Evaluation of Droplet Combustion Models in Spray Combustion

Jiunn-Shyan Huang
Department of Mechanical Engineering
Kuang Wu Institute of Technology
Taipei, Taiwan, 112, R.O.C.
E-mail address: kent1007@ms58.hinet.net
and
Huei-Huang Chiu
Institute of Aeronautics and Astronautics
National Cheng Kung University
Tainan, Taiwan, 701, R.O.C.
E-mail address: hhchiu@sprax.iaa.ncku.edu.tw

ABSTRACT

Keywords：*Droplet model, Spray combustion, Group combustion, Multi-state behavior*

This study compares the spray combustion characteristics predicted by six different droplet models under various atomization conditions. The droplet models examined were (1) DEM which assumed droplet could only evaporate, (2) DCM which employed local reactivity as the criterion for droplet burning, (3) MDCM1 which employed both local reactivity and droplet ignitability as the criterion for droplet burning, (4) MDCM2 which modified droplet ignitability of MDCM1 to include the convective effects, (5) MDCM3 which modified MDCM2 to classify the flame type of a burning droplet into the wake flame and envelope flame, and (6) MDCM4 which adopted the multi-state behavior of a droplet in the convective flow field to identify the droplet state. It was found that DEM failed to predict the droplet burning when the spray droplets are large. DCM may fail to describe the combustion mode for small-droplet sprays and over-predict the fuel consumption ratio for large-droplet sprays. MDCM1, MDCM2, MDCM3, and MDCM4 can determine the adequate combustion modes qualitatively for both large and small droplet sprays. MDCM1, MDCM2, and MDCM3 may over-predict the fuel consumption ratio for large-droplet sprays based on the results of MDCM4.

INTRODUCTION

Evolution of liquid spray in the combustion process has been recognized by experimental studies [1-4] to behave the characteristics of group combustion theory advocated by Chiu and co-workers [5,6]. The group combustion number (or *Chiu number* [7])G_c is defined as an indicator of the atomization conditions for the identification of the overall combustion characteristics. Under the condition when total liquid mass flow is kept constant, a high G_c value implies a small-droplet spray with a large number of droplets and a low G_c value represents a large-droplet spray with a small number of droplets. Based on different initial droplet size distribution, the spray combustion modes are classified into three categories [2,8]. A small-droplet spray (high G_c value) was characterized by a long gas-phase diffusion flame and termed external group combustion mode. An intermediate-droplet spray, with equal importance of gas-phase diffusion flame and individual droplet burning was the critical spray group combustion. A large-droplet spray (low G_c value), dominated by massive droplet burning with small portion of gas-phase flame was identified as the internal spray combustion. From the above discussion, it is recognized that droplet burning may occur in practical spray. However, most computational models for spray combustion [9,10] simply assumed that droplets could only evaporate (DEM) and neglected all effects by possible droplet burning. Jiang and Chiu [11] proposed to employ local reactivity as the criterion for droplet burning based on group combustion theory [5,6]. All droplets in the oxidizer-rich mixture are assumed in the state of burning once the droplets are heated up to their boiling point (DCM). Jiang and Chiu [12] further proposed that, in addition to local reactivity, droplet ignitability should also be considered to meet with the results of ignition study for a stationary droplet (MDCM1) [13]. Jiang and Hsu [14] concluded that MDCM1 is more accurate than DEM and DCM based on the qualitative comparison of their predictions with experimental observations [2]. Chiu and coworkers [15,16] further perceive that a droplet in a convective flow field exhibits much more complex multi-state behaviors including envelope flame combustion, wake flame combustion and vaporization mode. Based on the results of Chiu and coworkers [15,16], Huang and Chiu [17] modified MDCM1 to MDCM2, MDCM3, and MDCM4 to include the convective effects. The present study compares the spray combustion characteristics predicted by above six droplet models under various atomization conditions. The spray combustion modes and axial fuel consumption ratios will be the main basis for the present comparison.

FORMULATION

The Eulerian-Eulerian approach is adopted for the present study. Detail mathematic formulation and numerical method can be found in computational study of Jiang and Chiu [8]. Six droplet models depicted below were used to identify the droplet state after the droplet temperature reached the boiling point.

(1) DEM: This model assumes that droplets evaporate and no droplet combustion occurs. This model is applied

in most computational models for spray combustion [9,10].

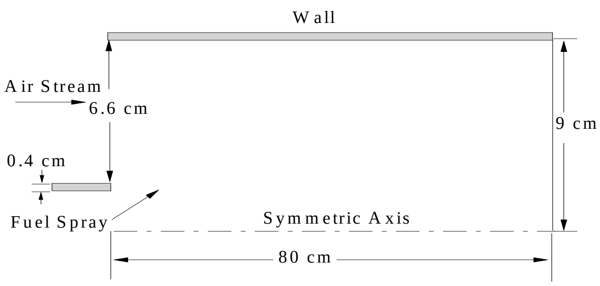
(2) DCM: The equivalence ratio is used to represent the local reactivity to determine whether or not the environment is suitable for droplet combustion [11]. When the equivalence ratio is less than unity, the environment is oxidizer-rich and the droplet combustion is able to take place. When the equivalence ratio is greater than unity, the environment is oxidizer-lean and the droplet will simply evaporate.

(3) MDCM1: The droplet burning is assumed when the droplet ignitability and the local reactivity are satisfied. The droplet ignitability is assured if the Damköhler number is greater than the ignition Damköhler number [12].

(4) MDCM2: The determination process of the droplet state is the same as MDCM1 but ignition Damköhler number is formulated under the conditions that the droplet state transformed from vaporization to combustion in a convective flow field [16].

(5) MDCM3: The flame type of a burning droplet is further divided into wake flame and envelope flame. Both the ignition Damköhler Da_I and the reattachment Damköhler number Da_R [16] are used to identify the droplet state. The first step is to check whether the droplet combustion is possible or not by the same process as MDCM2. The second step is to identify the type of flame i.e. the envelope flame for $Da > Da_R$, or a wake flame for $Da < Da_R$.

(6) MDCM4: The multi-state behavior of a droplet in the convective flow field is adopted. The droplet state is identified by the Damköhler number, four critical Damköhler numbers, and the initial state of the droplet. Detail procedures for the determination of the state follow the scheme shown in the study of Huang and Chiu [16].



	$M_{f,in}$ (kg/s)	$M_{air,in}$ (kg/s)	u_g^0 (m/s)	u_l^0 (m/s)	T_g^0 (K)	T_l^0 (K)	P_g^0 (atm)
Fuel Spray	0.00624	0.0	40	50	600	298	1.0
Air Stream	0.0	0.44	40	NA	600	NA	1.0

Fig.1 The schematic of the cylindrical non-premixed combustor and the inlet conditions for the present study.

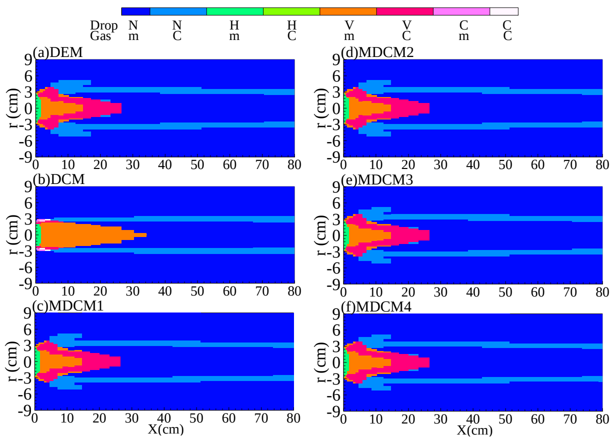


Fig. 2 Spray combustion mode predicted by various droplet models (mean droplet radius=10 μ m, group of 9.6 μ m; C: combustion, m: mixing, V: vaporization, H: heating, N: no droplet).

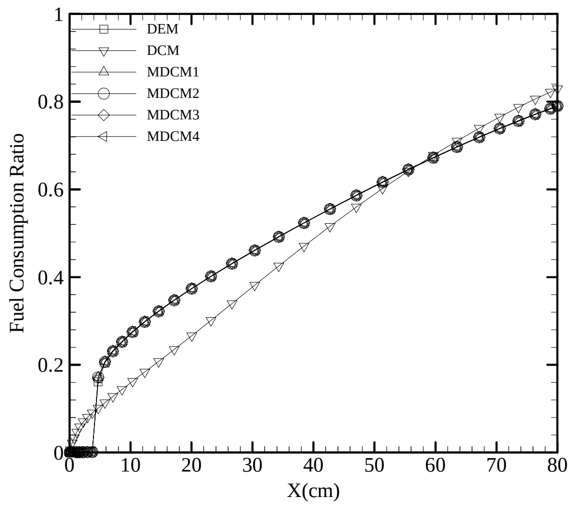


Fig.3 Axial fuel-consumption ratio predicted by various droplet models (mean droplet radius=10 μ m).

RESULTS AND DISCUSSIONS

The schematic of the cylindrical non-premixed combustor and the inlet conditions for the present study are shown in Fig. 1. N-Octane is used as the fuel to provide a fuel-lean spray at a fuel-air ratio of 0.0118 and the spray cone angle of 30°. The numerical calculation is carried out at three volume-mean droplet radius 10 μm , 30 μm , and 50 μm . The comparison of the global prediction by these six models is demonstrated by the spray combustion mode and the fuel consumption ratio along the axial direction. The fuel consumption ratio is defined as the ratio of the fuel consumption rate to the inlet total fuel flow rate.

First, the spray with an inlet volume mean radius 10 μm (a small-droplet spray) is examined. The spray combustion modes predicted by all models except DCM behave a typical gas-phase diffusion flame without droplet burning as shown in Fig. 2. Both droplet combustion and gas-phase combustion are predicted by DCM. In Fig. 3, the fuel consumption ratio for all the models except DCM is very small near the inlet and increases abruptly at x=4cm where the strong gas-phase combustion commences. In the result by DCM, fuel is consumed very quickly near the inlet where both droplet combustion and gas-phase combustion occurs and the consumption rate decreased to be nearly constant at x>4 cm where only gas-phase combustion occurred. From the above results, all the droplet combustion models except DCM can well be applied to the small-droplet spray to make the results qualitatively agree with the experimental observation by Yule and Bolado [2]. The droplet combustion predicted by DCM for this small-droplet spray is considered to be physically unrealistic.

Next, the spray with an inlet volume mean droplet radius of 30 μm , representing an intermediate-droplet spray, is examined. The spray combustion modes predicted by all models are shown in Fig. 4. The results of DEM exhibit a lump gas-phase combustion area in the primary zone where the fuel vapor produced by the vaporizing droplet is enough to support the reaction. In the results of DCM, the droplets which can arrive at the outer oxidizer-rich region are in combustion mode so that only the vaporizing droplets in the fuel-rich region can contribute the fuel vapor to sustain the gas-phase combustion. The results predicted by MDCM1, MDCM2, MDCM3, and MDCM4 are just between those by DEM and DCM. Their gas-phase combustion zone is smaller than that predicted by DEM, but larger than that by DCM. The fuel vapor basically comes from both the vaporizing droplets in the inner fuel-rich zone and the non-ignitable vaporizing droplets in the outer fuel-lean zone. Since the convective effect is included in MDCM2, MDCM3, and MDCM4, the droplet combustion zone predicted by these three models are located further downstream than that predicted by MDCM1. The droplet combustion zone by the MDCM4 calculation is larger than that of MDCM2 and MDCM3 because the multi-state phenomenon is also included in MDCM4. The curves of fuel consumption ratio by all models are shown in Fig. 5. The fuel consumption ratio calculated by DEM is lower than others because it fails to predict the droplet combustion that is believed to be important for larger droplets [13,16]. The fuel consumption ratio by DCM is larger than other models in the upstream region where droplets are ignited with no delay, but lower than MDCM1, MDCM2, MDCM3, and MDCM4 in the downstream region where the intensity of gas-phase combustion by DCM is weaker than those predicted by others. By comparing the experimental observation [2], the results by MDCM1, MDCM2, MDCM3, and MDCM4, is more applicable in this intermediate-droplet spray.

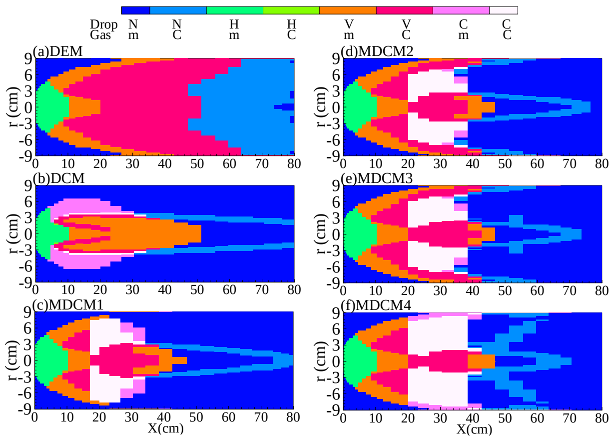


Fig. 4 Spray combustion mode predicted by various droplet models (mean droplet radius=30 μ m, group of 28.9 μ m; C: combustion, m: mixing, V: vaporization, H: heating, N: no droplet).

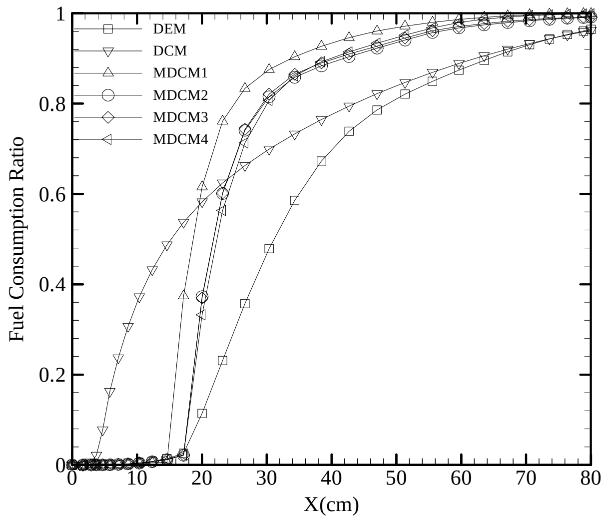


Fig.5 Axial fuel-consumption ratio predicted by various droplet models (mean droplet radius=30 μ m).

Finally, the case of inlet volume mean droplet radius 50 μm which represent a large-droplet spray is examined. The spray combustion modes are shown in Fig. 6. Due to the larger preheating zone, the lump gas-phase combustion zone, predicted by DEM, shifts to the downstream region. In the result calculated by DCM, the larger preheating zone also causes more air to flow into the central region so that all droplets are able to burn immediately after preheating. That is, all fuel vapor is consumed by the droplet combustion and no gas-phase combustion is predicted by DCM. The result by MDCM1 is somewhat similar to the result in DCM but still has the gas-phase combustion zone. When the convective effect is included, the droplet combustion, predicted by MDCM2, MDCM3, and MDCM4 can only occur in the low relative velocity region. The curves of fuel consumption ratio are shown in Fig. 7. Because a large-droplet spray is dominated by massive droplet burning with small portion of gas-phase flame [2,8], fuel consumption ratio was under-predicted by DEM and over-predicted by DCM. The results are highly affected by the selection of droplet combustion models. Since detail convective effect on droplet state criteria has been included in MDCM4. MDCM4 may be superior to other five models in the determination of droplet state. Therefore, MDCM1, MDCM2, and MDCM3 may over-predict the fuel consumption ratio for large-droplet sprays based on the results of MDCM4.

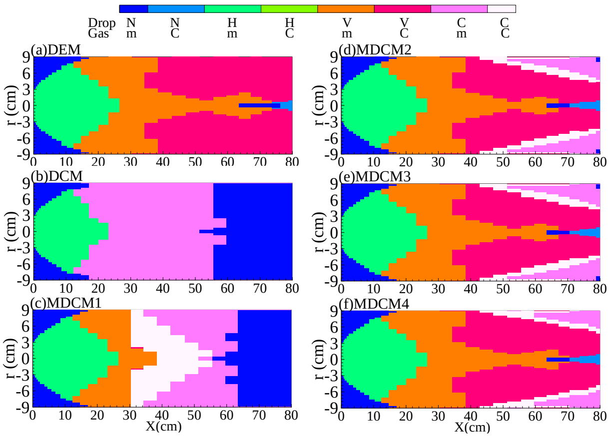


Fig. 6 Spray combustion mode predicted by various droplet models (mean droplet radius=50 μ m, group of 48.1 μ m; C: combustion, m: mixing, V: vaporization, H: heating, N: no droplet).

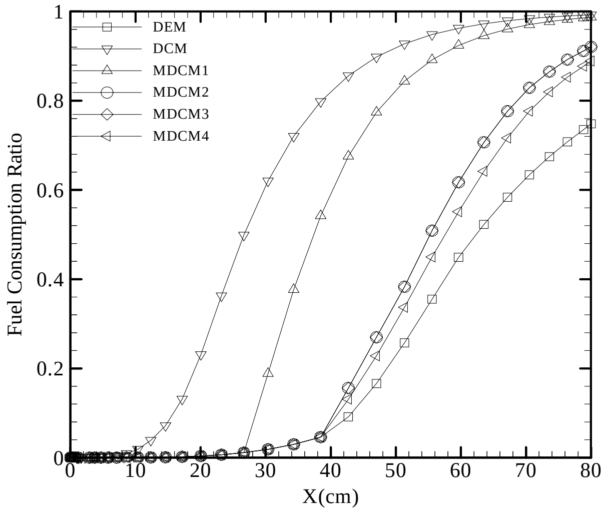


Fig.7 Axial fuel-consumption ratio predicted by various droplet models (mean droplet radius=50 μ m).

CONCLUSIONS

The present study has compared combustion modes and axial fuel consumption ratios by six models under various inlet mean droplet sizes implied large-droplet, intermediate-droplet, and small-droplet sprays. The major conclusions are summarized: (1) DEM only reasonably predicted the combustion modes for small-droplet sprays but failed to predict droplet burning when spray droplets are larger, (2) DCM failed to describe the combustion mode for small-droplet sprays and over-predict fuel consumption ratio for large-droplet sprays, and (3) MDCM1, MDCM2, and MDCM3 may over-predict fuel consumption ratios for large-droplet sprays based on the results of MDCM4.

For an even more realistic prediction of spray combustion, MDCM4 should include the effects of drop-drop interaction; work that is currently in progress.

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