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LEAN BLOWOUT PREDICTIONS OF A NON-PREMIXED V-GUTTER STABILIZED FLAME USING A DAMKOHLER NUMBER METHODOLOGY

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ABSTRACT

The lean blowout stability of a non-premixed, V-gutter stabilized flame was investigated using a Damkohler number methodology. The flow and chemical timescales were extracted from the reacting RANS CFD results on a cell-by-cell basis. Assessment of three representative definitions of flow and chemical timescales for Damkohler number based on different blowout mechanisms was performed. By examining the Damkohler number fields, the structure of the flame or the possibility of blowout can be estimated. The results demonstrated that a distinct transition between stable and unstable flames was observed by decreasing the fuel-air ratio or increasing the inlet velocity at atmosphere pressure and an inlet temperature of 537K. All three definitions can predict the lean blowout limit in a reasonable consistent with the available experimental data through adjusting the critical Damkohler number of each definition in the current study. The performances and physical differences of three definitions were also discussed.

1. INTRODUCTION

Predicting the lean blowout stability where flame cannot be stabilized is an important issue in any practical propulsion combustion device. While a variety of devices to stabilize flame, V-gutter flameholder is the focus in this paper. Due to unresolved complexities of the coupling of fluid dynamics, chemical kinetics and acoustics, lean blowout mechanism is still poorly understood and therefore it is quite challenges to predict accurately[1,2]. Since the 1950s, some lean blowout predictions for V-gutter stabilized flames have been made using the empirical correlations, such as those of King [3], DeZubay [4], Ozawa [5], Plee [6], Lefebvre and his colleagues [7-11]. However, those correlations, based on inlet velocity, temperature, and pressure, are not incorporated many critical factors into the correlations so that the correlations just predict well on their defined parameter space. Some other global correlations were proposed based on Damkohler number to predict the flame stability such as those of Zukoski and Marble [12], Spalding [13] and Longwell[14]. These approaches also require a large degree of empirical assumption of chemical timescale, do not account well for local variations in the flow, and are applicable over a narrow range of conditions or combustors.

With the development of CFD techniques, Large Eddy Simulation (LES), a powerful tool for understanding the complex process of turbulence-chemistry interaction, has been applied to mimic the combustion instability phenomena, such as ignition[15] and lean blowout[16,17]. However, these phenomena are dictated by real complex chemistry and fluid dynamics, and it is still too expensive computationally to implement realistic turbulence and detailed chemistry directly into LES. Consequently, LES is not a practical design tool currently to predict the lean blowout limits of a realistic combustor. Meanwhile, the traditional RANS method is not capable of calculating the unsteady flows accurately. As a result, it is essential for combustion system designers to develop a computational model that incorporates complex physical processes via CFD calculations so that the gap between an accurate prediction of lean blowout and available computational capabilities can be bridged.

Recently researchers address the issue of defining Damkohler number by taking advantage of local flow and thermochemical properties extracted from a CFD solution on a cell-by-cell basis. Knaus[18] employed the ratio of turbulent kinetic energy and dissipation, which was extracted from non-reacting CFD results, to form the flow timescales, and the chemical timescales defined as a global ignition delay time were calculated in a perfectly stirred reactor model and applied locally. A critical region in the reaction zone, where the flame was attached to the railing edge of the flameholder, was utilized

for the lean blowout prediction. Knaus[19] overcame the shortcomings of the previous paper[18] and established a local extinction mechanism for determining stability. The flow timescale was defined as the inverse of the flow rate of strain in each CFD cell. The chemical timescale was expressed as the inverse of extinction strain rate, which was computed by chemical kinetic software. By examining the Damkohler number fields, the integrity of the flame or the possibility of blowout can be estimated. Roach [20] developed the flow timescales from non-reacting CFD results whereas chemical timescales were extracted from the reacting results based on various combustion models. A critical Damkohler number was formulated based on reacting CFD solutions. To summarize, as blowout mechanism is poorly understood, each definition above of flow and chemical timescales is not strictly validated and as they differ from one another, it results in different criteria for determining the lean blowout stability, but the existing results in premixed V-gutter stabilized flames show that this methodology is promising and gives a rather reasonable prediction [18-20].

In order to predict the lean blowout stability of non-premixed V-gutter stabilized flame, which is encountered in many realistic applications including ramjet and turbojet afterburner systems, this paper extends the Damkohler number methodology. Then the lean blowout stability is investigated at atmosphere pressure, an inlet temperature of 537K, and for variable fuel-air ratio and inlet velocity. Finally, assessment of three representative definitions of flow and chemical timescales based on different blowout mechanisms is also performed.

2. DAMKOHLER NUMBER METHODOLOGY

In general, blowout occurs when the time required for significant chemical reaction becomes longer than the flow or mixing residence time of the combustion zone. As such, Damkohler number is defined as:

$$Da = \frac{\tau_{chem}}{\tau_{flow}} \tag{1}$$

where τ_{chem} is the chemical timescale, and τ_{flow} is the flow timescale. When $Da < 1$, it indicates a stable flame, otherwise, it indicates an unstable flame.

For Damkohler number fields in this paper, the flow and chemical timescales are extracted from the reacting RANS CFD results on a cell-by-cell basis. The stable and unstable flame cells are characterized by a critical Damkohler number and distribute spatially in the Damkohler number fields. The local Damkohler number data do not indicate immediately whether the flame will blow out or not. By examining the structure of the flame, the likeness of blowout can be estimated. It is necessary to note that stable and unstable flame cells derived from the mesh cells may not represent the real whole flame structure. The detailed explanations will be given in the following section.

To maximize the analysis efficiency, the CFD cells with a local equivalence ratio between 0.5 and 2.0 are calculated to get the Damkohler number data whereas the other cells are set to a large value directly. The critical equivalence ratio range is determined according to the kerosene flammability limit [21], and the calculated cells are regarded as CFD-predicted flame cells. Note that here local equivalence ratio ϕ can be directly related to the mixture fraction Z, a frequently used conserved scalar in a non-premixed combustion. Under the definition of Z=1 in pure fuel and Z=0 in pure air, the conversion from ϕ to Z is given by

$$Z = \frac{\phi}{\phi + 1/FAR_{st}} \tag{2}$$

where FAR_{st} is the stoichiometric fuel/air mass ratio[22].

In order to identify the characteristic chemical and flow timescales, a logical mechanism for physical descriptions of blowout must be established. However, as far as authors' knowledge, few studies of blowout mechanisms for non-premixed V-gutter stabilized flames were conducted over the past decades. Ballal and Lefebvre's work is one of those pioneering studies[11], which successfully correlates the lean blowout limits of non-premixed V-gutter stabilized flames and premixed ones using the effective mass fraction of fuel that is vaporized within the combustion zone. According to the correlation, if the rate of fuel evaporation is sufficiently high to ensure that all the fuel is fully vaporized within the combustion zone, then the effect of fuel evaporation on lean blowout stability is quite small. If the fuel is not fully vaporized, the lean blowout limit is modified in terms of the effective fuel evaporation rate. Besides, Lefebvre [21] pointed out that, the lean blowout stability is independent of SMD when SMD is smaller than 100 microns in his conditions. Meanwhile, Mellor proposed a characteristic-time model by utilizing three characteristic times: a droplet evaporation time, a chemical reaction time and a shear layer residence time. The model predicts the blowout stability using such a criterion [23]: "In order for the flame to continue burning stably, fuel droplets must evaporate and ignite within the time that they are in the initial shear layer". To summarize, apparently, fuel evaporation plays an important role in the blowout mechanism and must take into account. Fortunately, the processes of spray, evaporation, trajectory and combustion of fuel droplets have been calculated in the reacting CFD cases. Moreover, due to highly intensified turbulence promoting a molecule-level mixing, the combustion zone operates effectively as a homogenous stirred reactor with a well-mixed vaporized kerosene droplets and air. In consequence, in this paper, it is assumed that the blowout mechanism of premixed V-gutter stabilized flame can be employed here. Considering that a universal blowout mechanism is not exist, then three representative blowout mechanisms associated with three

definitions of chemical and flow timescales for Damkohler number are applied and estimated.

2.1 THE FIRST DEFINITION OF FLOW AND CHEMICAL TIMESCALES

As analyzed above, the combustion zone, referred to here as CFD-predicted flame cells, can be assumed to be perfectly stirred reactors. Then the first chemical timescale is defined as the blowout residence time, which means the minimum residence time for which non-negligible reaction progress occurs in a perfectly stirred reactor. The flow timescale is characterized by two local flow timescales. One is the large-eddy mixing time scale and can be obtained from turbulence kinetic energy and kinetic energy dissipation rate. For the present demonstration, we use the ratio of turbulent kinetic energy and dissipation to represent the local rate of turbulent mixing [18]. Another flow timescale is the nominal residence time of a perfectly stirred reactor which is related to the reactor volume and the mass flow rate by [24]:

$$\tau_{residence} = \frac{\rho v}{\dot{m}} \tag{3}$$

where ρ denotes the density, v denotes the velocity, $\dot{m}$ denotes the mass flow rate. The flow timescale is determined by the smaller value of the two local flow timescales.

The Damkohler number is then written as:

$$Da = \frac{\tau_{blowout\ residence}}{\min(k/\varepsilon, \tau_{residence})} \tag{4}$$

It can be deduced from the above equation that, in each CFD-predicted flame cell, flame extinction occurs when the time for turbulent mixing or flow to residence is less than the blowout residence time. This expression is considered to be another interpretation of Longwell's theory [14] which suggested that flame blowout occurs when the time available for chemical reaction becomes less than the time required to generate sufficient heat raise the fresh mixture up to its ignition temperature.

2.2 THE SECOND DEFINITION OF FLOW AND CHEMICAL TIMESCALES

Following Lefebvre's model [21], "flame blowout occurs when the rate of heat release in the combustion zone becomes insufficient to heat the incoming fresh mixture up to the required reaction temperature". Thus, the second chemical timescale is related to the rate of heat release and defined as:

$$\tau_{chem} = \rho / r_{fuel} \tag{5}$$

where ρ and r_{fuel} represent the density and fuel consumption rate, respectively. The fuel consumption rate in each CFD-predicted cell is calculated based on the local cell pressure, temperature and mean gas composition [19].

The flow timescale is still represented by the smaller value of the two local flow timescales as the first definition. The Damkohler number is then expressed as:

$$Da = \frac{\rho / r_{fuel}}{\min(k/\varepsilon, \tau_{residence})} \tag{6}$$

2.3 THE THIRD DEFINITION OF FLOW AND CHEMICAL TIMESCALES

Blowout and local extinction event are different physical phenomenon. A notable fact is that flame can persist indefinitely with certain levels of local extinction under certain condition [25]. However, as the amount of local extinctions increase to some levels, blowout occurs eventually [25-27]. Furthermore, Damkohler number correlations based on local extinction are successfully in correlating blowout limits [25, 26].

Therefore, local extinction is related to the blowout event even though it does not fundamentally describe the ultimate blowout phenomenon [25-27]. Base on the above considerations, the third chemical timescale, namely the inverse of the extinction strain rate is given [19]. And we hypothesize that the reactants are homogeneously mixed within the CFD-predicted flame cell. Then, the extinction strain rate is determined by performing numerical calculations in an opposed premixed flame model using OPPDIF computer codes [28]. Here the global extinction strain rate is defined as:

$$\kappa_{extinction} = \frac{4U}{L} \tag{7}$$

where U is the jet velocity at extinction and L is the separation distance between the jets [29].

Thus, the chemical timescale is expressed as:

$$\tau_{chem} = 1/\kappa_{extinction} \tag{8}$$

The flow timescale is defined as the inverse of the flow strain rate:

$$\tau_{flow} = 1/\kappa_{strain} \tag{9}$$

where κ_{strain} is calculated by the magnitude of the cell strain tensor.

$$\kappa_{strain} = \left\| S_{ij} \right\| = \frac{1}{2}\left\| \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right\| \tag{10}$$

The Damkohler number is then given as:

$$Da = \frac{\tau_{chem}}{\tau_{flow}} = \frac{\kappa_{strain}}{\kappa_{extinction}} \tag{11}$$

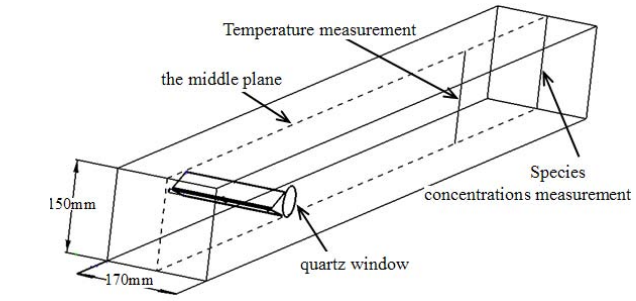
3. TEST CASES

3.1 GEOMETRY DESCIRPTION

The model combustor rig is shown in Figure.1 below. The computational domain based on the model combustor is illustrated in Figure 2. The duct is 150mm×170mm and an

open V-gutter flameholder with a width of 40mm is installed. The length of V-gutter flameholder and spray bar are 165mm. The spray bar is a hollow cylinder with three 1-mm-diam holes spaced 55 mm apart spanning from the center to both sides and centered on the same axis as the V-gutter. Kerosene is discharged against the upstream through holes drilled in the spray bar. The temperature is measured by thermocouples and species concentrations are taken samples by TESTO 360 in the middle cross-section. A quartz window, on one side wall of the duct is used to watch the flame structure behind the flameholder. Other relevant details are marked on the Figure 2.

Figure 1. Model combustor



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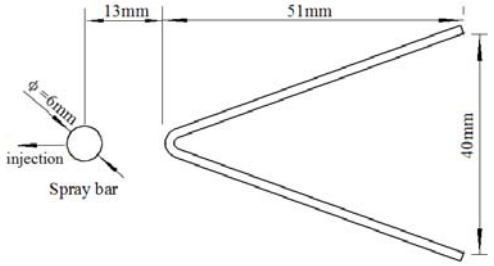

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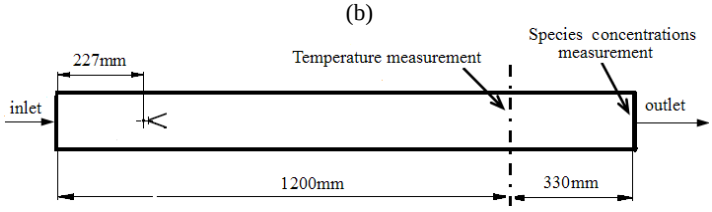

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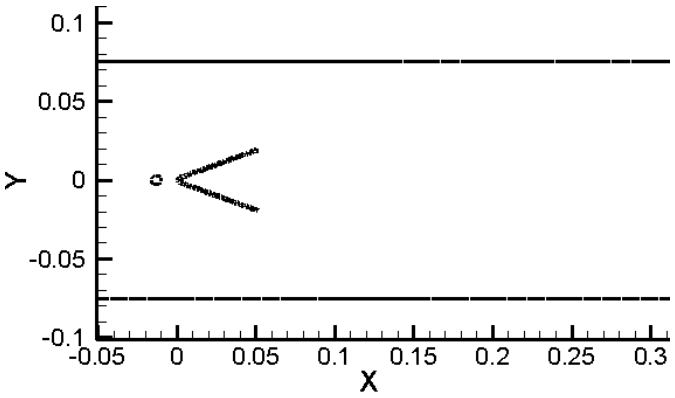


(d)

Figure 2. Schematics of the model combustor with V-gutter flame stabilizer

3.2 COMPUTATIONAL DETAILS

The unstructured mesh contained approximately 1.5M and 3.0M cells were generated using GAMBIT. All the CFD reacting simulations were performed in commercial software package FLUENT. Realizable $k-\varepsilon$ turbulence model with wall function, SIMPLE algorithm and non-premixed flamelet combustion model were employed. The turbulence intensity was estimated about 4% from an empirical correlation for pipe flows. The applied chemical mechanism for kerosene combustion, containing 297 irreversible reactions of 66 species, was reduced based on the detailed mechanism. The detailed mechanism, consisting of 131 species of 1020 irreversible reactions, was assembled using the combustion mechanism of Aachen surrogate fuel (80%decane and 20%1, 2, 4-trimethylbenzene by weight) [30] and NOx formation mechanism [31]. The combustion mechanism is validated using experimental data obtained from shock tubes, rapid compression machines, jet stirred reactors, burner stabilized premixed flames, and a freely propagating premixed flame [30]. The NOx mechanism accounts for thermal, prompt, and nitrous oxide contributions to NOx formation, and for NOx reburn by hydrocarbon radicals and amines (NHx) [31]. The applied reduced mechanism reproduced the ignition characteristics and major combustion performances on the typical gas turbine combustor working conditions. More details about the reduced mechanism can be found in Ref [32]. The liquid phase was described using a Lagrangian formulation with an initial Rosin–Rammler distribution. The Sauter mean diameter was calculated by empirical correlations and equaled 60 microns. The dispersed phase was presumed to comprise discrete spherical droplets and to occupy a relatively small volume fraction so that effects due to droplet collisions, breakup and coalescence were negligible. Flow conditions are listed in table 1.

Table 1. Summary of flow conditions

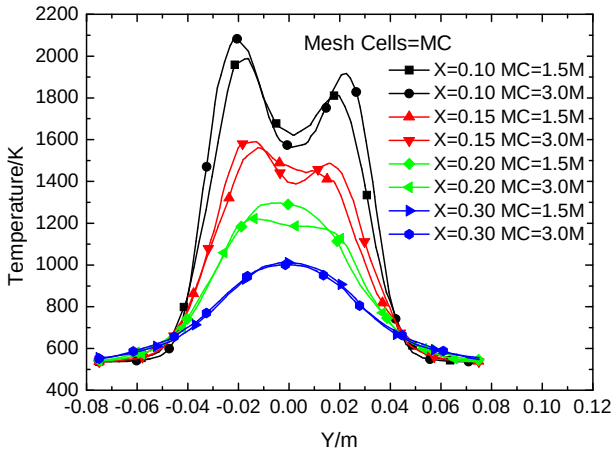
Inlet(pure air)	
Temperature(K)	537

Bulk velocity(m/s)	75,80,85,90
Turbulence intensity	4%
Hydraulic Diameter(mm)	160
Fuel Injection	
Fuel mass flow rate(g/s)	5,6,7,8
Outlet	
Ambient Pressure(Pa)	101325
Ambient Temperature(K)	300

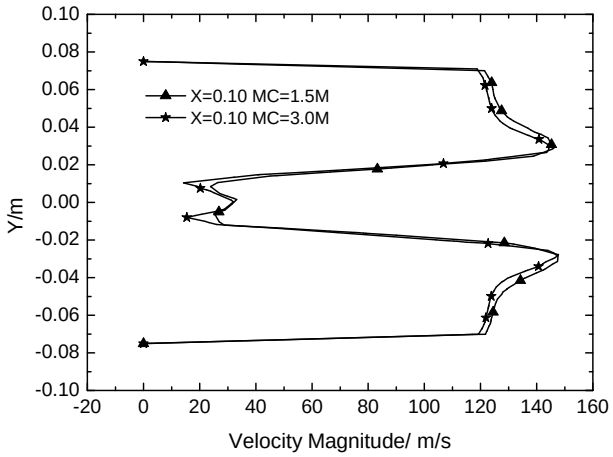
4. RESULTS AND DISCUSSION

4.1 VALIDATION THE CFD METHODOLOGY

A grid-dependence test was firstly performed with 1.5M and 3.0M cells and the results shown in Figure 3 demonstrated that the 1.5M cells were enough for the computations. In order to validate our computational models, numerical simulations using steady flamelet model for temperature field, main species and unsteady flamelet model for pollutant formation (in slow reactions) was conducted at the condition: inlet temperature of 537K, velocity of 75m/s and fuel mass flow rate of 6g/s. The experiment was carried out in the model combustor rig, which included a preburner in the incoming section and transited the circular pipe to a rectangular duct, as shown in Figure 1. To keep the inlet temperature of 537K with velocity 75m/s, the preburner was ignited and the incoming flow for V-gutter flameholder was a vitiated mixture in the experiment while the simulation cases were the pure air. It was observed that flame structure in the simulation shows better agreement with the experimental flame structure as depicted in Figure 4. A good agreement with the rig experimental data in temperature and NO concentrations (without O_2 correction) were also achieved in Figure 5. These results indicated that the computational models and chemical mechanism were appropriate here. Moreover, Lefebvre's work demonstrated that the lean blowout stability is independent of SMD when SMD is smaller than 100 microns in his conditions which is similar to here [21]. Then for the sake of simplicity, it is logical to apply the same Rosin-Rammler distribution in our narrow working condition range.



(a)



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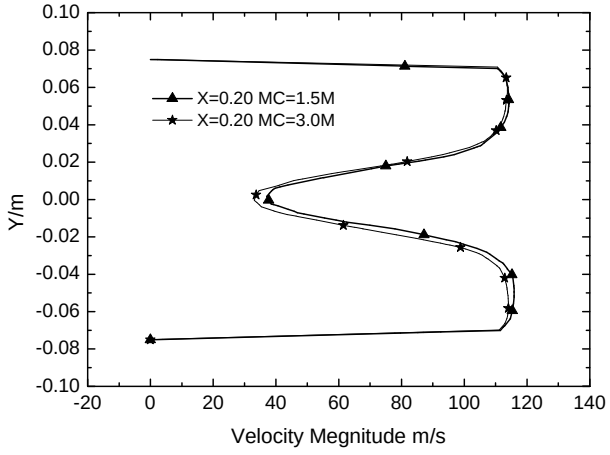

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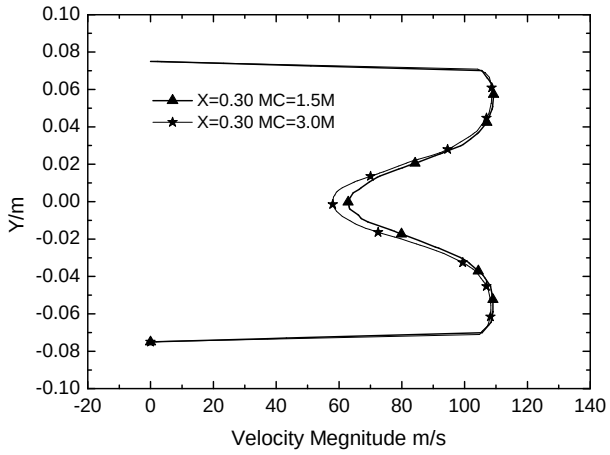
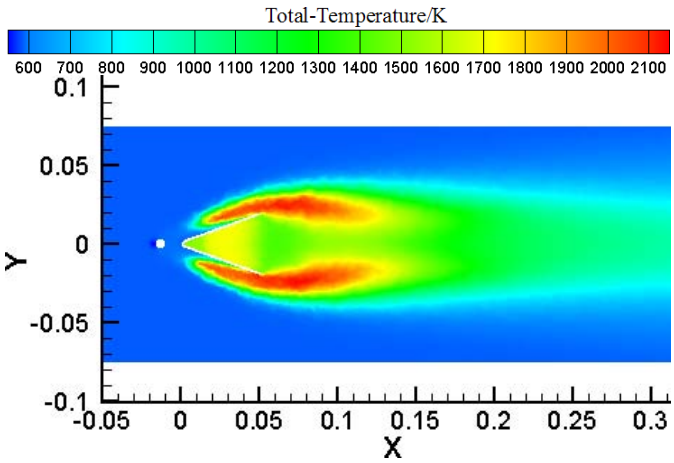


(d)

Figure 3. Temperature and velocity magnitude profiles on the middle plane (Grid-dependence test.).



(a)

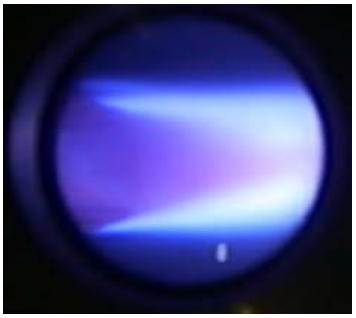


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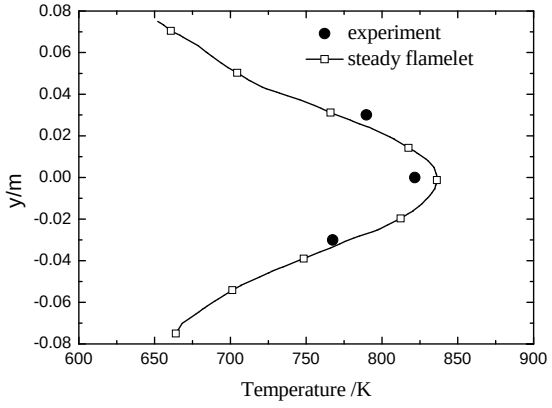
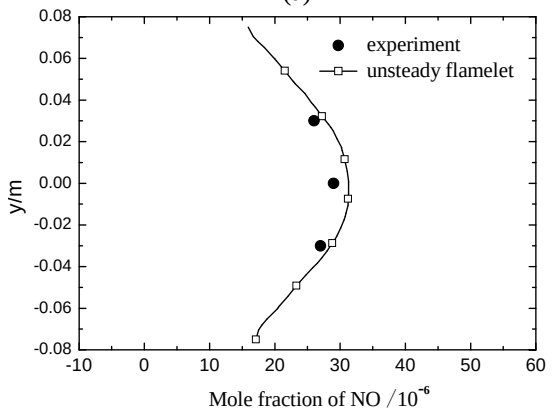
Figure 4. Contours of temperature on the middle plane and the experimental photo



(a)



(b)

Figure 5. Comparison of temperature and NO concentrations between simulation results and experimental data

4.2 LEAN BLOWOUT PREDICTION

In this paper, the lean blowout stability is investigated at two conditions with constant pressure and inlet temperature of 537K. One is to fix the inlet velocity at 75m/s with the fuel mass flow rate varied. The other is to fix the fuel mass flow rate at 7g/s with inlet velocity varied. Local Damkohler number in each CFD-predicted flame cell is calculated to form the fields that are used to predict stability. It is noteworthy that the first and third definitions of chemical timescales can be calculated using the chemical kinetics solvers independently. Therefore, to describe the flame characteristics accurately, the detailed mechanism is used to calculate these chemical timescales. In practice, the blowout residence time and extinction strain rate are calculated as a function of equivalence ratio in advance at the interested condition, as illustrated in Figure 6 and Figure 7. These data are used to provide chemical timescales for each CFD-predicted flame cell according to the local equivalence ratio.

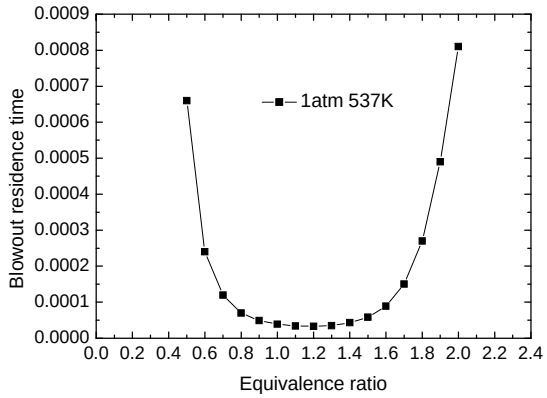


Figure 6. Blowout residence time as a function of equivalence ratio

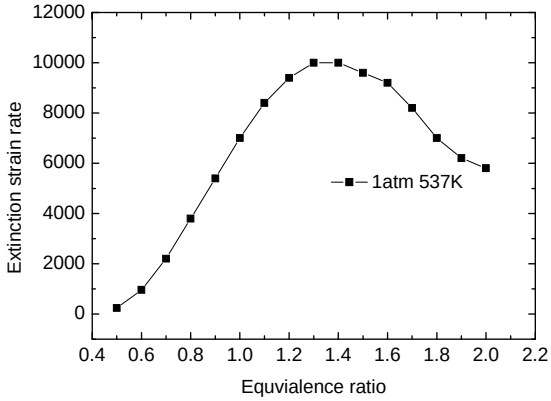
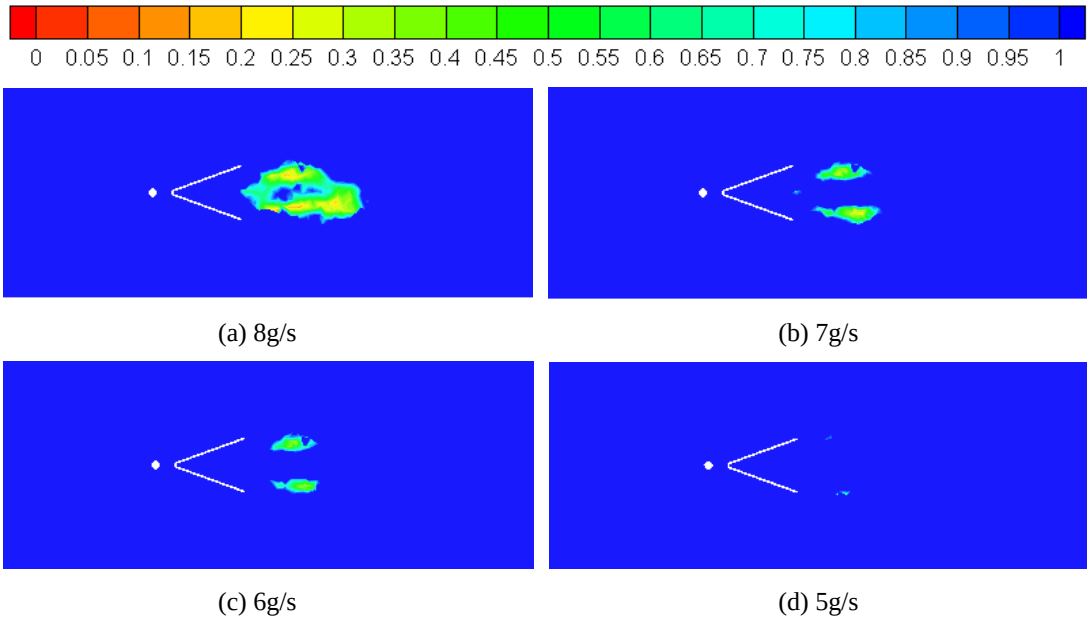


Figure 7. Extinction strain rate as a function of equivalence ratio for a kerosene/air flames

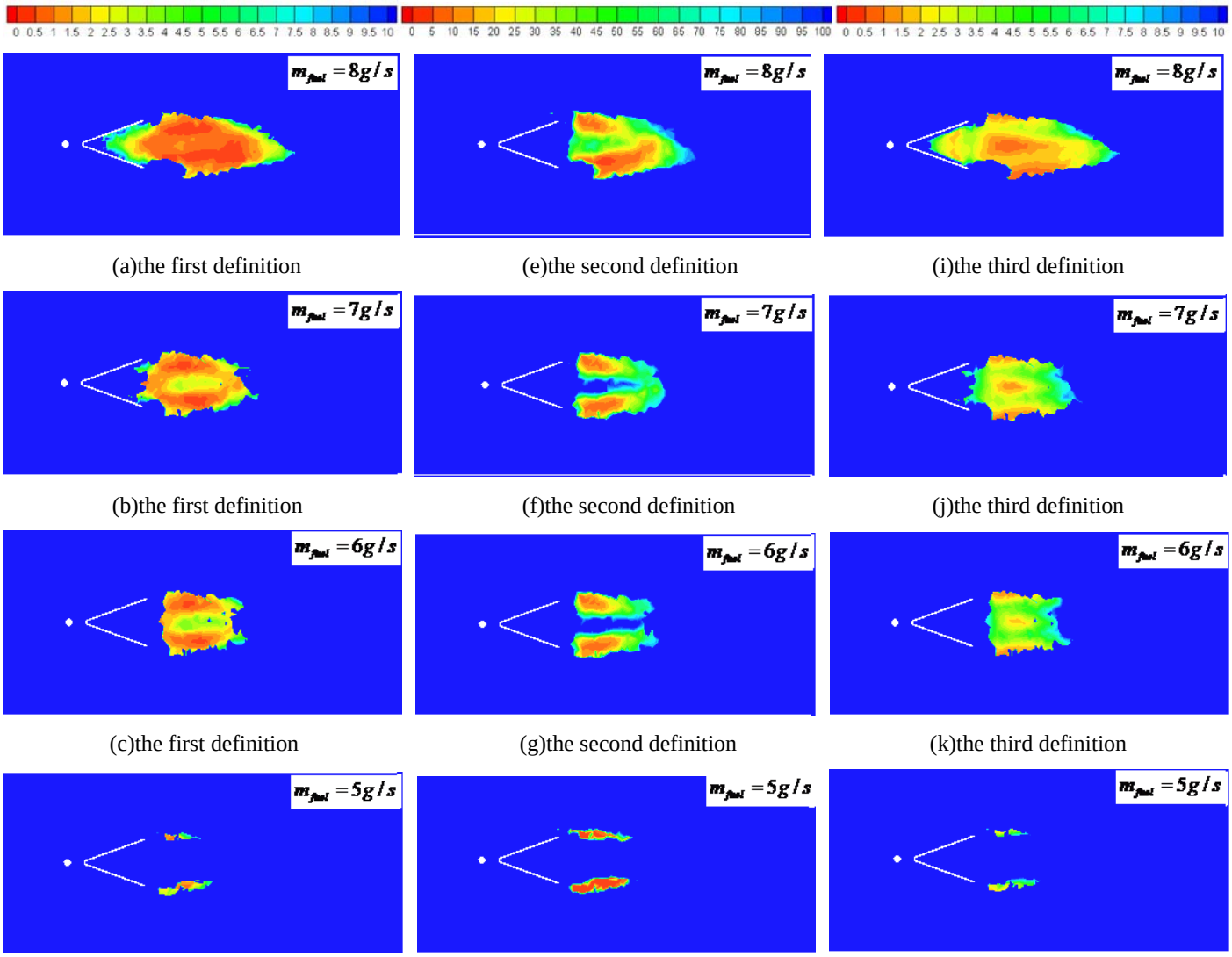
Figure 8 presents the Damkohler number fields calculated by the first definition of flow and chemical timescales on the middle cross section. The resulting Damkohler number contours are using 0 as the lower bound while 1 as the upper bound. Since blue typically means "cold" (no flame) while red means "hot" (flame OK), correspondingly low Damkohler number (red color) indicates a stable flame cell whereas high Damkohler number (blue color) indicates an unstable flame cell. It can be clearly seen that the 'flame zones' appear to be more and more 'weaken' as the fuel mass flow rate decreases. As seen in Figure 8(b) and (c), flames seem to blow out because the stable flame cells in the recirculation zone are separated and surrounded by blue unstable flame cells. However, when the fuel mass flow rate was 6g/s, flames were stable enough in the experimental observation even though the incoming flow was a vitiated mixture with less oxygen than in the simulation case with pure air. That means the critical Damkohler number is inappropriate and inaccurate here and need to be calibrated, because the critical Damkohler number depends on other factors in practical combustion system, particularly in the present research flow and chemical timescale are not rigorously validated. Therefore, in Figure 9(a)-(d), the cutoff criterion (critical Damkohler number) is increased to 10. As can be seen from the Figure 9(a)-(d), a distinct transition is observed. A gradual deterioration of the reaction zone firstly occurs as decreasing the fuel mass flow rate step by step from Figure 9(a) to Figure 9(c), and then flames extinguish when flames cannot withstand on that condition in Figure 9(d).



(a) 8g/s (b) 7g/s

(c) 6g/s (d) 5g/s

Figure 8. Calculated Damkohler number fields using the first definition of flow and chemical timescales as a function of fuel mass flow rate on the middle plane of the model combustor (inlet velocity=75m/s, temperature=537K). Note that range is clipped above ***Da***>1



(a)the first definition (e)the second definition (i)the third definition

(b)the first definition (f)the second definition (j)the third definition

(c)the first definition (g)the second definition (k)the third definition

(d)the first definition (h)the second definition (l)the third definition

Figure 9. Calculated Damkohler number fields using three definitions of flow and chemical timescales on the middle plane of the model combustor (inlet velocity=75m/s, temperature=537K).

Similarly, the same conclusion can be drawn through adjusting the critical Damkohler number for the second and third definitions of Damkohler number, as shown in Figure 9(e)-9(h) and Figure 9(i)-9(l). Note that if the equivalence ratio of a mesh cell falls outside the range of critical equivalence ratio, the cell is set to a large value. (This is why there are jagged boundaries in Figure 9.)

As mentioned previously, the Damkohler number map may not show the true flame structure. A notable example is at the experimental condition (inlet temperature of 537K, velocity of 75m/s and fuel mass flow rate of 6g/s) where simulation and experimental results show stable flames start from the leading edge of V-gutter (shown in Figure 4), by contrast, there is no visual flame attaching on the V-gutter flameholder in the Damkohler number map (Figure 9). This phenomenon can be explained as follows. As illustrated in Figure 10, there are fuel droplets around the V-gutter flameholder, which manifests a two-phase combustion state apparently far deviated from the previously analyzed premixed combustion or perfectly stirred reactor assumption. Thus the flame at the leading edge of flameholder cannot be indentified correctly under the premixed assumption. However, the recirculation zone rather than the leading edge plays an important role in flame stabilization. Furthermore, in the recirculation zone fuel droplets are completely evaporated and mixed well with air due to fully developed turbulence promotion. Meanwhile, it can be seen from Figure 11 that the equivalence ratio contours of the recirculation zone fall into the range from 0.5 to 2.0. Therefore,

in the recirculation zone our premixed flame assumption for non-premixed flame lean blowout analysis is credible in the present study.

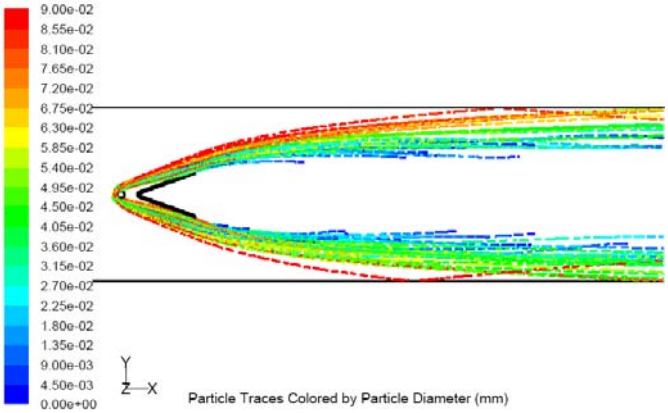


Figure 10. Trajectories of particles discharged from the central injection hole on the spray bar.

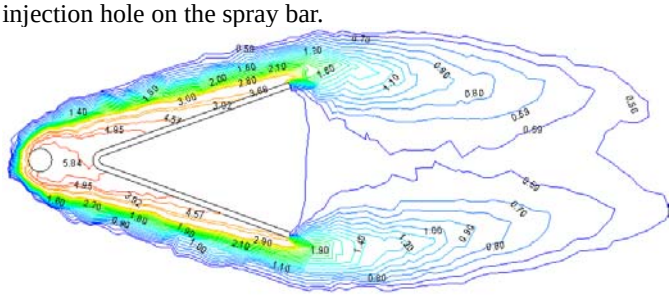


Figure 11. Equivalence ratio contours on the middle plane.

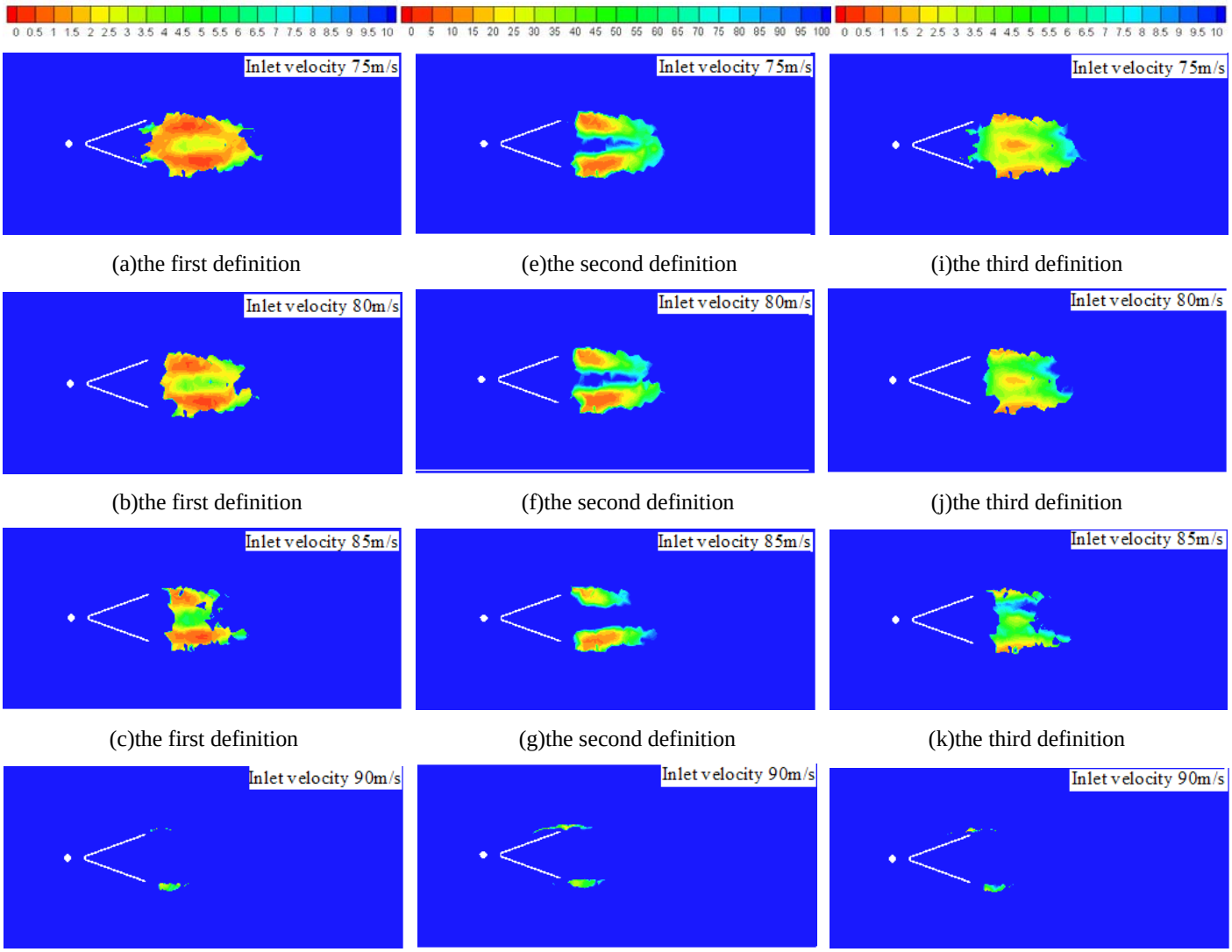
Flames are capable of withstanding certain levels of strain before extinction. The blowout residence time, the chemical timescale of the first definition of Damkohler number, is calculated when flames blow out in a perfectly stirred reactor due to too much strain. From the prospective of physical essences, the blowout residence time is another characterization of flame strain. In this sense, the first definition of Damkohler number is similar to the third definition but the computing methods of chemical and flow timescales are different for each definition. That is why different flame intensity in an almost identical flame region is observed at the same condition, as shown in Figure 9(a)-9(c) and 9(i)-9(k) correspondingly. It is known that most of lean blowout models tend to fall into two main categories. One of these, following Longwell et al [14], views the recirculation zone essentially as homogeneous chemical reactor where fresh air and fuel are mixed well and combustion takes place. From Figure 9(a) to 9(c) or 9(i) to 9(k), major flame regions in the Damkohler number map are located in the recirculation zone, and flame regions become smaller as the fuel mass flow rate decreases. Thus, a conclusion that the first and third definitions of Damkohler number for lean blowout prediction fall into the models of Longwell's category can be drawn. When few flames exist in the recirculation zone as shown in Figure 9(d) and 9(l), flame extinction occurs. The other category is focused mainly on the shear layer surrounding the wake region. According to Zukoski and Marble[12], ignition of the fresh mixture occurs in the shear layer when it is turbulently mixed with combustion products from the recirculation zone. Since the second definition is related with the fuel consumption rate and density, the strongest reaction regions are identified in Figure 9(e)-9(g) and the flame regions in the Damkohler number map are close to the positions of real flame structure locating on the shear layer of wake region. Therefore, the third definition for lean blowout prediction falls into the models of Zukoski and Marble's category. In Figure 9(h), weak flames are observed in the shear layer, that is to say, the fresh mixture cannot be ignited by the hot recirculation zone and then flame extinction occurs.

Which of these two mechanisms of flame stabilization has the most fundamental significance and relevance to flame stabilization is uncertain now. However, these results demonstrate that, from an engineer's perspective, any above-mentioned blowout mechanism, given an empirical critical Damkohler number based on experimental data, three kinds of flow and chemical timescales can predict the reasonable lean blowout limit in present study.

From the Figure 9, we cannot deduce what the precise lean blowout limit is, but it is no doubt that flames blow out when the fuel mass flow rate is between 6g/s and 5g/s. Suppose that the lean blowout limit is not much influenced by vitiated incoming flow, our prediction is reasonable consistent with the experimental data. However, determination of the exact lean blowout limit is unclear now unless a new empirical criterion is proposed. For example, if no flame cells are to occur for a certain volume of the total recirculation volume where the mean velocity is negative, blowout would occur [19].

Figure 12 compares Damkohler number fields at four inlet velocities with fuel mass flow rate of 7g/s. For each definition, the critical Damkohler number is the same as those in Figure 9 and noticeable transition is also observed for inlet velocity stepped with increments of 5m/s. Here is just for demonstration, so we selected the increment of 5m/s in our engineering experience. Due to increasing the velocity and reducing the fuel mass flow rate are contribute to flame stability equally. Thus, based on the previous analysis, the lean blowout limit is between 85m/s and 90m/s in Figure 12.

Here we are not expected to predict the lean blowout limit accurately. It is can be imagined that if we reduced the increments of fuel mass flow rate in Figure 9 or inlet velocity in Figure 12, then a more precise results can be obtained. Our stress is to develop and illustrate the Damkohler number methodology in non-premixed environment and test three definitions of Damkohler number for lean blowout prediction. It has been shown the results are encouraging but future improvements will be necessary. For instance, how to get rid of the empirical or 'random' critical Damkohler number and apply for a practical combustor.



(a)the first definition (e)the second definition (i)the third definition

(b)the first definition (f)the second definition (j)the third definition

(c)the first definition (g)the second definition (k)the third definition

(d)the first definition (h)the second definition (l)the third definition

Figure 12. Calculated Damkohler number fields using three definitions of flow and chemical timescales as a function of inlet velocity on the middle plane of the model combustor (fuel mass flow rate =7g/s, inlet temperature=537K).

5. CONCLUSION

This paper extended the Damkohler number methodology to predict the lean blowout stability of a non-premixed, V-gutter stabilized flame. Three definitions of flow and chemical timescales for Damkohler number based on different blowout mechanisms were employed. The results at atmosphere pressure and an inlet temperature of 537K demonstrated that a distinct transition between stable and unstable flame was observed by decreasing the fuel-air ratio or increasing the inlet velocity. Either definition of flow and chemical timescales for Damkohler number can predict the lean blowout in a reasonable agreement with the available experimental data through adjusting the critical Damkohler number in the present work. From an engineer's perspective, the designers would determine the critical Damkohler number based on the available experimental data, and then obtain a reasonable prediction of lean blow out limit with an affordable computational expense. From the perspective of academic research, we plan to explore the method further to overcome the shortcoming of empirical or 'random' critical Damkohler number in current investigation, and validate the method in more realistic combustor configurations.

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NOMENCLATURE

Da	Damkohler number
FAR_{st}	Stoichiometric fuel/air mass ratio
k	Turbulent kinetic energy
ε	Turbulent kinetic energy dissipation rate
L	Jet separation distance in an opposed premixed flame
U	Jet velocity in an opposed premixed flame
Z	Mixture fraction
ρ	Density
S_{ij}	Flow rate of strain tensor
v	Velocity
$\dot{m}$	Mass flow rate
ϕ	Equivalence ratio
κ_{strain}	Flow strain rate
$\kappa_{extinction}$	Extinction strain rate
r_{fuel}	Fuel consumption rate
$\tau_{blowout\ residence}$	Chemical timescale derived from a perfectly stirred reactor
τ_{chem}	Chemical timescale
τ_{flow}	Flow timescale
$\tau_{residence}$	Nominal residence time of a perfectly stirred reactor

Abbreviations

CFD	Computational Fluid Dynamics
LES	Large Eddy Simulation
RANS	Reynolds-Averaged Navier–Stokes
SMD	Sauter Mean Diameter

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