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Experimental and Numerical Investigations into Evaporation Rates of Some Fuels Utilized in Aviation Gas Turbine Engines

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Abstract. Fuels utilized in aviation gas turbine engines are multi-component and supplied into the two-phase flow environment (fuel and air) under high temperature and pressure conditions of the combustion chamber. Examining aviation fuel evaporation in these conditions is quite challenging. Currently, there are different models available in the literature for examining evaporation characteristics for both mono- and multi-component drops in the multi-phase flow medium. However, a scientific approach to select suitable models for practical fuels such as the ones utilized in aviation gas turbine engines is scarce. In this paper, an experiment has been conducted under quiescent droplet conditions, zero velocity gas flow, and at the atmospheric pressure. Combining the experimental outcomes and evaporation rates obtained from different models, suitable models for computing evaporation rates of aviation fuels is analysed and suggested. The analysis shows significant gaps in evaporation rates when using different models. It is suggested that using an equilibrium model like the M2 model is one option to provide reasonable evaporation rates for small droplets (e.g. <0.1 mm). However, further studies are required to provide a fair conclusion for modelling aviation fuel drops when accounting for multi-component issues as well as variable drop sizes.

Keywords: Aviation fuel · Drop evaporation · Droplet evaporation models · Gas turbine engine

1 Introduction

Currently, there exist different numerical models available in the literature for examining mono-component droplet evaporation in the multi-phase flow medium, for example, two versions of the transient classical model [1, 2], four heat-mass transfer analogy models [3–5] and two non-equilibrium models based on the Langmuir-Knudsen evaporation law [6]. These models overcome the disadvantages of the classical D-squared model as they are capable of describing phase interactions as well as the first period (heat-up period) of the evaporation process. These models can be adoptable for examining the evaporation rate of mono-dispersed droplets having a large range of diameters. Regarding multi-component fuels, several models are also available in the literature, for example, diffusion limit (DL) [7] and distillation curve

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(DC) models [8]. Although DC and DL models are more suitable for practical fuels utilized in heat engines, they require high computational cost and as such non-equilibrium and equilibrium models are commonly used in the literature.

Fuels utilized in aviation gas turbine engines are multi-component, and when injected into the combustion chamber, the fuels pass through different complex processes including evaporation. In the multi-phase flow conditions, there exist interactions between the liquid fuels and the intake air in the two-phase stream. These interactions along with the multi-component characteristic add complexities to the fuel evaporation process. This leads to challenges in examining the evaporation mechanism. Due to the fact of different numerical models found in the literature for evaporation rate estimation, choosing the ones to suitably describe the evaporation phenomenon needs to be considered. Approaches to choose good models for multi-component fuels utilized in gas turbine engines are scarce in the literature.

As mentioned earlier, due to expensive computational cost when using multi-component models (e.g. DC & DL), in this paper, our analysis is limited to using the multi-phase flow models available in the literature to calculate the evaporation rate of some aviation fuels. An experiment has been set up to measure the drop evaporation rate of jet A-1 fuel. An in-depth analysis is provided to evaluate suitable evaporation models.

2 Mathematical and Experimental Models

2.1 Mathematical Modelling

Mathematical modeling utilized for characterizing droplet evaporation in multiphase flows is based on Lagrangian equations:

$$dX_i/dt = v_i \tag{1}$$

$$dv_i/dt = (f_1/\tau_d)(u_i - v_i) + g_i \tag{2}$$

$$dT_d/d_t = 1/3(f_2 Nu/Pr_G)(\theta_1/\tau_d)(T_G - T_d) + (L_v/C_L)(\dot{m}_d/m_d) - H_{\Delta T} \tag{3}$$

$$dm_d/d_t = -1/3\,(Sh/Sc_G)(m_d/\tau_d)H_M \tag{4}$$

In these equations, each method for f_1, f_2, Sh, Nu, $H_{\Delta T}$, H_M selection leads to a particular model. Eight models normally used for drop evaporation modelling in multi-phase flows are shown in Table 1 and these models are distinguished through the calculation of three heat and mass transfer terms f_2, $H_{\Delta T}$, and H_M. Steps used for calculating these parameters are detailed in [9]. Values of other parameters (*Sh, Nu, and* f_1) could be found in [10, 11]. M1 to M6 are called equilibrium models while M7 & M8 are non-equilibrium ones. This classification depends on the assumptions of the non-equilibrium effects of the vapor layer near the evaporation surface (the Knudsen layer) [12].

Table 1. Evaporation models available in literature

Model	Name	f_2	$H_{\Delta T}$	H_M
M1	Classical rapid mixing	1	0	$\ln\left[1+B_{\mathrm{M,eq}}\right]$
M2	Abramzon–Sirignano	$\frac{-\dot{m}_{\mathrm{d}}}{m_{\mathrm{d}}B'_{\mathrm{T}}}\left[\frac{3\,\mathrm{Pr_G}\,\tau_{\mathrm{d}}}{Nu}\right]$	0	$\ln\left[1+B_{\mathrm{M,eq}}\right]$
M3	Mass analogy Ia	1	0	$B_{\mathrm{M,eq}}$
M4	Mass analogy Ib	$(1+B_{\mathrm{T}})^{-1}$	0	$B_{\mathrm{M,eq}}$
M5	Mass analogy IIa	1	0	$\left(Y_{\mathrm{s,eq}}-Y_{\mathrm{G}}\right)$
M6	Mass analogy IIb	$(1+B_{\mathrm{T}})^{-1}$	0	$\left(Y_{\mathrm{s,eq}}-Y_{\mathrm{G}}\right)$
M7	Langmuir–Knudsen I	G	0	$\ln\left[1+B_{\mathrm{M,neq}}\right]$
M8	Langmuir–Knudsen II	G	$\frac{2\beta}{3\,\mathrm{Pr_G}}\left(\frac{\theta_1}{\tau_{\mathrm{d}}}\right)\Delta_{\mathrm{s}}$	$\ln\left[1+B_{\mathrm{M,neq}}\right]$

2.2 Experimental Model

A simple experimental model is constructed as shown in Fig. 1, which aims to determine the evaporation rate of the stationary fuel droplet in a hot environment. A fuel droplet is suspended on a metal wire (diameter = 115 μm) installed on a height-adjustable suspension bracket. The heated medium is created in a thermistor furnace, whose temperature is well regulated by a PID controller along with a thermocouple. When the required temperature in the furnace is stable, the fuel droplet is carefully and quickly carried down to the thermocouple position so that the evaporation process starts. The whole evaporation process is recorded using a full HD camera equipped with a magnifying lens and a light source setup similarly to a backlit (shadowgraph) technique as schematically shown in Fig. 1. The initial droplet size can be adjusted by changing the needle size. Obtained experiment images are processed using the binary method and image size measurement, which are built-in in ImageJ software [13].

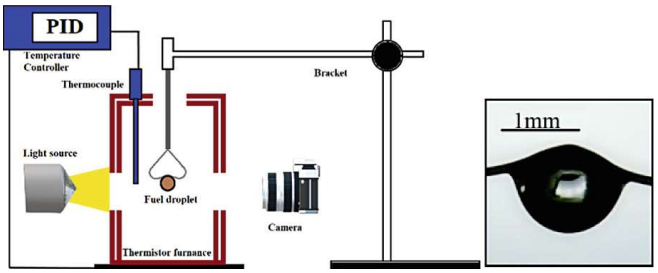

Fig. 1. Sketch of the fuel droplet evaporation experiment system.

3 Results and Discussion

3.1 Model Prediction

According to the expressions in ref. [9], a code based on GUI Matlab is developed to calculate the evaporation rate of a fuel droplet. This code includes eight models mentioned above, and they are used in this current study for several typical aviation fuels (e.g. RT, TS-1, Jet A-1, and JP4).

Figure 2 (2a for TS-1and 2b for Jet A-1) compares evaporation rate of the fuel quiescent droplet when using different models. For these fuels, the results shown in Fig. 3 could be classified into three groups: (i) Group I including models M1, M3, M5, M7, and M8 shows the shortest evaporation time; (ii) Group II ranks second and this is only for M2 model; and (iii) Group III includes the M4 and M6 representing the longest evaporation times. This difference, as mentioned above, is the reason for the difficulty in choosing a suitable evaporation model for a certain fuel.

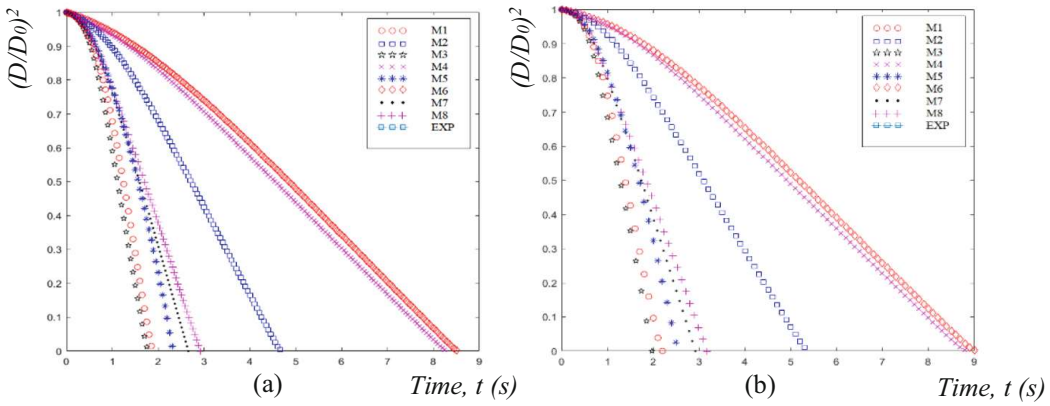

Fig. 2. Variation of $(D/D_0)^2$ versus time during evaporation process for (a) TS-1; (b) Jet A-1. Initial conditions: T_∞ = 800 K, T_{s0} = 300 K, D_0 = 1000 μm and P_{atm} = 101.33 kPa.

The non-equilibrium effect is evaluated through the ratio of the non-equilibrium contribution $2LK\beta/D$ (and the non-equilibrium surface mole fraction $\chi_{s,neq}$, where L_K is the Knudsen layer thickness, and β is the coefficient of evaporation. Figure 3 shows the non-equilibrium effect versus time for some of the initial diameter values of TS-1 droplets. Essentially, the non-equilibrium effect increases with increasing the evaporation time. Besides, the non-equilibrium effect becomes more significant as the droplet initial diameter decreases. Under the conditions shown in Fig. 3, these effects grow obviously when the initial droplet diameter is less than 100 μm, and they are important for small initial droplet sizes less than 50 μm. Therefore, for small fuel droplets, the non-equilibrium models are superior to the remaining models.

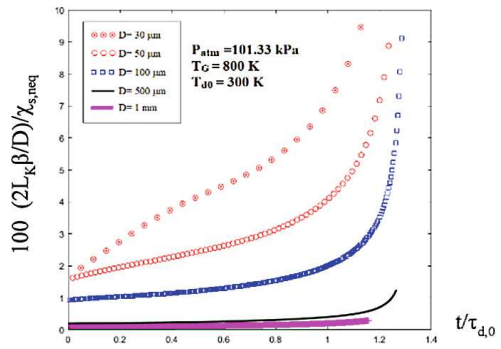

Fig. 3. Temporal evolution of the non-equilibrium contribution to the surface mole fraction for Langmuir–Knudsen model M8 for the fuel TS-1.

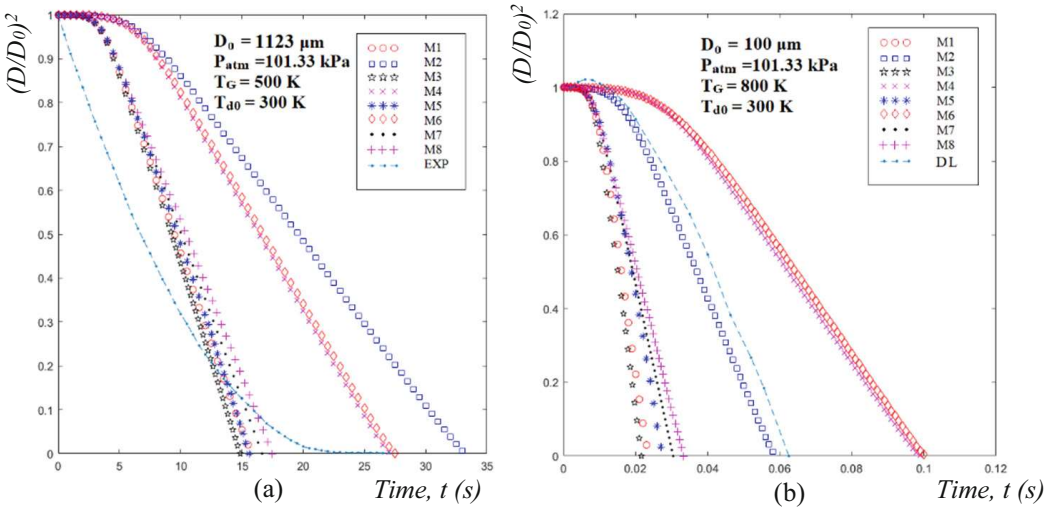

Fig. 4. (a) The experimental result of the evaporation rate for Jet-A1. (b) A comparison between M1–M8 and DL models (a multi-component model) for Jet A-1 (DL model data in [8]).

3.2 Experimental Comparison

It can be seen in Fig. 4a, for a large Jet A-1 droplet (1123 μm) under low ambient temperature (T_G = 500 K), the initial heating period cannot be distinguished, and the evaporation rate decreases with time. The reason is due to the difference in evaporation rate between the components of Jet A-1. The volatile components will quickly escape from the droplet surface lead to a rapidly decreasing in the droplet size. The remaining (poor evaporative) components will persist until the end of the process make the evaporation rate decrease. Here, the M4 and M6 model approximately predicts the droplet lifetime, but overall, models M1 to M8 are not suitable for this case. In Fig. 4b, for a small Jet A-1 droplet (100 μm) placed at high ambient temperature (800 K),

although the non-equilibrium effects become significant, the non-equilibrium models (e.g. M7 and M8) are getting high errors. Our first effort to include the DL model here, and it is clearly shown in Fig. 4b that M2 and DL models are quite close. Although further studies are required to provide a fair conclusion for modelling aviation fuel drops when accounting for multi-component issues as well as variable drop sizes, using the M2 model is one option to provide reasonable evaporation rates for small droplets as shown in this study.

4 Conclusion

In this paper, an evaluation for choosing suitable models available in the literature to compute evaporation rates for aviation fuels is presented. An initial effort to set up an experimental system to study drop evaporation has also been provided. In this setup, the evaporation rate of Jet A-1 drops has been measured. The numerical and experimental results show big gaps in the predicted results when using different models. Models M1 to M8 cannot accurately compute vaporization rates for a large drop (e.g. 1.123 mm Jet A-1 drop tested in this study). Whereas, the M2 model predicts quite well evaporation rates for small droplets (e.g. <100 μm). M2 and DL models show quite close results, and as such, the M2 model can be a cheap solution for estimating the evaporation rate of aviation fuel droplets with small diameter.

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