

Multi-fuel combustion performance analysis and operating characteristics of a vortex-tube combustor

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Abstract: In this work, an ultra-steady combustion technique was attempted to achieve fuel adaptability combustion. The combustion performances of five representative gaseous fuels in a stratified vortex-tube combustor were investigated in terms of the stability limit, pressure fluctuation, and flame topology. Results show that the lean stability limit of the global equivalence ratio for the five fuels can always be less than 0.15 with a uniform flame front, whilst the amplitude of pressure fluctuations is always below 2300 Pa, indicating a super-steady combustion process. The non-premixed flame structure guarantees a high mass concentration near the reaction zone, whilst the vortex flow also decreases the local flow velocity, inhibiting flame blow-out, and suggesting good self-adjusting capacity under various global equivalence ratios. The synergistic action of the flow and flame structures transports the interior high-enthalpy burnt gas and exterior unburnt gas to the exterior unburnt gas and reaction zones to promote the ignition and reaction procedures, resulting in an intensified combustion. The large tangential velocity and density gradient result in the large values of Richardson number, which indicates that laminarization of the flow arises and results in good aero-dynamic and thermo-dynamic stabilities. The resultant good self-adjusting capacity and three types of dynamic stabilities are the intrinsic causes of the ultra-steady combustion process in this combustor. Ultimately, the generalized criterion of stabilization can be defined by the combination of Richardson and Rayleigh numbers, for which large Richardson and small Rayleigh numbers are required for a highly steady combustion process.

Keywords: Fuel adaptability; Flame-dynamic; Generalized criterion; Intensified combustion; Stabilization

Nomenclature:			
CFL	Courant–Friedrichs–Lewy	RMVC	Rapidly mixed vortex-tube combustor
C-N	Crank-Nicholson		
CDS	Central difference scheme	R_i^*	Modified Richardson number
E-M	Euler-Maruyama	$Ra(x)$	Rayleigh parameter
$\text{grad } \rho$	Density gradient	sgs	Sub-grid-scale
h	Enthalpy	S_u	Flame speed
HRR	Heat release rate	SVC	Stratified vortex-tube combustor
h_e	Filtered sensible enthalpy	t	Time
J	Transport flux of species	TVD	Total variation diminishing
J_h	Transport flux of enthalpy	T_b	Burned gas temperature
k	Constant coefficient	T_u	Unburnt gas temperature
LES	Large-eddy simulation	u_j	Velocity
N	Number of stochastic fields	u	Velocity normal to the flame front or unburnt species
N_s	Number of species	$\partial U / \partial r$	Gradient of axial velocity
P	Pressure	$V_{\theta \max}$	Maximum tangential velocity
$p'(t)$	Pressure fluctuation	W	Tangential velocity
pdf	Probability density function	x, y, z	Coordinate axis
PIV	Particle image velocimetry	Y_α	Mole number of chemical species
q_f	Fuel flow rate [L/min]	Z	Mixture fraction
$q'(t)$	Volume-averaged HRR fluctuation	Z_{st}	Stoichiometric mixture fraction
r	The distance normal to the flame front or unburnt species	Z / Z_{st}	Mixture fraction ratio
Greek:			
α	Species	σ	Prandtl/Schmidt number
φ	Local equivalence ratio	τ	Integration time
φ_g	Global equivalence ratio	τ_{ij}	Stress tensor
δ_{ij}	Kronecker delta	μ	Dynamic viscosity
ζ_f	Flame index		
ρ	Fluid density		

1. Introduction

Combustion as a significant contributor to energy conversion systems is widely employed in internal engines [1], aero-engine [2], gas turbines [3], various industrial combustors [4], and in people's everyday life. The current move to clean and renewable energy systems implies that further research into combustion is required [5]. If multiple fuels can be burnt in a single combustor or engine at the same time, it will be of great importance to the world energy power system, carbon-neutral national policy, and the dependence on mono fuels. However, it remains a challenge due to the different physical and chemical properties of different fuels as combustion instability and incomplete combustion may inevitably arise.

Decades of fundamental research and application development have shown that the vortex-tube combustion technique or vortex-tube combustor has various features and advantages and gives rise to a highly simple and convenient flame configuration [6], a large flammability range [7], low NOx

emission and strong stabilization properties [8]. Thus, the vortex-tube combustor provides a good potential for overcoming fuel adaptability problems due to its high stabilization properties, which mainly consist of aerodynamically [9] and thermodynamic [10] stability.

Up to now, various configurations of vortex-tube combustors have been developed [11] and evolved [9] significantly. A typical vortex-tube combustor mainly consists of either the premixed vortex-tube combustor or the rapidly mixed vortex-tube combustor. Although a good fuel flexibility has ever been demonstrated in the RMVC preliminarily by Ishizuka [12], where it was noted that the RMVC could burn a variety of fuels. However, this was not quantified and a comprehensive comparison for different fuels was not carried out, i.e., the stability limit, and pressure fluctuation amplitude.

Additionally, the traditional vortex-tube combustor has defects and deficiencies. The first is the premixed burning mode; typical vortex-tube combustors are based predominately on premixed burning, which will inevitably affect the stabilization properties. Syred et al. [13] point out that premixed burning in swirl combustion systems is normally undesirable because it is predisposed to produce a large precessing vortex core, which can cause instability and narrow the operational limits. The second is the strict requirement that the mixing time should be shorter than the chemical reaction time for the establishment of the vortex-tube flame for the RMVC. The above two issues limit its use in industrial applications to a certain extent.

As a consequence, a stratified vortex-tube combustor (SVC) or combustion technique, proposed by the Guangzhou Institute of Energy Conversion, does not need a premixed region near the center of the combustor and provides a local stratification of species [14], which improves the mixing quality and overcomes the negative effects of the premixed condition in swirling combustion systems [15]. Instead, a binary (or triple) flame structure is formed in the SVC, which is crucial for stabilization. The good stabilization properties of the SVC have been explored and discussed in detail in previous works [16, 17]. Because of the stratified property of species, the SVC provides a large heat release rate, which can enhance the density gradient along the radial direction, leading to stable combustion consistent with the Rayleigh stability criterion [18]. For example, with methane as fuel, the lean global equivalence ratio stability limit of the SVC can be lower than 0.18, which is much lower than that in the typical vortex-tube combustor [19]. Additionally, the amplitude of pressure fluctuation is always lower than 4 kPa, which is superior to that of typical vortex-tube combustors [20]. In addition, oxygen-deficient combustion has already been investigated and indicates that the SVC retains a large stability limit with a low-pressure fluctuation amplitude and uniform flame front [21]. Therefore, the ultra-steady vortex-tube combustion technique provides an excellent potential to overcome fuel adaptability problems. The present paper describes the results of the fuel adaptability aspects of the stratified vortex-tube combustor and provides a generalized criterion for steady combustion. The corresponding conclusions will be important for future design upgrades and transformation of various engines, gas turbines, and industrial combustors.

1. Physical model of the combustor and research method

2.1 Physical model and boundary conditions

The stratified vortex-tube combustor (SVC) consists of a combustion tube and four tangential slits, as shown in Fig. 1. The internal diameter, tube length, and slit width are 0.05, 0.5, and 0.002 m, respectively. The fuel slit length is 0.005 m and the oxidant slit length is 0.03 m, immediately

downstream of the fuel slit. $z = 0$ mm locates in the position of the beginning of the fuel slit along the axial direction. The swirl number of this combustor is 13.46.

The gaseous fuels (methane, ethanol, propane, n-heptane, and kerosene) of 550 K and oxidant (air) of 500 K are injected into the combustor through their inlet slits at atmospheric pressure (1.01×10^5 Pa). The preheating of fuels and oxidant is to ensure complete gasification of the liquid fuels. The global equivalence ratio ϕ_g is based on all the fuel and oxidant injected into the combustor, which ranges from 0.04 to 1.0. The volumetric flow rate of fuel q_f is 12.0 L/min. The pressure fluctuation information is recorded at the position corresponding to $x = -0.024$, $y = 0$, $z = 0.06$ m.

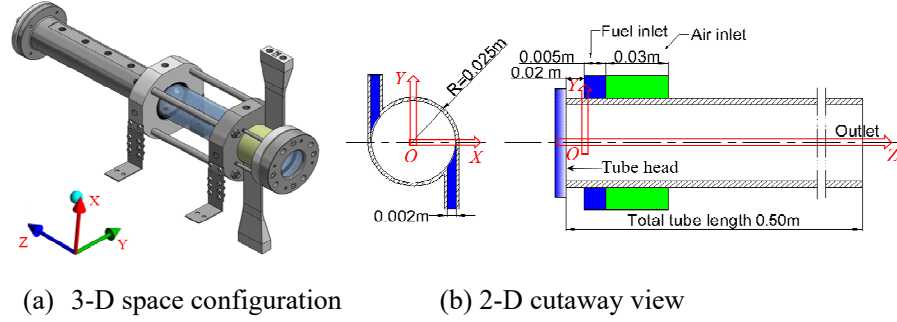


Fig. 1 Structure of the stratified vortex-tube combustor.

2.2 Mathematical modeling

In the simulation, a three-dimensional (3-D) structured hexahedral grid with 1,800,000 elements is employed encompassing the complete combustor configuration after the independent mesh verification. We used meshes comprising 50,000, 100,000, 150,000, 1,800,000 and 2,000,000 nodes to investigate grid independence. From the distributions of temperature, species, and heat release rate in SVC we found that the difference between the solutions with the 1,800,000 and 2,000,000 meshes were within 0.5 %. Thus, the results shown in the paper were obtained with 1800,000 nodes.

The minimum size of the mesh near the wall is approximately 0.01 mm, and about 0.005 mm in the reaction zone. The grid quality is above 0.85 and the y^+ near the tube wall is 1.0. The expansion ratio, the aspect ratio, and the skewness are 1.02, 1.02, and 0.0132, respectively. The chemical kinetics mechanisms used for the different fuels are shown in table 1. The kerosene is represented by $N-C_{10}H_{22}$.

Table 1 Detailed information on the oxidation reaction mechanism and sources of each fuel

Fuels	Number of species	Reaction-steps	Source
methane	19	15	[22]
propane	33	124	[23]
ethanol	28	180	[24]
n-heptane	22	112	[25]
kerosene	36	62	[26]

The in-house block-structured, parallel, compressible large-eddy simulation (LES) code Boundary Fitted Flow Integrator (BOFFIN-LESc) [27] has been employed for the simulation. In LES the equations of motion are solved directly for the resolved large-scale turbulent motions, and eight stochastic fields are employed to account for the sub-grid scale fluctuations. The computational time step varies between 1.0 and 20.0×10^{-7} s resulting in a maximum Courant–

Friedrichs–Lewy (CFL) number, based on the flow velocity, that is below 0.3. At the outflow, non-reflective conditions were applied to minimize flow distortion and numerical reflection [28]. Non-adiabatic combustion chamber walls are applied to improve the accuracy of near-wall regions. Radiative heat transfer is considered in the simulations through a radiation model described in [29]. Soret and Dufour's effects have been neglected in this work and all gases obey the ideal gas law. The spatial and temporal discretization schemes used in BOFFIN-LESc, details of which are given in Jones et al. [30] are summarized in Table 2.

Table 2 Discretization schemes used in BOFFIN for the different terms in the momentum and stochastic fields equations

	Convection	Diffusion	Stochastic	Temporal
Momentum	CDS	CDS	-	C-N
Stochastics fields	TVD	CDS	E-M	C-N

where the CDS is a second-order central difference scheme, TVD denotes the total variation diminishing scheme, E-M indicates the Euler-Maruyama scheme, and the C-N refers to the time-centered Crank-Nicholson scheme. In all cases, simulations were carried out for more than 100 flow-through times based on the bulk velocity and combustor length to ‘wash’ the effects of initial conditions, and statistics were then collected further over 10 flow-through times.

In LES a spatial filter is applied to the equations of motion with the result:

2.2.1 Filtered conservation equations

Continuity:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_j}{\partial x_j} = 0 \quad (1)$$

where t is the time, $\tilde{u}_j$ and x_j denote the velocity and spatial coordinate in j direction, $\bar{\rho}$ is the fluid density.

Momentum [30]:

$$\frac{\partial \bar{\rho} \tilde{u}_i}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_i \tilde{u}_j}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[-\frac{2}{3} \mu \frac{\partial \bar{u}_k}{\partial x_k} \delta_{ij} + \mu \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right] - \frac{\partial \tau_{ij}^{sgs}}{\partial x_j} \quad (2)$$

where $\bar{p}$ is the pressure, δ_{ij} denotes the Kronecker delta, τ_{ij}^{sgs} denotes the sub-grid scale (sgs) stress tensor, which is determined via the dynamically calibrated Smagorinsky model [31].

Mass (Species) [32]:

$$\frac{\partial \bar{\rho} \tilde{Y}_\alpha}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_j \tilde{Y}_\alpha}{\partial x_j} = -\frac{\partial}{\partial x_j} \left(\left(\frac{\mu}{\sigma} + \frac{\mu_{sgs}}{\sigma_{sgs}} \right) \frac{\partial \tilde{Y}_\alpha}{\partial x_j} \right) + \overline{\rho \dot{\omega}_\alpha} \quad (3)$$

here μ is dynamic viscosity, σ is the Prandtl/Schmidt number, $\tilde{Y}_\alpha$ is specific mole number of the α -th chemical species, $\tilde{Y}_\alpha = [Y_1, \dots, Y_{Ns}]$, where Ns denotes the number of species ($1 \leq \alpha \leq Ns$), the subscript sgs indicates the sub-grid scale values, $\overline{\rho \dot{\omega}_\alpha}$ represents the net formation rate through a chemical reaction.

Enthalpy [32]:

$$\frac{\partial \bar{\rho} \tilde{h}}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_j \tilde{h}}{\partial x_j} = \frac{\partial \bar{p}}{\partial t} + \tilde{u}_i \frac{\partial \bar{p}}{\partial x_i} - \frac{\partial}{\partial x_j} \left(\left(\frac{\mu}{\sigma} + \frac{\mu_{sgs}}{\sigma_{sgs}} \right) \frac{\partial \tilde{h}}{\partial x_j} \right) \quad (4)$$

where the $\tilde{h}$ denotes the enthalpy, including enthalpies of formation.

2.2.2 Sub-grid *pdf* and stochastic fields approach

Because of the difficulties encountered in evaluating the chemical source terms, equations (3) and (4) are not solved directly but rather an approach based on a modelled evolution equation for the spatially filtered joint fine-scale probability density function (*pdf*) is adopted [33], as revised by Brauner et al [34]. The temporal evolution of the joint *sgs-pdf* is represented by an ensemble of N stochastic fields, with each field involving the $N_s + 1$ scalars, denoted $\xi_\alpha^n(x, t)$ with $1 \leq n \leq N$ and $1 \leq \alpha \leq N_s + 1$. In the present work, the Itô formulation of the stochastic integral is adopted; further details can be found in Jones et al [32]. The fields evolve according to:

$$\begin{aligned} \bar{\rho} d\xi_\alpha^n + \bar{\rho} \tilde{u}_j \frac{\partial \xi_\alpha^n}{\partial x_j} dt = & \frac{\partial}{\partial x_j} \left[\left(\frac{\mu}{\sigma} + \frac{\mu_{sgs}}{\sigma_{sgs}} \right) \frac{\partial \xi_\alpha^n}{\partial x_j} \right] dt + \sqrt{2 \bar{\rho} \frac{\mu_{sgs}}{\sigma_{sgs}}} \frac{\partial \xi_\alpha^n}{\partial x_j} dW_j^n \\ & - \frac{C_d \bar{P}}{2 \tau_{sgs}} (\xi_\alpha^n - \tilde{\phi}_\alpha) dt + \bar{\rho} \dot{\omega}_\alpha^n (\xi_\alpha^n) dt \end{aligned} \quad (5)$$

where the final term on the right-hand side is $\frac{D\bar{p}}{Dt} dt$ for enthalpy and the net formation rate through

a chemical reaction in the case of chemical species. $\tilde{\phi}_\alpha$ denotes either the specific mole number of the α -th chemical species or the enthalpy. The Wiener process dW_j^n is different for each field but independent of the spatial location x is approximated by time-step increments $\eta_j^n \sqrt{dt}$ containing the $\{-1, 1\}$ dichotomic random vector η_j^n . The solutions of the stochastic fields equation are continuous and differentiable in space and continuous but not differentiable in time.

2.3 LES verification

First of all, the flow velocity under isothermal conditions was verified by comparing the results of the simulations with the particle image velocimetry (PIV) measurements of Zhang [35]. The combustor length and diameter are 250 and 36 mm, respectively. The slit length and width are 100 and 3 mm, respectively and the flow rates are 80 L/min. The simulated axial and tangential velocities at cross-section $z = 160$ mm are compared with the measurements in Fig. 2. It can be observed that the computed results are in good agreement with the measurements with the maximum velocity deviation being less than 5 %.

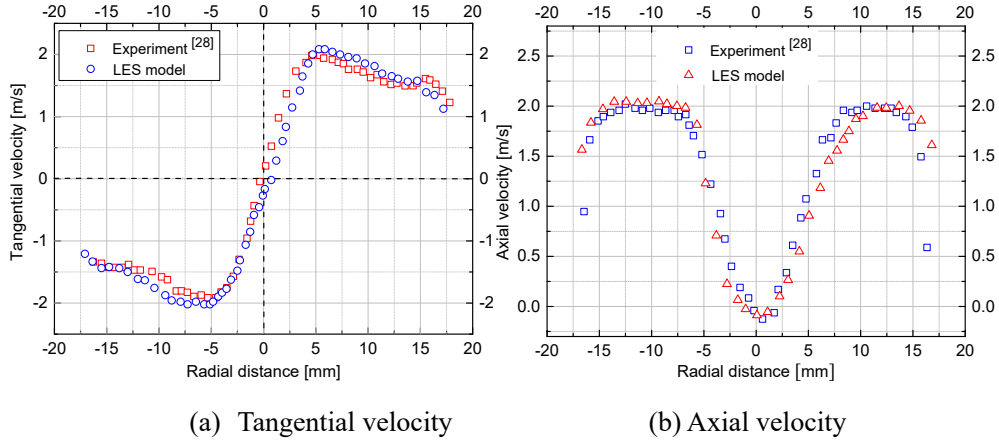


Fig. 2 LES calculation model verification in the vortex-tube combustor under the cold condition at $z = 160$ mm. (a) Tangential velocity, (b) Axial velocity.

Next, the simulated flame topology is compared with a photograph [16, 19] taken under the condition $\phi_g = 0.8$ and $q_f = 12.0$ L/min. Methane was employed as fuel in this comparison. Fig. 3 indicates that the binary flame structure is reproduced reasonably well by the LES. The experimentally observed and simulated flames at positions A and A' and B and B' display a strong similarity. Additionally, the flame diameter, length, and bifurcation also show good agreement.

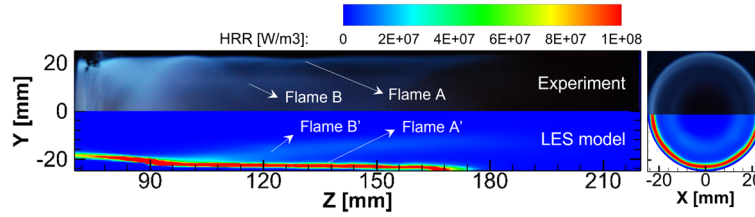


Fig. 3 Flame topology verification of the LES model in the vortex-tube combustor at $\phi_g = 0.8$ and $q_f = 12.0$ L/min.

The simulated chemical species concentrations and temperature are compared with measurements in Fig. 4 where profiles of concentration and temperature at $\phi_g = 0.6$ and $q_f = 12.0$ L/min are shown: the dots denote the measurements while the lines represent the LES results. It can be observed that the LES results correspond closely to the measurements for both the species concentration and temperature distributions. The maximum deviation is always within 5 %, as above suggesting good reliability of the LES model.

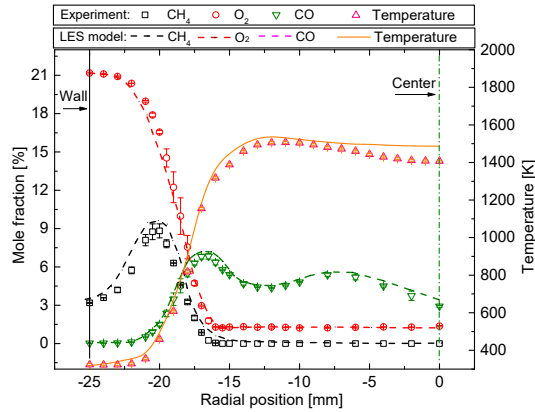


Fig. 4 The reaction species and temperature distributions of the LES model and experiment on line_60 at $\phi_g = 0.6$ and $q_f = 12.0$ L/min.

2. Results

Figure. 5 displays the stability limit, in terms of equivalence ratio ϕ_g , of different fuels at a flow rate, $q_f = 12.0$ L/min. The Figure indicates that the lean flammable limits are all lower than 0.15 in the stratified vortex-tube combustor for the five selected fuels, indicating a wide flammable limit that is much lower than that of typical vortex-tube combustion [19, 36]. For methane, the lean flammable limit as is low as $\phi_g = 0.15$, which is close to the propane lean flammable limit of $\phi_g = 0.14$. For ethanol, the lean flammable limit can be as low as $\phi_g = 0.11$ comparable to that of kerosene. The fuel n-heptane displays the widest ϕ_g lean flammable limit with a value of $\phi_g = 0.10$. In the present study, the lean flammable limit is found to equal the lean stability limit.

Based on the wide flammability limits of the SVC, the pressure fluctuations of the five selected fuels are examined at conditions corresponding to $q_f = 12.0$ L/min and $\phi_g = 0.6$. Fig. 6 indicates that the amplitude of pressure fluctuations (ΔP) is always less than 3000 Pa. For methane, propane, ethanol, and n-heptane, ΔP is always within 1000 Pa, indicating a highly steady combustion process. For methane case ①, it can be observed that ΔP is about 120 Pa; for propane case ② ΔP is around 450 Pa, which is approximately twice that of ethanol; ethanol case ③ ΔP is just under 250 Pa. For n-heptane, the pressure fluctuation amplitude is a little larger than that in the cases ① ~ ③ as seen in case ④ where ΔP is about 1000 Pa, but it is still much lower than the 5 % operating pressure (around 5000 Pa), indicating a highly steady combustion process in the SVC. For the kerosene combustion, the ΔP has a distinct increase, being about 2300 Pa, but is still less than the 5 % operating pressure. It is worth mentioning that the octane number of n-heptane is extremely low, but the combustion process is still very steady. Although the ΔP of kerosene can reach up to 2300 Pa, the thermal power output is around 64 kW, which is 8.1 times as large as that of methane. When the heat output of kerosene equals that of methane, the pressure fluctuation amplitude is about 250 Pa. The ΔP in the SVC for different fuels is still much smaller than that of a typical RMVC combustion [37] and exhibits good steady combustion characteristics and good multi-fuel adaptability.

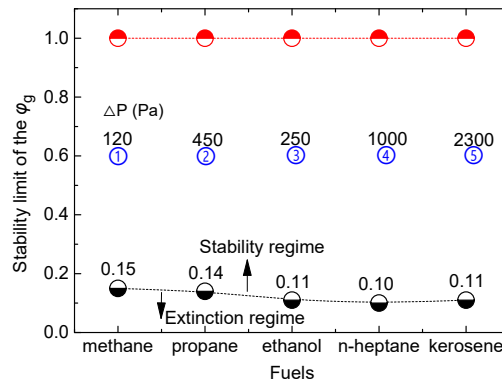


Fig. 5 The ϕ_g stability limit of different fuels at $q_f = 12.0$ L/min in the SVC.

In addition to the flammability limits and the pressure fluctuations, the flame topologies for different fuels are also investigated. This is represented by the time-averaged heat release rate (HRR). The results for methane, Fig. 7 (a) show the time-averaged heat release rate for $q_f = 12.0$ L/min and ϕ_g

= 0.6, indicating that the peak HRR is about $1.0 \times 10^8 \text{ W/m}^3$, which occurs in the axial position $z = 40 \sim 80 \text{ mm}$, whilst a binary flame structure can also be observed clearly. The flame triple point occurs at around the region $z = 50 \text{ mm}$. The exterior flame strength is stronger than the interior one although the two flame branches are uniform. Fig. 7 (b) displays the corresponding time-averaged temperature distribution and indicates that the temperature ranges between 300 to 2200 K with the high-temperature region being mainly distributed in the interior. A spindle-shaped flame topology is generated in the SVC. Additionally, from the $z = \text{constant}$ plane, it can also be seen that the flame front is highly uniform throughout the SVC, and the HRR and temperature distributions are approximately circular. The temperature and HRR distributions for the other four fuels on the $x = \text{constant}$ plane are shown in Fig. 8. For propane a binary flame structure can also be seen. Compared with methane the peak HRR region occurs further toward the tube head with a value nearly twice of methane. The interior HRR strength increases correspondingly. As a whole, both the heat release and temperature distributions are approximately uniform.

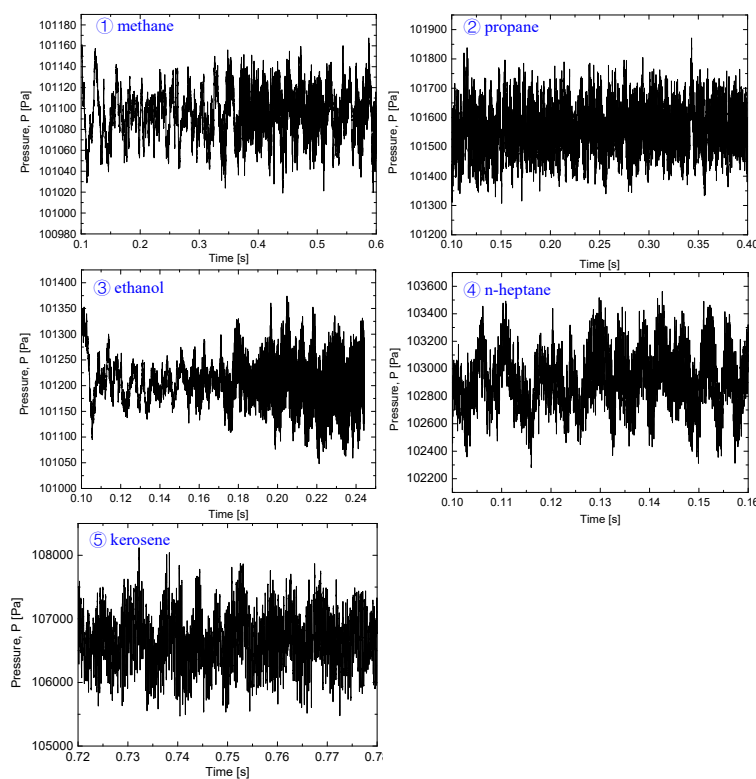
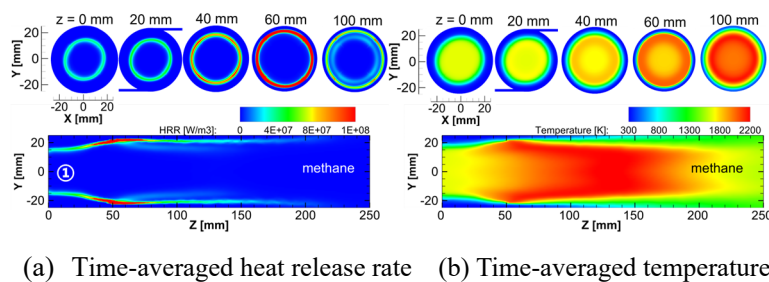
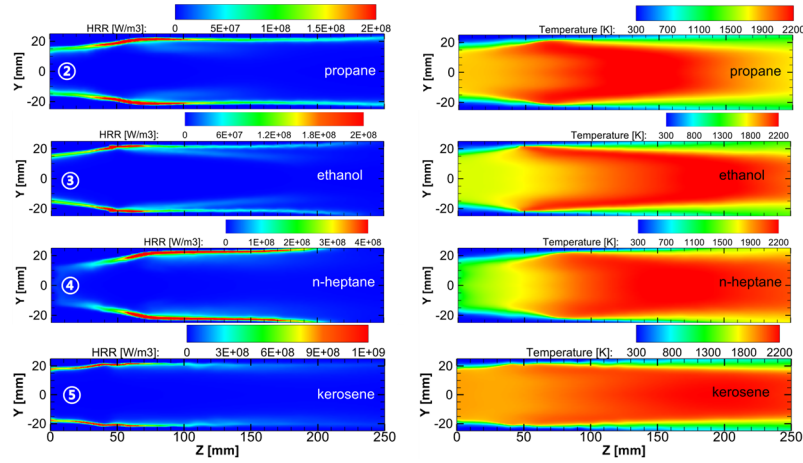


Fig. 6 Pressure fluctuations of different fuels at $q_f = 12.0 \text{ L/min}$ and $\phi_g = 0.6$.



(a) Time-averaged heat release rate (b) Time-averaged temperature

Fig. 7 Flame topologies of methane in the SVC on xy and yz planes at $q_f = 12.0 \text{ L/min}$ and $\phi_g = 0.6$.



(a) Time-averaged heat release rate (b) Time-averaged temperature

Fig. 8 Flame topologies of different fuels in the SVC on yz planes at $q_f = 12.0$ L/min and $\phi_g = 0.6$.

For ethanol and n-heptane, the heat release rate is also very uniform as is the temperature distribution. For kerosene, it can be seen that the exterior flame front is wrinkled, but the degree is very weak. The temperature distribution is still uniform and the high-temperature region also located in the interior. To summarize, the flame topology and temperature distributions are relatively uniform, although the flame configuration and combustion temperature distributions of each fuel are different. The high interior and low exterior temperature distribution accord with thermodynamic stability, which is also one of the reasons for the small amplitude of pressure fluctuations in cases of methane, propane, ethanol, and n-heptane. Furthermore, the large amplitude of pressure fluctuation for kerosene indicates that the method for evaluating combustion stability in terms of aerodynamic and thermodynamic properties has its limitations. The contribution of the flame dynamics behavior, i.e., the thermo-acoustic coupling, to the combustion stability in the SVC should also be considered.

3. Discussion

3.1 Flow and flame structures

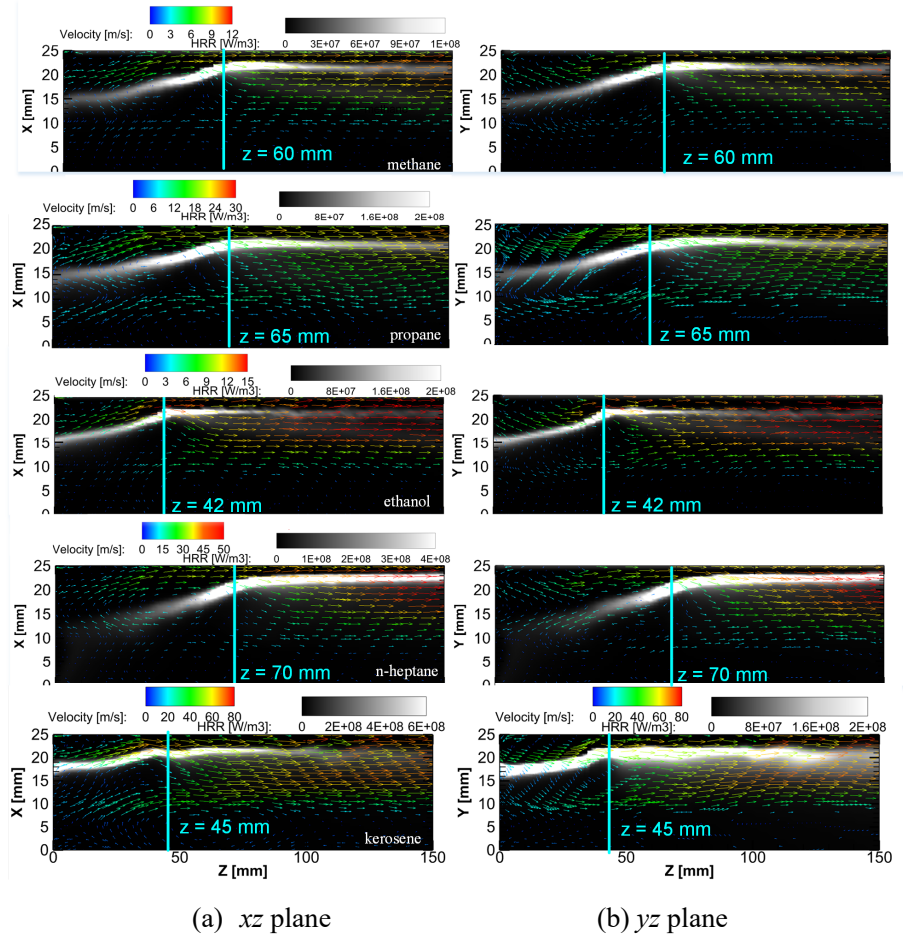


Fig. 9 Flow field vector and HRR distribution of different fuels at $q_f = 12.0$ L/min and $\phi_g = 0.6$.

Figure. 9 displays the flow velocity vector together with the HRR on the xz and yz planes in the SVC, wherein the high levels of HRR denote the position of the reaction zone. This figure indicates that the local flow velocity in the vicinity of the reaction zone is much lower than the injected gas velocity due to the strong vortex flow, indicating a flow field adaptive to different fuels. Fig. 10 exhibits radial profiles at axial positions that correspond to the position of maximum HRR for the different fuels. The local flow velocities at these positions are: methane 7.6 m/s at $z = 60$ mm; propane 17.9 m/s at $z = 65$ mm; ethanol 10.9 m/s at $z = 42$ mm; n-heptane 21.2 m/s at $z = 70$ mm; kerosene 56.6 m/s at $z = 45$ mm. This indicates a decreased local flow velocity near the flame front.

Additionally, Fig. 9 also implies that the flow field structure is different in the xz and yz planes because of the three-dimensional nature of the flow field, whilst the flow field structures for different fuels in the same plane are similar. For the xz planes, the figures indicate that there is a vortex-flow in the upstream section before $z = 60$ mm for different fuels, except for kerosene, where a low local velocity occurs. The location of the vortex core varies slightly with different fuels. The presence of a vortex flow in the yz section is not obvious, but the flow still continuously passes in and out of the flame front with a decreased local flow velocity.

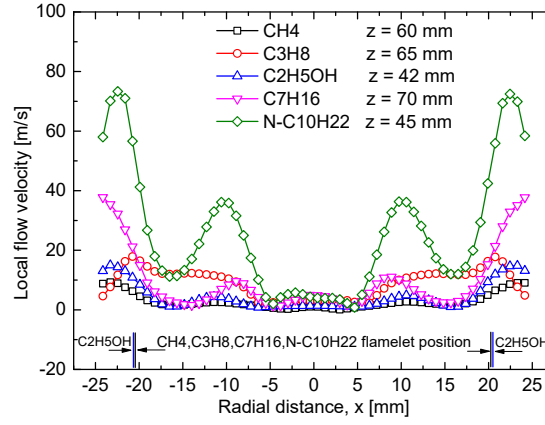


Fig. 10 Flow velocity of different fuels at different feature positions on the xy plane at $q_f = 12.0$ L/min and $\phi_g = 0.6$.

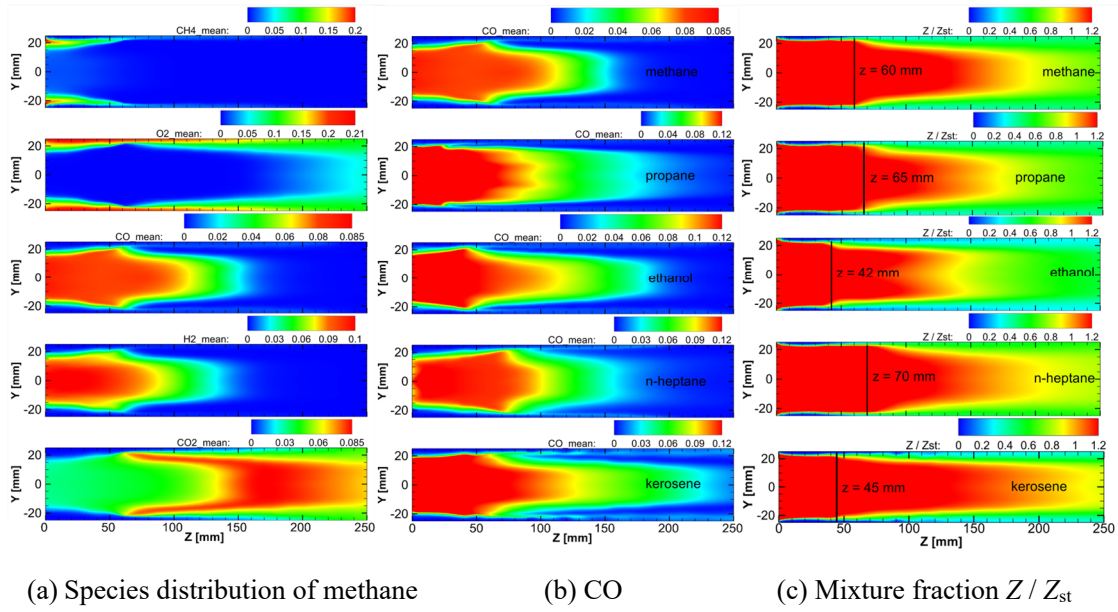


Fig. 11 Flame structure of different fuels at $q_f = 12.0$ L/min and $\phi_g = 0.6$.

Figure 11a displays contour plots of the mean concentrations of CH_4 , O_2 , CO , H_2 , and CO_2 for methane while Fig. 11b and 11c show contours of CO and mixture fraction divided by the stoichiometric value Z_{st} , for all five fuels. Combined with Figs. 7 and 8, Fig. 11a suggests that the oxygen concentration near the flame front is low while the CO level is high. This is consistent with the high levels of stratification experienced within the combustor. The high CO concentrations that occur for all fuels are indicative of high levels of stratification. Fig. 11c shows the ratio of mixture fraction Z and its stoichiometric value Z_{st} , indicating that the mixture fraction ratio Z / Z_{st} increases along the radial direction towards the centreline for all of the five fuels where all exceed 1.0 in the interior region. Further, the flame index, ξ_f was examined and is given by [38]:

$$\xi_f = \nabla Y_s \times \nabla O_2 \quad (6)$$

where Y_s represents the mole fraction of the reactive species (Fuels, CO , and H_2).

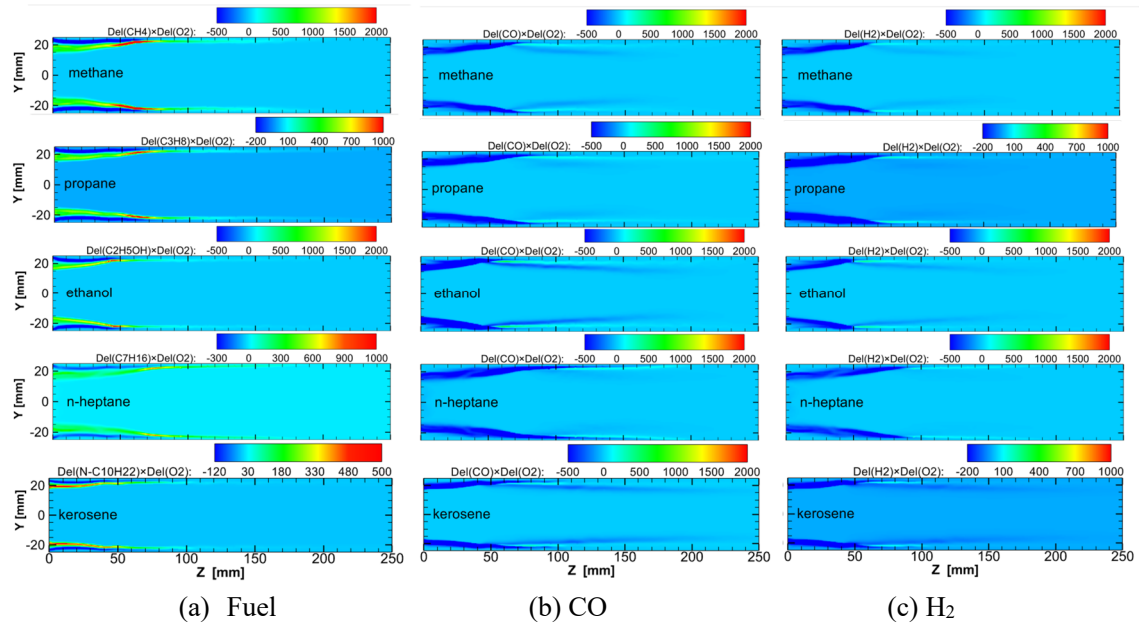


Fig. 12 Flame index of different fuels on xz plane at $q_f = 12.0$ L/min and $\phi_g = 0.6$.

The flame index ζ_f provides a representation of the combustion process. When the value of ζ_f is negative, non-premixed combustion takes place while a positive value indicates premixed combustion. Fig. 12 displays the flame index from which it is easily observed that the Fuel and O₂ mainly lead to premixed combustion, whereas the CO and H₂ with O₂ result in non-premixed combustion. Thus, the interior flame branch in Fig. 8 exhibits non-premixed burning, while the exterior one exhibits premixed burning, indicating a non-premixed flame structure in the SVC. Furthermore, Fig. 13 (a) displays profiles of the mixture fraction ratio (Z / Z_{st}) in the xy plane at the different axial positions given in Fig. 11c. It can also be easily observed that Z / Z_{st} increases from the wall towards the centreline. When the x coordinate is less than about 21.5 mm, the values of Z / Z_{st} all exceed 1.0. Therefore, non-premixed burning arises in the combustor.

The non-premixed flame is the key factor in the generation of the binary (or triple) flame structure shown in Figs. 7 and 8. The non-premixed burning results in a relatively high concentration of fuel and CO in the vicinity of the reaction zone as shown in Fig. 13(b). The reaction zone automatically adjusts to produce large concentrations of CO and fuel concentrations under various ϕ_g conditions. This figure indicates that the fuel mass concentration is above 20 g/m³ near the reaction zone for all of the five representative fuels, whilst the CO mass concentration is above 20 g/m³ implying a high reactive mixture near the flame front. Based on the specific flow field structure as discussed above, the high reactive species concentration in the combustor will be transported to the reaction zone, and result in an intensified combustion.

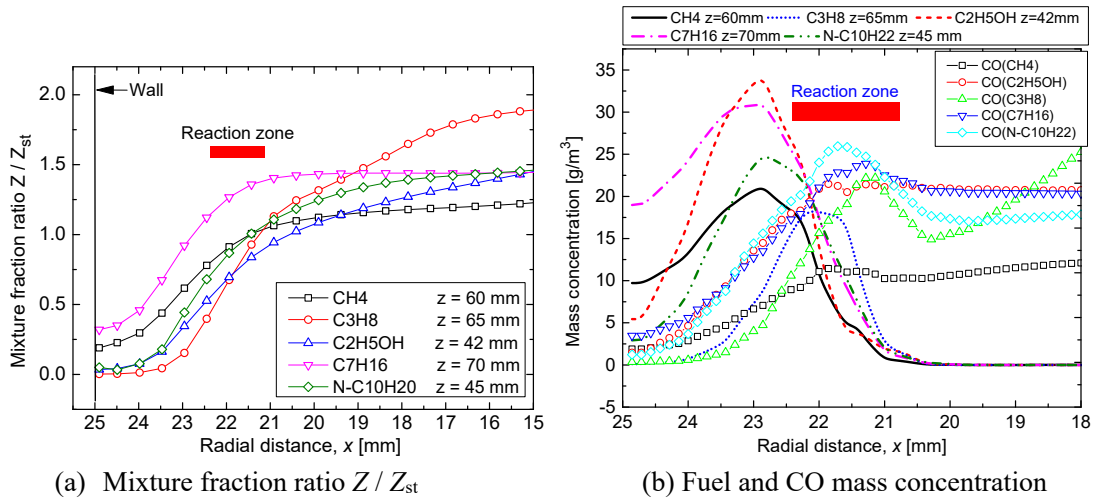


Fig. 13 The flame structure of the five representative fuels on xz plane at $q_f = 12.0$ L/min and $\phi_g = 0.6$.

Thus, the non-premixed flame structure and vortex flow can improve the ability of the combustor to adapt to the use of different fuels and different working conditions. It is the principal factor in the resultant large flammable limits and good stability properties of the combustor. In addition, the temperature or sensible enthalpy and species distributions and the flow field structure will lead to enthalpy transport to the exterior unburnt gas region and reaction zone, which will inevitably affect the combustion process. These will be further analyzed in section 3.2 below.

3.2 Vortex-flame interaction and combustion intensification

To investigate the underlying mechanisms providing good stabilization performance and large flammable limits with a uniform flame, the vortex-flame interaction was investigated by analyzing the transport flux of the sensible enthalpy and the reactive species. Attention is focused on the strengthening of the combustion process and preheating aspects. Fig. 14 displays the enthalpy field, the dominant species distributions and their corresponding transport flux fields, and the heat release rate distribution for methane in the xz and yz planes for $q_f = 12.0$ L/min and $\phi_g = 0.6$. Fig. 14(a) indicates that the flow field transports the high sensible enthalpy and burnt gas to the flame front at a position corresponding to a low HRR which facilitates the reaction process. In addition, high values of sensible enthalpy are transported to the exterior unburnt gases (CH₄ and O₂) region to preheat the unburnt species, thus promoting the ignition procedure. Additionally, based on the species distribution in the SVC discussed above, the flow field can also transport the reactive species to the reaction zone to intensify the combustion process. It is worth mentioning that the spindle-shaped flame topology can lead to the normal direction of the reaction zone and exterior unburnt gas region having both radial and axial transport flux components, yielding large transport fluxes of enthalpy and reactive species.

To clarify matters further, the data on line-ab, line-cd, and line-a'b' are extracted to quantify the impact as shown in Fig. 15. The line-ab denotes the line normal to the flame front and the intersection at $z = 20$ mm in the xz plane. The line-cd represents the line normal to the flame front at $z = 60$ mm position where a peak in HRR occurs. The a'b' indicates the line normal to the flame front at $z = 20$ mm position in the yz plane.

Figure. 15(a) shows the relevant data on line-ab, which indicates, based on the flow direction being from b to a point in the normal direction of the flame front, that the transport flux of the

sensible enthalpy (J_h) near the reaction zone can reach $2000 \text{ (kJ} \cdot \text{m)/(kg} \cdot \text{s)}$, while, J_h in the exterior unburnt gas region can in addition reach $1500 \text{ (kJ} \cdot \text{m)/(kg} \cdot \text{s)}$. Based on the transport equation of the enthalpy and species [32], the transport flux of the sensible-enthalpy and species can be obtained from the following equations:

$$J_h = \widetilde{u h_e} + \left(\frac{\mu}{\sigma} + \frac{\mu_{sgs}}{\sigma_{sgs}} \right) \frac{\partial \widetilde{h_e}}{\partial r} \quad (7)$$

$$J = \widetilde{u Y_k} + \left(\frac{\mu}{\sigma} + \frac{\mu_{sgs}}{\sigma_{sgs}} \right) \frac{\partial \widetilde{Y_k}}{\partial r} \quad (8)$$

where h_e denotes the filtered sensible enthalpy, u is the velocity normal to the flame front or unburnt species, r refers to the distance normal to the flame front or unburnt species, Y_k represents the mass concentration of the species k , μ and μ_{sgs} are the molecular and sgs viscosities with σ and σ_{sgs} being the molecular and sgs Prandtl/Schmidt numbers.

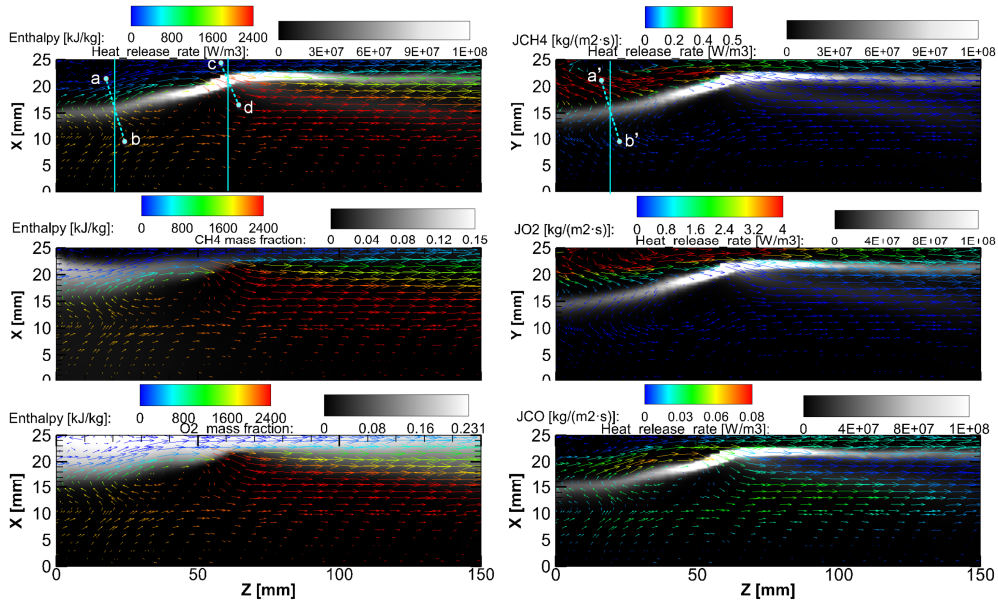


Fig. 14 The flow field vector colored by different critical variables with HRR of methane at $q_f = 12.0 \text{ L/min}$ and $\phi_g = 0.6$.

The results demonstrate that a certain amount of sensible-enthalpy is transported to the reaction zone and the unburnt gas region thus promoting the reaction in the tube head region and ignition. Correspondingly, Fig. 15(b) exhibits the relevant data along line-a'b', where the flow direction is from a' to b'. The exterior high enthalpy and unburnt species are transported to the flame front, thereby promoting combustion.

Figure. 15(b) implies that the transport flux of CH_4 and O_2 can reach 0.005 and $0.0072 \text{ kg/(m}^2 \cdot \text{s)}$ respectively, which is relatively small as a consequence of the low local velocity and low O_2 concentration here (local ϕ is 2.78). It is also the reason that the combustion process in the region near the tube head is not intense. However, the combustion on line-cd is very intense as seen in Fig. 15(c), where the HRR can reach $6.0 \times 10^8 \text{ W/m}^3$; the flow direction is from point c to d. Fig. 15(c) shows that the transport flux of CH_4 and O_2 can reach up to 0.025 and $0.113 \text{ kg/(m}^2 \cdot \text{s)}$ respectively. The transport fluxes of CH_4 and O_2 are around 5 and 15.7 times of those in line-ab. The local ϕ of 1.13 results in the mixture being much more reactive, which is the essential reason for the highest

HRR on line-cd. The intensified combustion can give rise to a large density gradient denoted as $\text{grad } \rho$, which can facilitate thermo-dynamic stability according to the Rayleigh stability criterion[18]. Additionally, the increase of $\text{grad } \rho$ can also give rise to an increase in the flame speed [39] according to the expression:

$$S_u = V_{\theta \max} [k \cdot \text{grad } \rho]^{0.5} \quad (9)$$

in which S_u is the flame speed, $V_{\theta \max}$ denotes the maximum tangential velocity in Rankine's combined vortex, k represents a constant coefficient, and $\text{grad } \rho$ indicates the density gradient.

The flame speed increase mechanism in a vortex flow has been interpreted by Ishizuka et al., [39, 40]. Based on the flame speed increase mechanism and Eq. (9), it is evident that S_u increases with the $\text{grad } \rho$. Given the intensified combustion is in favor of increasing the $\text{grad } \rho$, consequentially the flame speed will increase and improve the matching of local flow velocity and flame speed, resulting in a steady and uniform flame topology as seen in Fig. 6

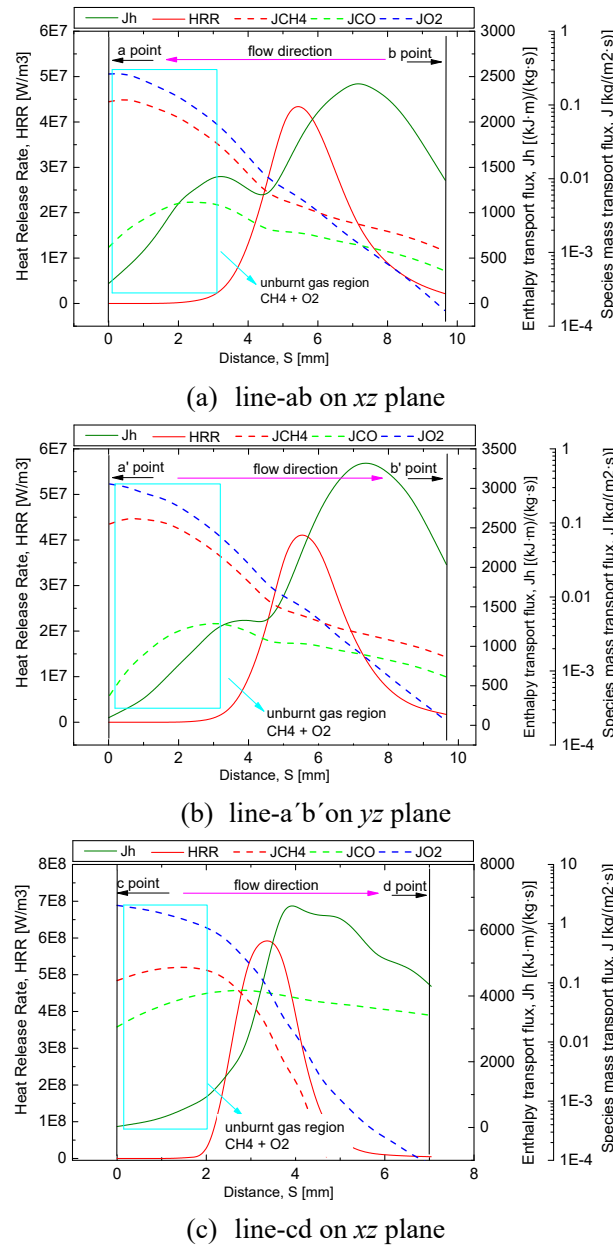


Fig. 15 The enthalpy and species transport property of methane in the normal direction of flame-

front at different feature positions.

The profiles for the other four fuels are also extracted and as shown in Figs. 16 and 17. In Fig. 16, line-ab and the profiles at different axial positions on the xz plane are shown. The selection of the different axial positions is based on the position of the peak HRR in the axial direction. As for line-ab, the flow is in the same direction as methane, viz., from b to a point. Fig. 16 indicates that the enthalpy transport fluxes J_h of the other four fuels are also high in the flame front and exterior unburnt gas regions. To put it concisely, the J_h is always above 5000 (kJ · m)/(kg · s) in the reaction zone. The values of J_h in the unburnt gas region are 1043 (kJ · m)/(kg · s) for C_3H_8 , 3928 (kJ · m)/(kg · s) for C_7H_{16} , 4321(kJ · m)/(kg · s) for $C_{12}H_{23}$, and 3591(kJ · m)/(kg · s) for C_2H_5OH . Correspondingly, exterior unburnt gas will be heated and then the ignition of the unburnt gases will arise.

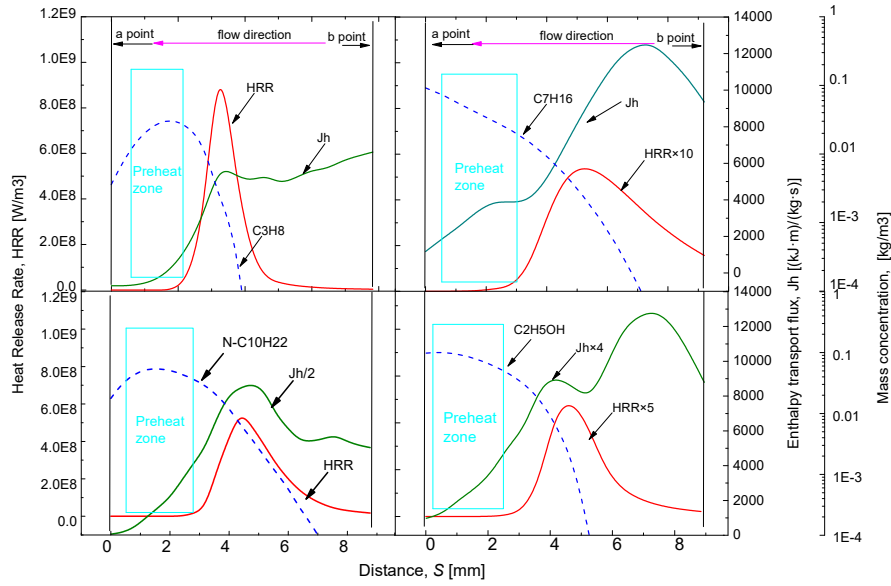


Fig. 16 The enthalpy and species transport property of different fuels in the normal direction of flame-front on line-ab.

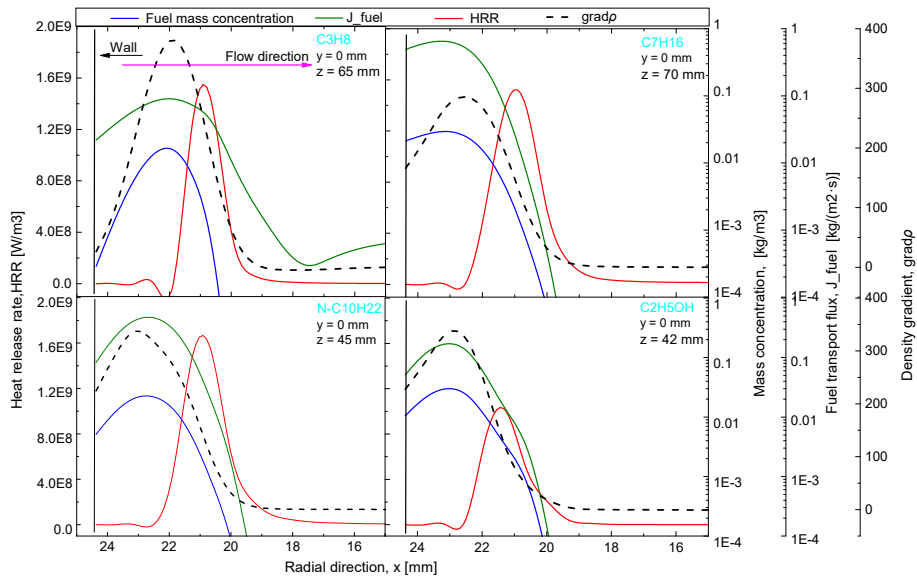


Fig. 17 The enthalpy and species transport properties of different fuels on the xz plane at different

axial positions.

Figure. 17 displays the profiles for the different fuels at various axial positions in the xz plane based on the position of the peak HRR in the axial direction. The flow is from the wall to the center. For C_3H_8 , the HRR peak is at $z = 25$ mm. The mass concentration of C_3H_8 in the exterior unburnt gas region can reach 0.018 kg/m^3 , and the corresponding transport flux $J_{C_3H_8}$ can reach $0.089 \text{ kg/(m}^2 \cdot \text{s)}$, yielding an intensified combustion with an HRR of $1.40 \times 10^9 \text{ W/m}^3$. The resultant grad ρ at the HRR peak position is around 176.4, giving rise to good thermo-dynamic stability and a high flame speed based on Equation 9. By the same token, the high concentration of fuel and the high species transport fluxes to the reaction zone for the other fuels are also the principal reason for the intensified combustion in the SVC. The resultant HRR maxima are 1.42×10^9 for C_7H_{16} , 1.51×10^9 for $C_{12}H_{23}$, and $9.98 \times 10^8 \text{ W/m}^3$ for C_2H_5OH . The corresponding grad ρ at the position of maximum HRR is 190.0 for C_7H_{16} , 89.3 for $C_{12}H_{23}$, and 100.8 for C_2H_5OH , indicating good thermo-dynamic stability and a high flame speed.

3.3 Dynamics and stabilization

The modified Richardson number R_i^* provides an indication of the degree of aero-dynamic and thermo-dynamic stability. It provides a measure of the ratio of centrifugal forces to the inertia force in a field with density gradients and can be expressed by the following [41].

$$R_i^* = \frac{(1/\rho)(\partial\rho/\partial r)(W^2/r)}{(\partial U/\partial r)^2} \quad (10)$$

where ρ is the density, r is the radial position, $\partial\rho/\partial r$ is the density gradient, W is the tangential velocity, and $\partial U/\partial r$ is the gradient of axial velocity.

When R_i^* exceeds 1.0, the stabilization effect of centrifugal forces with density gradients is larger than those of the destabilizing inertia forces resulting in laminarization of the turbulent flow. Based on the intensified combustion in this combustor, the density gradient is very likely to be large. Equation 10 indicates that R_i^* increases with the density gradient (grad ρ). Considering the large value of the grad ρ as seen in Fig. 17, R_i^* was evaluated to quantify the stabilization influence.

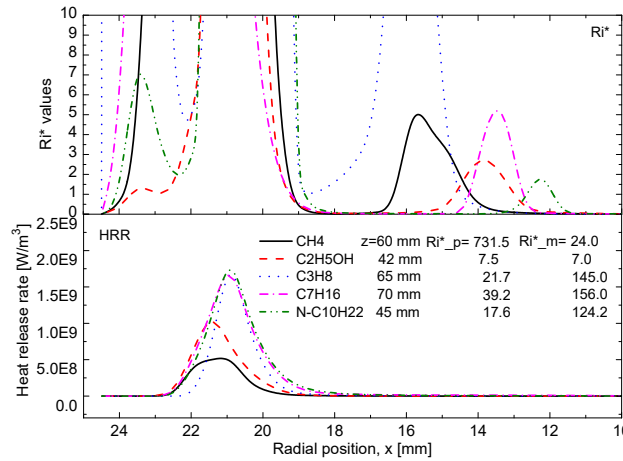


Fig. 18 R_i^* values of different fuels on the xz plane at different feature positions.

Fig. 18 displays the profiles of R_i^* values along the radial direction at different axial positions in xz plane, based on the position of maximum HRR in the axial direction. It can easily be observed that the values of R_i^* in the flame-front region $R_i^*_p$ are always larger than 1.0 for all fuels. The $R_i^*_p$ of methane is 731.5, which will give rise to laminarization and stabilization of the flow.

Similar effects are evident for the other fuels. Another interesting phenomenon is that the pressure fluctuation amplitude ΔP does not correlate with Ri^*_p . Similarly, the mean values of Richardson number Ri^*_m at the different positions are always larger than 1.0 but are not closely related to the variation of ΔP . The respective values of $Ri^*_p = 39.2$ and $Ri^*_m = 156.0$ for kerosene are large, but the corresponding ΔP is the largest of 4000 Pa. This is because the Richardson number is uninfluenced by flame dynamics, which is of additional importance for combustion stability.

In order to quantify the effect of the flame dynamic, the Rayleigh parameter $Ra(x)$ is evaluated for the different fuels with results being shown in Fig. 19. The $Ra(x)$ is defined as the time-averaged product of the pressure fluctuation $p'(t)$ at the point_60 position and volume-averaged heat-release fluctuation $q'(t)$, as shown in equation 11. It provides a qualitative measure of the extent to which unsteady heat release drives or suppresses instabilities [42].

$$Ra(x) = \frac{1}{\tau} \int_{\tau} p'(t) q'(t) dt \quad (11)$$

where t , τ are time, and the integral time, respectively.

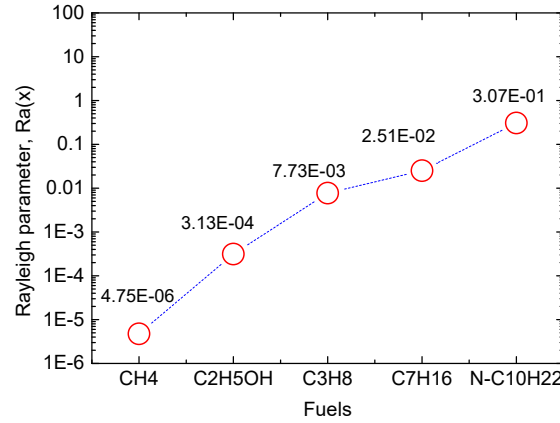


Fig. 19 Rayleigh parameters $Ra(x)$ values of different fuel situations at $q_f = 12.0$ L/min and $\phi_g = 0.6$.

Figure. 19 displays the values of $Ra(x)$ for the five fuels at $q_f = 12.0$ L/min and $\phi_g = 0.6$. The numbers printed on the figure are the corresponding amplitudes of the pressure fluctuations. Fig. 19 shows that the Rayleigh number, $Ra(x)$ correlates closely with the ΔP . When $Ra(x)$ increases the corresponding ΔP increases also. The values of $Ra(x)$ are all above zero, which indicates that the thermo-acoustic coupling takes place for all fuels at the specified flow rate and equivalence ratio. However, with the exception of kerosene, the $Ra(x)$ values are small, thus the thermo-acoustic coupling effect on the pressure fluctuation is correspondingly small as a consequence of the stabilizing influences of the swirling motion and stratification. The amplitude of the pressure fluctuations is small and less than 1000 Pa (see Fig. 6). In the case of kerosene, the value of the Rayleigh number is 0.307, a value much larger than that of the other four fuels. This is the reason for the larger amplitude pressure fluctuations observed with kerosene.

Figure 20 illustrates the pressure and heat release fluctuations of kerosene at $q_f = 12.0$ L/min and $\phi_g = 0.6$. It can be easily observed that the heat release rate, HRR , shows a strong correlation with the pressure fluctuation, consistent with the occurrence of thermo-acoustic coupling. The pressure fluctuations for kerosene are the largest among the five fuels. The amplitudes of heat release rate are about 6×10^6 W/m³ while that of pressure is around 2300 Pa, about 2.3 % of the operating pressure. The combustion is essentially steady suggesting a large Ri^* and small $Ra(x)$ is sufficient for a steady

combustion process.

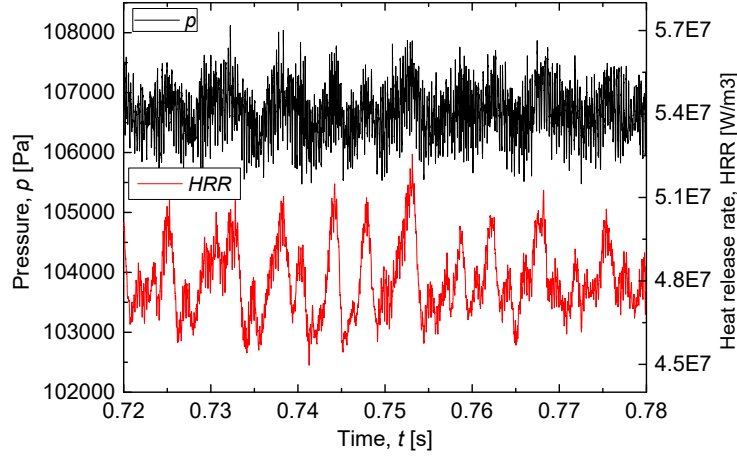


Fig. 20 The pressure and heat release fluctuation properties of kerosene at $q_f = 12.0$ L/min and $\phi_g = 0.6$.

4. Summary and conclusions

In this study, five representative fuels, methane, propane, n-heptane, ethanol, and surrogate kerosene, are employed to investigate the fuel adaptability of the stratified vortex-tube combustor (SVC). To simplify the comparisons only gaseous fuels were considered thereby avoiding the complication issues of evaporating sprays. Results show that the combustion process is always highly steady, indicating good multi-fuel adaptability. The underlying mechanism leading to fuel adaptability in the SVC has also been explored in detail. The specific conclusions are summarized as follows:

1. The lean flammability limits are all lower than 0.15 in the stratified vortex-tube combustor (SVC) for the five selected representative fuels with a highly uniform flame topology. The amplitude of pressure fluctuation is always less than 2300 Pa, indicating good fuel adaptability and high combustion stability.
2. The strong swirling motion in the SVC can decrease the local velocity in the region near the reaction zone. The non-premixed flame structure ensures that the reaction zone always has a relatively high concentration of reactive species, which is beneficial in increasing the combustion intensity and flame speed, subsequently improving the matching of local velocity and flame speed. These suggest a good self-adjusting capacity for both flow field and species concentration.
3. Based on the spindle-shaped flame topology and structure, the flow field can transport a large amount of sensible enthalpy and burnt gas to the exterior unburned gas region and thereby promoting the ignition of the unburned gas. The flow field can also transport a large number of preheated reactive species to the reaction zone, yielding a high combustion intensity. The intensified combustion leads to a large density gradient, subsequently promoting thermo-dynamic stability.
4. The large value of Richardson numbers arises for all of the fuels considered: the values are always larger than unity leading to laminarization of the flow, viz., good aero-dynamic and thermo-dynamic stabilities can be obtained. Additionally, the influence of flame dynamic is quantified by the Rayleigh number further, the resultant low value indicates a good flame dynamic. The three types of dynamic stabilities are the principal reasons for the super-steady

combustion in the SVC.

Thus, a combination of Richardson and Rayleigh numbers should be considered to determine a generalized criterion of stabilization: large Richardson and small Rayleigh numbers are required for a highly steady combustion process. This should be important in the future design upgrades and transformation of various engines, gas turbines, and industrial combustors.

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References:

- [1] Aliramezani M, Koch CR, Shahbakhti M. Modeling, diagnostics, optimization, and control of internal combustion engines via modern machine learning techniques: A review and future directions. *Prog Energ Combust*. 2022;88:100967.
- [2] Cheng Y, Jin T, Luo K, Li Z, Wang H, Fan J. Large eddy simulations of spray combustion instability in an aero-engine combustor at elevated temperature and pressure. *Aerosp Sci Technol*. 2021;108:106329.
- [3] Nassini PC, Pampaloni D, Meloni R, Andreini A. Lean blow-out prediction in an industrial gas turbine combustor through a LES-based CFD analysis. *Combust Flame*. 2021;229:111391.
- [4] Nicolai H, Debiagi P, Wen X, Dressler L, Massmeyer A, Janicka J, et al. Flamelet LES of swirl-stabilized oxy-fuel flames using directly coupled multi-step solid fuel kinetics. *Combust Flame*. 2022;241:112062.
- [5] Krzywanski J, Nowak W, Sztékler K. Novel Combustion Techniques for Clean Energy. MDPI; 2022. p. 4649.
- [6] Shi BL, Peng WK, Li B, Hu J, Wang NF, Ishizuka S. CO₂ diluted propane/oxygen combustion in a rapidly mixed tubular flame burner. *P Combust Inst*. 2017;36(3):4261-8.
- [7] Shimokuri D, Ishizuka S. Flame stabilization with a tubular flame. *P Combust Inst*. 2005;30:399-406.
- [8] Zhang YY, Ishizuka S, Zhu HY, Kee RJ. Effects of stretch and pressure on the characteristics of premixed swirling tubular methane-air flames. *P Combust Inst*. 2009;32:1149-56.
- [9] Ishizuka S. On the behavior of premixed flames in a rotation flow field establishment of tubular flames. *The Combust Ins*. 1985;1(20):287-94.
- [10] Ishizuka S. An Experimental Study on Extinction and Stability of Tubular Flames. *Combust Flame*. 1989;75(3):13.
- [11] Ishizuka S. On the flame propagation in a rotating flow field. *Combust Flame*. 1990;82:15.
- [12] Ishizuka S, Shimokuri D, Ishii K, Okada K, Takashi K, Suzukawa Y. Development of practical combustors using tubular flames. *Journal Combust Soc Jpn*. 2009;51(156):104-13.
- [13] Syred N. A review of oscillation mechanisms and the role of the precessing vortex core (PVC) in

swirl combustion systems. *Prog Energy Combust.* 2006;32(2):93-161.

- [14] Ren SJ, Yang HL, Jiang LQ, Zhao DQ, Wang XH. Numerical study on combustion characteristics of partially premixed tubular flame burner for DME. *Combust Sci Tech.* 2019;191(3):435-52.
- [15] Ren SJ, Yang HL, Jiang LQ, Zhao DQ, Wang XH. Flow field and combustion characteristics in localized stratified swirling tubular flame burner: numerical investigation. *Combust Sci Tech.* 2020;192(5):915-32.
- [16] Ren SJ, Yang HL, Jiang LQ, Zhao DQ, Wang XH. Stabilization characteristics and mechanisms in a novel tubular flame burner with localized stratified property. *Energy.* 2020;197:117235.
- [17] Ren SJ, Yang HL, Jiang LQ, Zhao DQ, Wang XH. An exploration of stabilization mechanisms in a novel vortex-tube combustor with localized stratified peculiarity. *Int J Energ Res.* 2020;44(7):5649-58.
- [18] Ishizuka S. Characteristics of tubular flames. *Prog Energy Combust.* 1993;19(3):187-226.
- [19] Ren SJ, Jiang LQ, Yang HL, Zhao DQ, Wang XH. Comparative study on the combustion performance in localized stratified and rapidly mixed swirling tubular flame burners. *Combust Sci Tech.* 2019;8(193):1444-62.
- [20] Ren SJ, Yang HL, Jiang LQ, Zhao DQ, Wang XH. Combustion Modes and Driving Mechanisms of Pressure Fluctuation in a Novel Vortex-tube combustor with Quasi-steady and Stratified Properties. *Exp Therm Fluid Sci.* 2020;117:110134.
- [21] Ren SJ, Yang HL, Wang XH. The oxygen-deficient combustion and its effect on the NO_x emission in a localized stratified vortex-tube combustor. *Energy.* 2021;235:121365.
- [22] Lu TF, Law CK. A criterion based on computational singular perturbation for the identification of quasi steady state species: A reduced mechanism for methane oxidation with NO chemistry. *Combust Flame.* 2008;154(4):761-74.
- [23] Lin KC, Chiu C-T. A compact skeletal mechanism of propane towards applications from NTC-affected ignition predictions to CFD-modeled diffusion flames: Comparisons with experiments. *Fuel.* 2017;203:102-12.
- [24] Bhagatwala A, Chen JH, Lu TF. Direct numerical simulations of HCCI/SACI with ethanol. *Combust Flame.* 2014;161(7):1826-41.
- [25] Liu S, Hewson JC, Chen JH, Pitsch H. Effects of strain rate on high-pressure nonpremixed n-heptane autoignition in counterflow. *Combust Flame.* 2004;137(3):320-39.
- [26] Yan Y, Liu Y, Di D, Dai C, Li J. Simplified Chemical Reaction Mechanism for Surrogate Fuel of Aviation Kerosene and Its Verification. *Energ Fuel.* 2016;30(12):10847-57.
- [27] Fredrich D, Jones WP, Marquis AJ. Thermo-acoustic instabilities in the PRECCINSTA combustor investigated using a compressible LES-pdf approach. *Flow Turbul Combust.* 2021;106(4):1399-415.
- [28] Jones WP, Marquis AJ, Prasad VN. LES of a turbulent premixed swirl burner using the Eulerian stochastic field method. *Combust Flame.* 2012;159(10):3079-95.
- [29] Barlow RS, Karpets AN, Frank JH, Chen JY. Scalar profiles and NO formation in laminar opposed-flow partially premixed methane/air flames. *Combust Flame.* 2001;127(3):2102-18.
- [30] Jones WP, Lyra S, Navarro-Martinez S. Large eddy simulation of a swirl stabilized spray flame. *P Combust Inst.* 2011;33(2):2153-60.
- [31] Piomelli U, Liu JH. Large-eddy simulation of rotating channel flows using a localized dynamic model. *Phys Fluids.* 1995;7(4):839-48.
- [32] Jones WP, Prasad VN. Large Eddy Simulation of the Sandia Flame Series (D-F) using the Eulerian stochastic field method. *Combust Flame.* 2010;157(9):1621-36.
- [33] Jones WP, Navarro-Martinez S. Study of hydrogen auto-ignition in a turbulent air co-flow using a

- Large Eddy Simulation approach. *Computers & fluids*. 2008;37(7):802-8.
- [34] Brauner T, Jones WP, Marquis AJ. LES of the Cambridge Stratified Swirl Burner using a Sub-grid pdf Approach. *Flow Turbul Combust*. 2016;96(4):965-85.
- [35] Zhang YY, Shimokuri D, Mukae Y, Ishizuka S. Flow field in swirl-type tubular flame burner. *Jsm Int J B-Fluid T*. 2005;48(4):830-8.
- [36] Ishizuka S, Motodamari T, Shimokuri D. Rapidly mixed combustion in a tubular flame burner. *P Combust Inst*. 2007;31:1085-92.
- [37] Shimokuri D, Shiraga Y, Ishii K, Toh H, Ishizuka S. An experimental study on the high frequency oscillatory combustion in tubular flame burners. *Combust Flame*. 2014;161(8):2025-37.
- [38] Rosenberg DA. A Method to Measure Flame Index in Turbulent Partially-Premixed Flames: University of Michigan, 2014.
- [39] Ishizuka S, Murakami T, Hamasaki T, Koumura K, Hasegawa R. Flame Speeds in Combustible Vortex Rings. *Combust Flame*. 1998;113(4):542-53.
- [40] Hasegawa T, Michikami S, Nomura T, Gotoh D, Sato T. Flame development along a straight vortex. *Combust Flame*. 2002;129(3):294-304.
- [41] Beér JM, Chigier NA, Davies TW, Bassindale K. Laminarization of turbulent flames in rotating environments. *Combust Flame*. 1971;16(1):39-45.
- [42] Huang Y, Hsieh SY, Sung HG, Yang V. Large-Eddy Simulation of Combustion Dynamics of Lean-Premixed Swirl-Stabilized Combustor. *J Propul Power*. 2012;19(5):782-94.