar flame speed was constant for all test cases (S_L= 0.14 m /s), while the fluctuation velocity varies with change in the turbulence intensity. The fluctuation velocity increases with increase in the turbulence intensity as shown in Table. 2, which indicate the values of the fluctuation velocities for the various turbulence intensities and at 5 cm length scale. In addition, the flame thickness was 0.0005421 m at the temperature 1400 K.

Table. 2 The values of fluctuation velocities for different turbulence intensities and 5 cm length scale.

Turbulence intensity [-]	5 %	10 %	15 %	20 %	25 %	30 %	35 %
Fluctuation velocity [m /s]	0.1165	0.1440	0.1571	0.1977	0.24751	0.2524	0.2588

Fig. 2, which represents the flame locations on the Borghi diagram for all the test cases, shows that the flames in the test cases are wrinkled and of corrugated flamelet types. The temperature field is used to measure flame location, which is assumed to be at 1400 K at the centerline of the combustor for all cases. Line probe is used along the axial direction of the diffuser combustor to measure the characteristics of the mixture combustion, such as instantaneous velocity, temperature, and flame area density. The results are discussed in three sections.
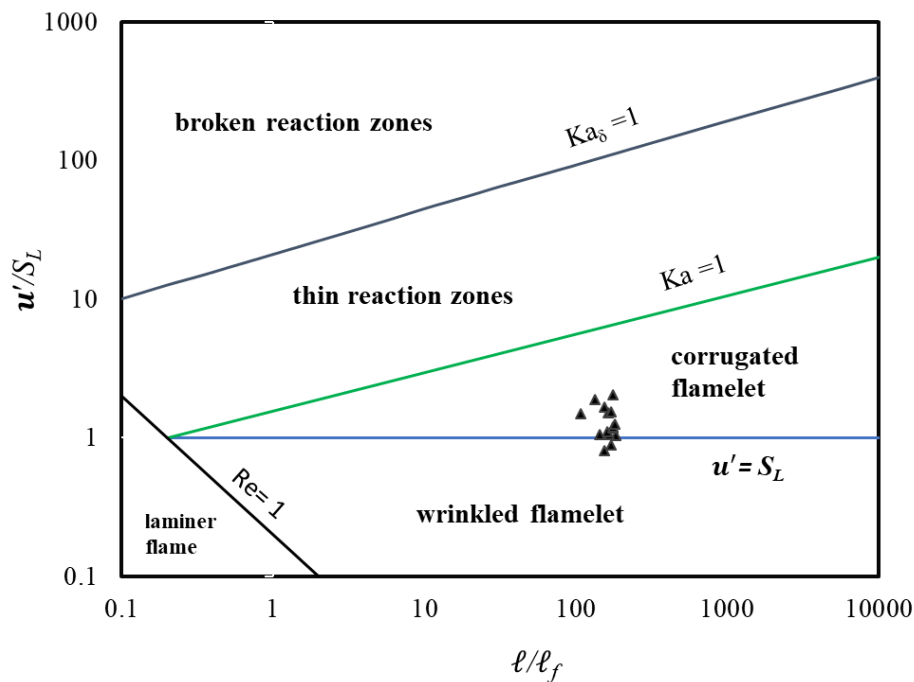

Fig. 2 Flame locations on the premixed turbulent combustion regime (Borghi diagram) for all cases.

The effects of turbulence intensity and length scale on flame location are explained in the first section, the effect of the secondary flow on flame location is discussed in the second section, and the flame area density and the flame shape are explained in the third section.

4.1 The Effect of Turbulence on the Flame Location

All temperature profiles are plotted together for the difference in turbulence intensities and length scales to indicate the influences of turbulence intensity and length scale on flame location. Fig. 3 compares temperature contours over various turbulence intensities and length scales, and Fig. 4 illustrates flame location on the axil direction respect to the diffuser length as a function of turbulence intensity and length scale.
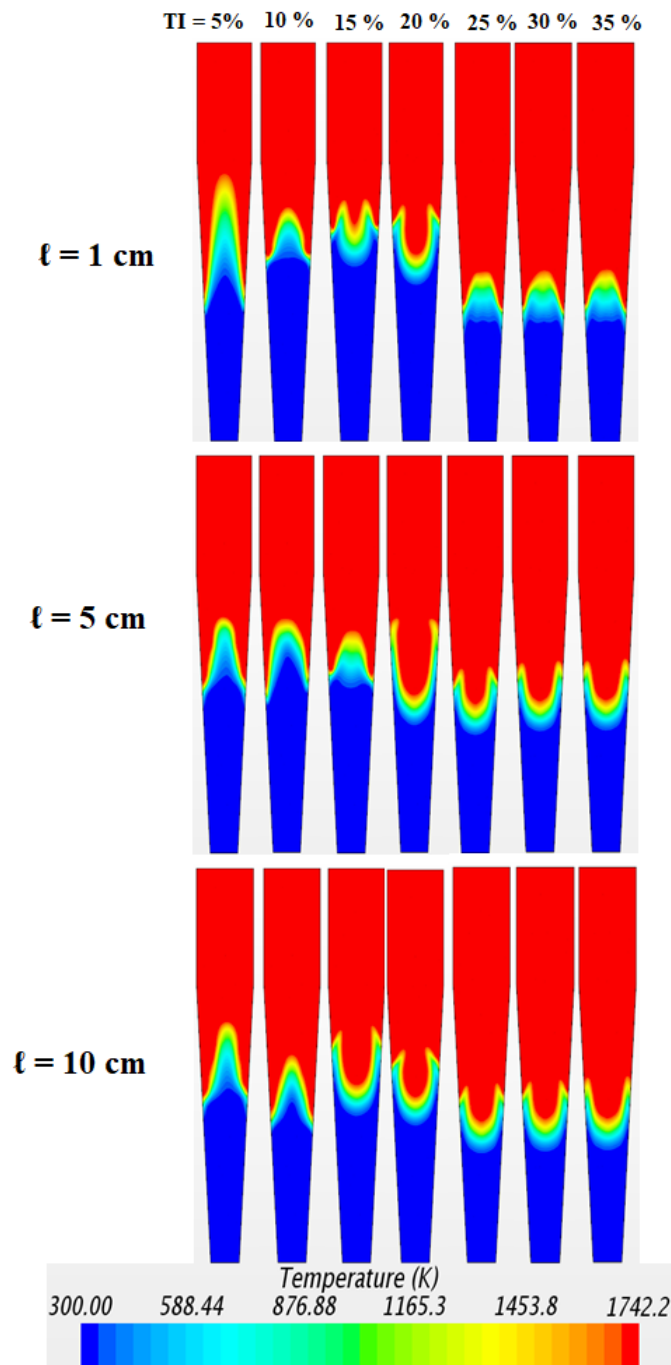

Fig. 3 Contours of temperature at different TI and ℓ.

These figures show that flame location depends on turbulence intensity and length scale, with the flame front location generally moving toward the diffuser inlet gradually with increases in the two factors. The impact of turbulence intensity on flame location is more visible than that of turbulence length scale. Flame location is stabilized with an increase in TI of 25% to 35%. Nevertheless, an increase in turbulence length scale at a constant TI generally causes a decrease in flame location. For $\ell = 5$ cm, it can be seen that the same the flame location almost as either $\ell = 1$ cm or $\ell = 10$ cm cases. The obtained results show that flame location depends on turbulence intensity and length scale. In addition to the change in flame location, flame shape may change when the turbulence intensity and length scale are varied.
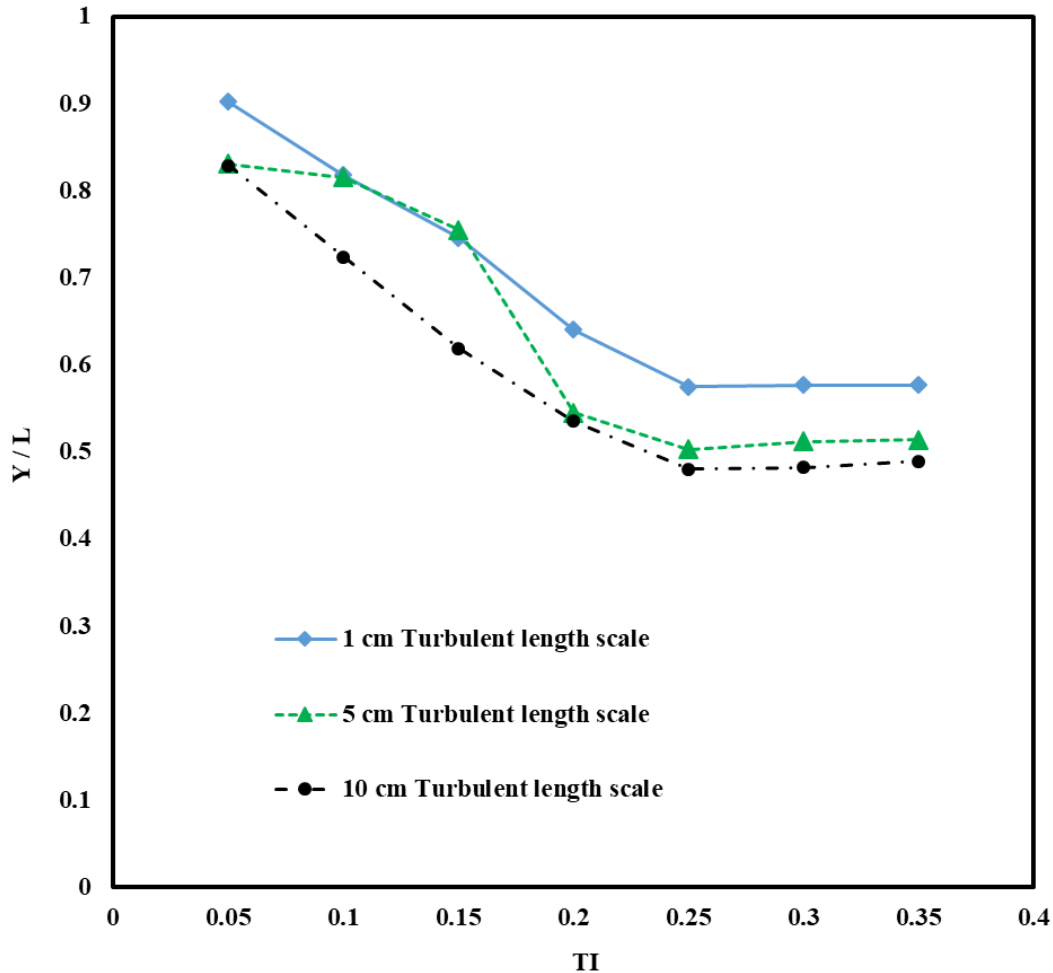

Fig. 4 Flame location normalized with the length of the diffuser at different TI and ℓ.

Similar effects of turbulence on flame has been indicated by many reasechers. For example, Yuan, Ju, and Law (2006) studied the influences of turbulence on flame front by changing turbulence intensity within 1% to 50% and found that hydrodynamic instability dominates the growth of flame cells at low turbulence intensities of 1% to 5%. Meanwhile, turbulence wrinkles the flame front and dominates the process at a high turbulence intensity of 50%. Therefore, we select the range of turbulence intensity within 5% to 35%, and the results indicate the expected effect of turbulence on the flame, i.e. the turbulent flame speed increases with turbulence and it moves toward the inlet.

4.2 Effect of Secondary Flows Structures

Most turbulence intensities and length scales give reasonable predictions for the behavior of flame location, but the flow separation that occurs within the diffuser combustor has an effect on this behavior as well. Line integral convolution is used to illustrate the imaging vector fields, which were proposed by (Cabral and Leedom 1993) to understand the flow separation. Fig. 5 shows the effects of flow separation and turbulence intensity on flame location for all cases. Flow separation occurs at the diffuser wall behind the flame front and causes an increase in the velocity at the combustor center.
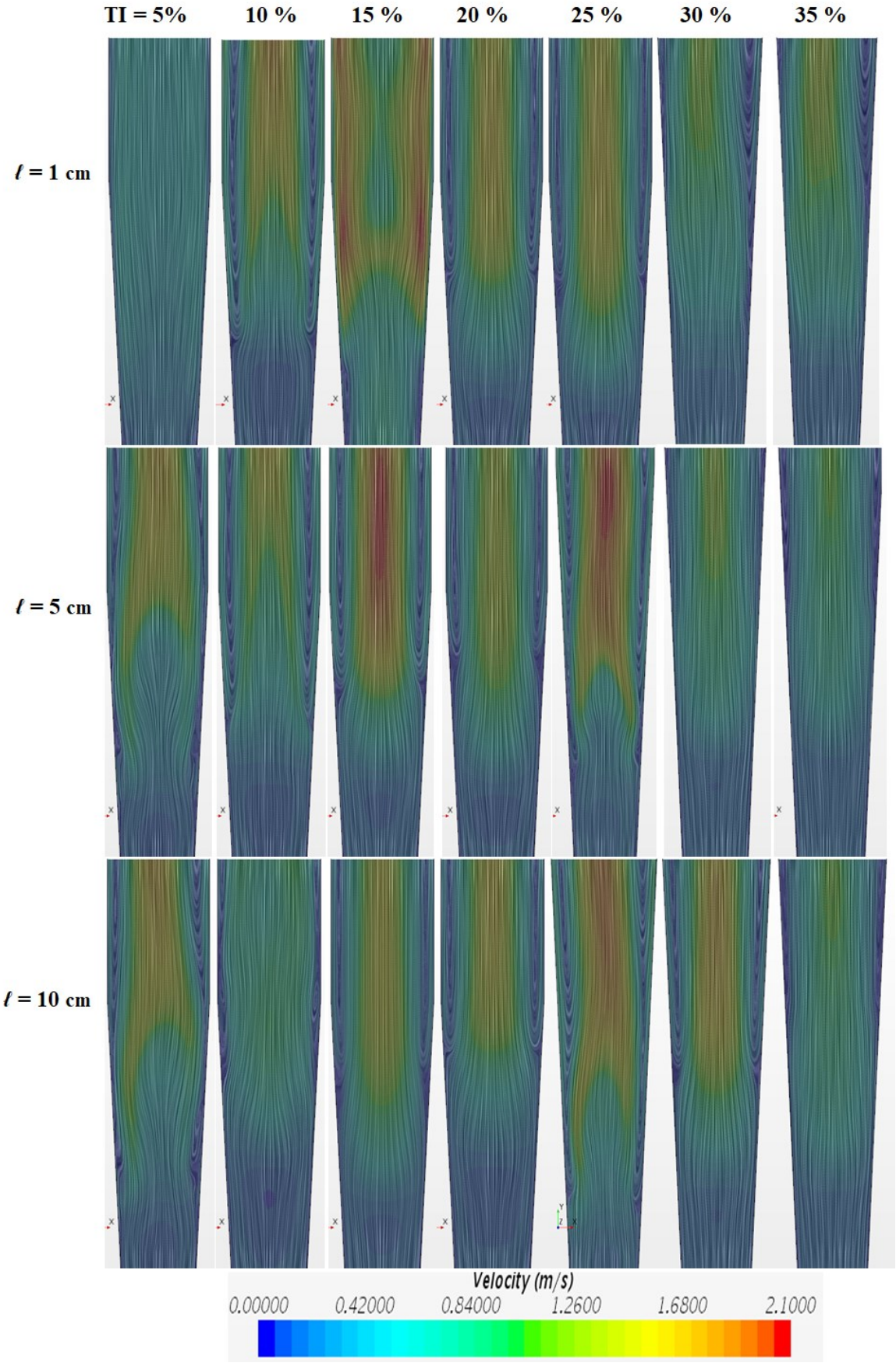
Fig. 5 Contours of the line integral convolution (flow streamline).

This flow separation is influenced by the increases in turbulence intensity and length scale. As flow separation occurs, the axial mean flow rises and pushes the flame away from the inlet. Consequently, flame location is influenced by the flow separation, which generally occurs downstream in the flame zones for most of the cases.

The turbulent kinetic energy along the central axis of the diffuser combustor is measured using a line probe. Fig. 6 illustrates the profiles of the turbulent kinetic energy with different turbulence intensities and length scales of 10 cm, in the diffuser. These profiles show the turbulent kinetic energy before combustion (cold zone) and after combustion (reacting zone). The turbulent kinetic energy changes with the increase in TI at the inlet and ℓ for all cases, as illustrated in Fig 6. In all cases, the TKE initially decays from turbulence dynamics as expected, and then rises suddenly within the flame region. The increase of the TKE that occurs within the region of the combustion starts at T = 1400 K. The TKE is based on the dissipation rate (ε) according to Eq. (9). Thus, an increasing TI means an increase in ε with a constant turbulent length scale. Therefore, the decay rate of the TKE downstream of the inlet is high when turbulence intensity is high.
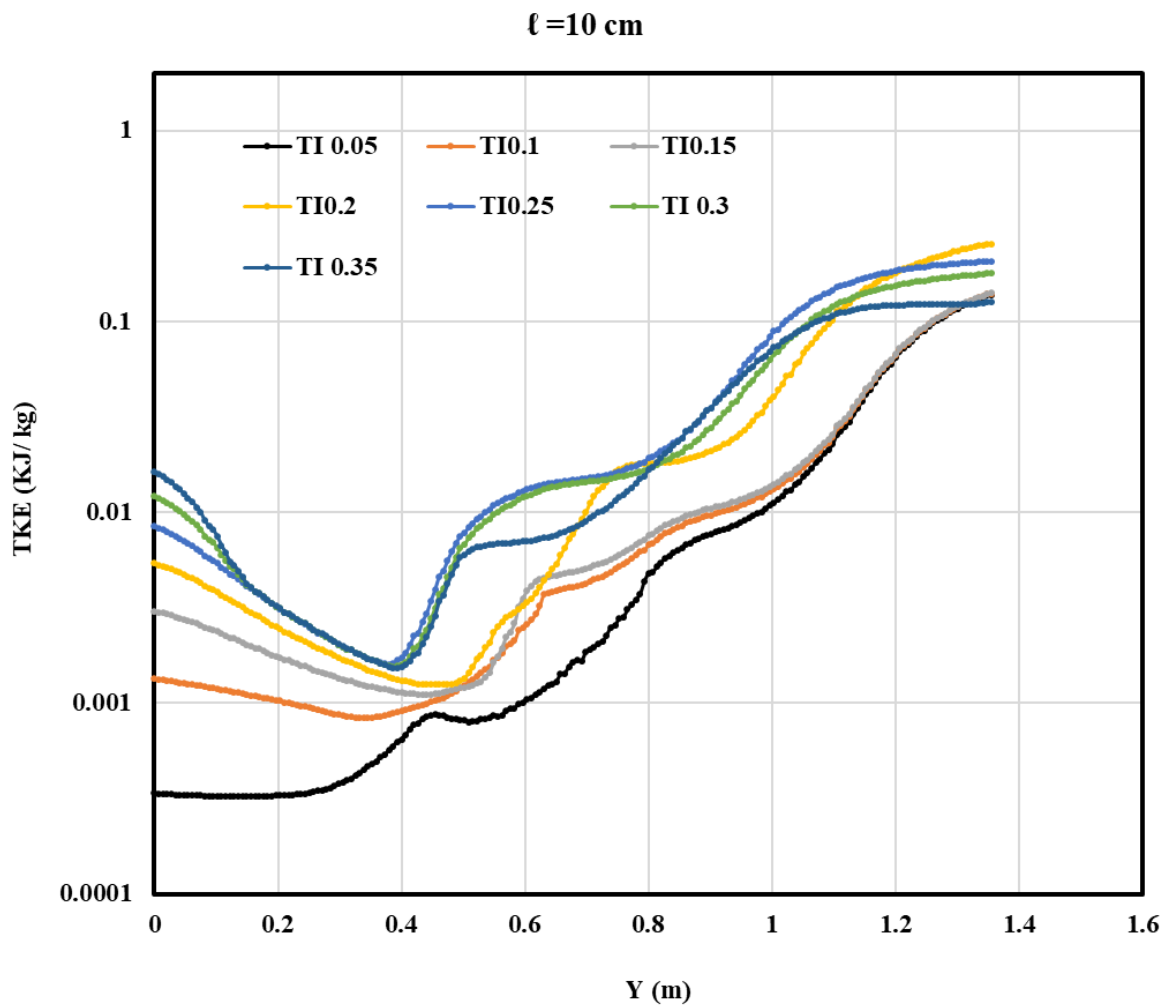

Fig. 6 Turbulent kinetic energy along the axial direction of the diffuser combustor with various turbulence intensities and at 10-cm turbulent length scale.

4.3 Flame area density

Fig. 7 shows the flame area density for various turbulence intensities and length scales. The shape of the value of the flame area density varies with the increases in turbulence intensity and length scale. The flame shape can be convex or concave. Many types of flame shapes exist depending on the shape factor, which is based on the flame position and axis planes (Rutland and Trouvi 1993, Chakraborty and Cant 2006, and Kerl et al 2013).
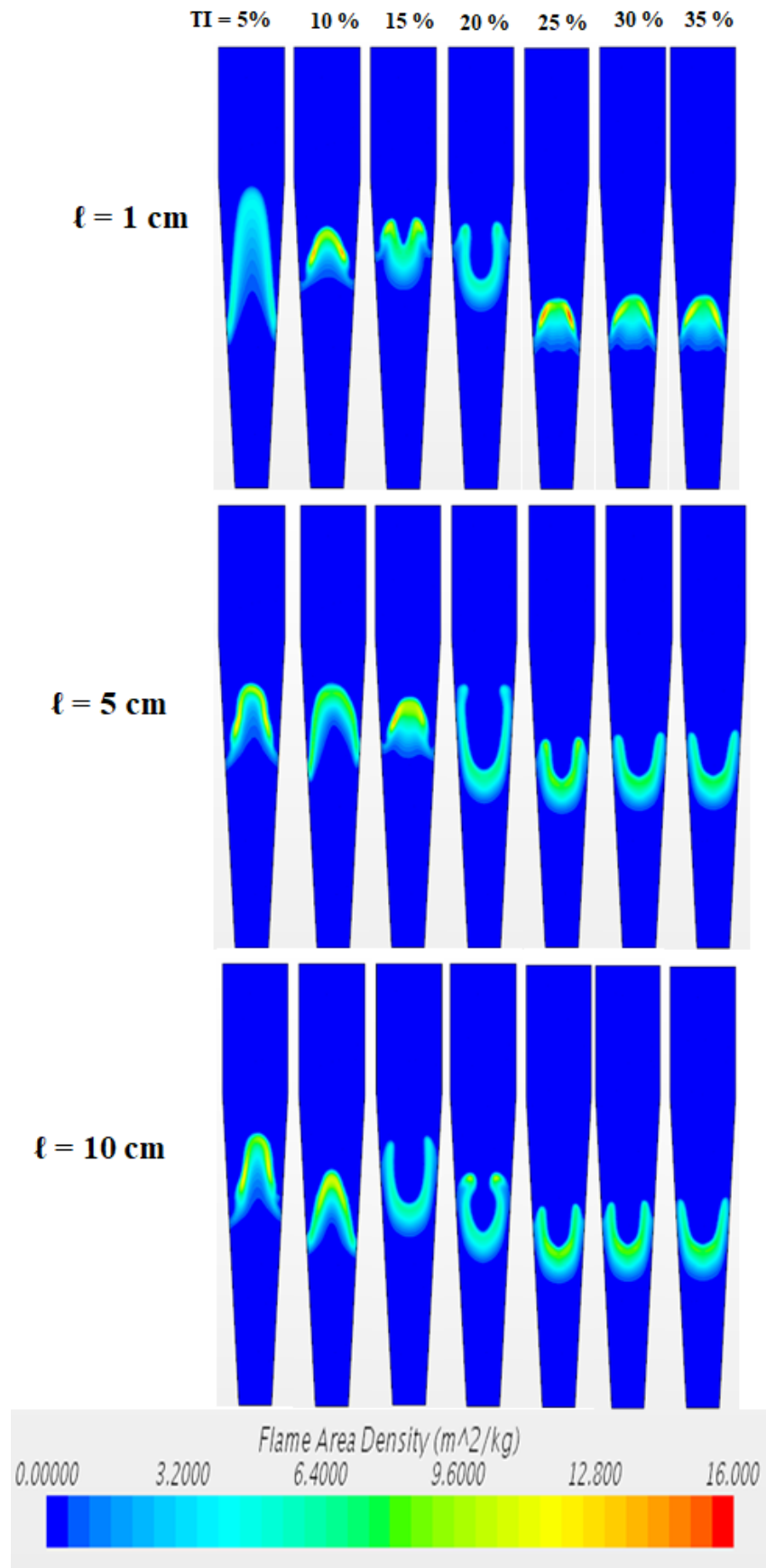
Fig. 7 Profile of the flame area density for various TI and ℓ.

(Kerl et al 2013) presented three flame shapes (hyperbolic, parabolic and elliptic) in a diffuser combustor with an annular swirling flow at its inlet. As this work is the most similar study to the present work, the flame shapes obtained here can be accepted to be realistic. (Clavin and Joulin 1983) indicated that front shape and motion can be controlled by flame stretch. In addition, it can be seen from the Fig.7 the maximum flame area density does not change with the increase in turbulence intensity. This result is consistent with those found by (Gülder and Smallwood 2007), who studied the flame area density in a premixed turbulent flame at a vast level of turbulence intensity in a Bunsen burner and concluded that the maximum flame surface density does not vary with turbulence intensity.

5. Conclusions

Flame location is investigated using a diffuser combustor to show its response to varying turbulence intensities and length scales for premixed propane–air combustion. Turbulence intensity and length scale and flow separation exert a significant effect on the flame location of the premixed turbulent combustion. The flame front moves toward the diffuser inlet with increases in turbulence intensity and length scale. However, the effect of turbulence intensity is more visible than that of turbulence length scale within the tested range. An increase in turbulent length scale at a constant turbulence intensity causes a decrease in flame location.

Flow separation occurs behind the flame zones in most of the cases, thereby influencing the location and shape of the flame front. Therefore, the value of the flame location and the flame shape are influenced by flow separation and turbulence intensity and length scale.

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