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Droplet evaporation under spray-like conditions

Rasoul Shahsavan Markadeh, Arash Arabkhalaj, Hojat Ghassemi*, Asghar Azimi

School of Mechanical Engineering, Iran University of Science and Technology, P.O.B. 16765-163 Tehran, Iran

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ABSTRACT

Evaporation of a droplet in a spray is affected by the neighboring droplets via their heat and mass diffusion. Aiming to investigate this effect, in this paper, the evaporation of a droplet is considered while it is assumed to be surrounded by the same evaporating droplets. A fully transient approach is applied to simulate the evaporation of a multicomponent droplet in a hypothetical spherical bubble. Three different fuels are employed; heptane, hexadecane, and a 50%-50% of their blend. The heat and mass influence extents of a droplet are introduced and their variations are investigated during the evaporation. To show the effects of neighbor droplets, the temperature and species concentration in both liquid and gas phases are compared to those of an isolated droplet. The effects of the droplet spacing, fuel types, and ambient temperature are studied. The result unveils that the effects of neighbor droplets become significant for spacing parameters less than 55 correspondings to the equivalence ratio around 10. Also, this effect becomes attenuate at higher ambient temperatures and lighter fuels.

1. Introduction

Sprays of liquid fuels have extensive applications like engines, turbines, and chemical reactors and the majority of energy demand is achieved by these processes. In order to improve the performance of liquid fuel reactors and combustors, the mixing of fuel and other reactants plays an essential role. The first step for the formation of an appropriate mixture is the evaporation of liquid fuel droplets. Evaporation of droplet in spray and mixing, in addition to ambient conditions, are a function of the droplet-to-gas ratio. In combustion and gasification, a descriptive parameter for this ratio is called equivalence ratio (φ), which one of its definitions is the proportion of oxidizer to fuel ratios in actual and stoichiometric conditions. For high equivalence ratio, like fuel-lean combustion, the number density of droplets is small and as a result, spray becomes dilute. On the other hand, in processes like gasification equivalence ratio is low and fuel spray is non-dilute. Hence, the equivalence ratio determines the droplet distance in the spray, which can be effective in droplets evaporation and consequent processes.

Droplet evaporation is a mass and heat transfer process; in which droplet receives thermal energy from surrounding and evaporated-vapor diffuses to the ambient. There is a region around an evaporating droplet, which interacts with the droplet, and its composition and temperature vary during the evaporation. The radius of this influence region in the lifetime of the droplet is zero at the beginning of the vaporization and reaches its maximum at the end of the process [1]. In a spray, if the front of the influence region of a droplet does not interfere in others, its evaporation can be considered similar to an isolated droplet. On the other hand, when droplets have overlapped influence regions, the effects of neighbor droplets should be considered. In order to investigate the droplet distance, several experimental studies have been conducted.

Deprédurand et al. by an experimental study showed that Nusselt and Sherwood number of isolated droplets should be modified to consider droplets interactions, and this modification depends on fuel nature [2]. The combustion of droplets stream is studied experimentally, and the significant influence of neighbor droplets on the burning rate is showed for the spacing parameter (the ratio of droplet spacing to its diameter) less than 9 [3,4]. Volkov et al. experimentally studied the evaporation of spray and observed that larger number density leads to lower evaporation rate and this effect is more significant for larger droplets [5].

According to these experimental observations, in spray and droplet models, the effects of droplet neighboring should be considered in order to obtain more accurate predictions. Although most of the droplet evaporation models are based on the isolated droplet assumption [6] (one of the widely used models is

* Corresponding author.
E-mail address: h_ghassemi@iust.ac.ir (H. Ghassemi).

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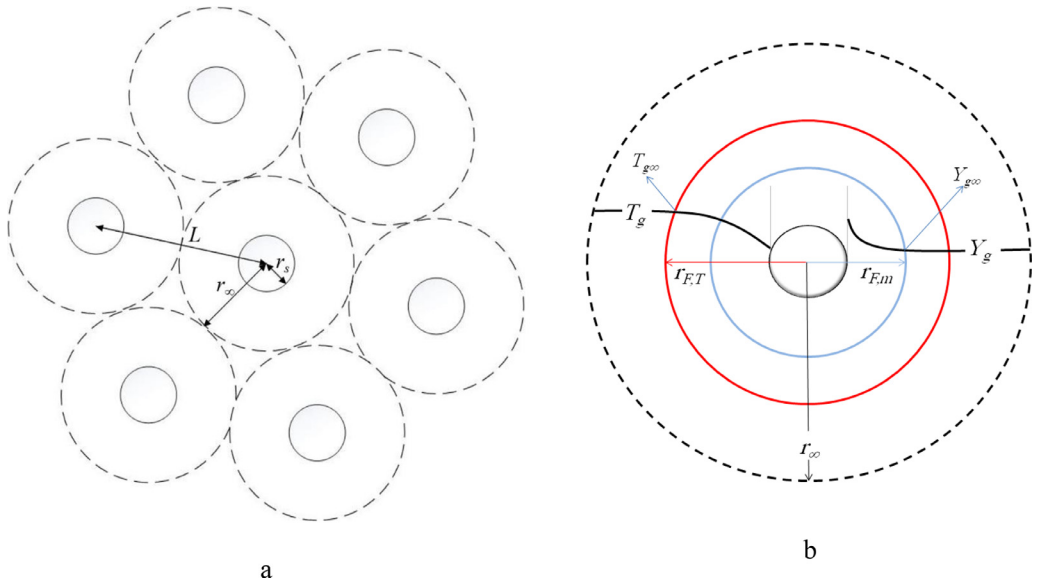

Fig. 1. (a) Schematic of droplets in the spray-like condition, b) Definition of heat and mass influence region. Dashed sphere: droplet bubble, Dotted sphere: Heat influence region, Dash-dotted sphere: mass influence region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

presented by Abramzon and Sirignano [7]), some models are developed considered neighboring effects.

Labowsky studied the evaporating cloud particles and showed that their interactions can reduce the evaporation rate even in dilute clouds [8]. He also by defining a spacing parameter, concluded that closer the droplets are to each other lower their burning rates become [9]. By surveying the evaporation of particles with different sizes and compositions in an array, it is reported that interaction has no significant effect on particles temperature [10]. Castanet et al. conducted a numerical simulation of the evaporating droplet in a row and derived correlation for droplet's Sherwood number under the influence of other droplets [11]. Cossali and Tonini represented an analytical solution for heating and evaporation of two interacting droplets and showed that variable gas density decreases mass flux on the surface of droplets [12].

One of the used models for considering droplet interactions is cellular or drop in bubble model [13]. In this model, a finite spherical domain is considered around the droplet in spray (in contrast with infinite domain for isolated droplet models). Zung, by using this model, concluded that droplets either evaporate completely or reach saturation, depending on droplet distance [14]. Bellan and Cuffel, by solving conservation equations in finite surrounding and by changing the equivalence ratio from lean to rich mixtures, determined different regimes for spray [15]. Sanyal and Sundararajan performed a parametric study to evaluate the effects of cell size and Reynolds number on droplet combustion [16]. Mukhopadhyay and Sanyal developed a spherical cell model for multicomponent droplet combustion and studied the effects of droplet spacing, ambient temperature and pressure and oxidizer concentration [17]. Pathak and Raessi solved steady and transient conservation equations in a finite domain around the droplet and compared the results with d^2-law [18].

Despite these studies, the effects of droplets' interaction on evaporation are not yet fully understood and require further investigation [19]. Based on our previous studies [20–22], in this paper, fully transient modeling of droplet evaporation in the presence of neighbor droplets is investigated. Due to the significant influence of properties' variations (as it was pointed out in [12] for gas density), all thermophysical and transport properties for both phases are considered variable in time and space. By assuming homogeneous distribution, the effects of interactions between mono-sized droplets in a uniform configuration are studied.

2. Physical model

In the present study, a droplet in the bubble model is considered as Fig. 1, for describing the droplet in the spray. The spray is assumed as a complex of mono-sized uniformly distributed droplets in bubbles (dash lines). In which L is the distance between the centers of two neighbor droplets, $r_{\infty,}$ r_s, $r_{F,T}$ and $r_{F,m}$ are the radii of bubble, droplet, heat and mass influence region, respectively. It is shown in Fig. 1b that the radius of influence regions are the closest distance from droplet which its state is the same as the ambient.

The present study considers a fully transient approach for estimating the evaporation process of the single and multicomponent droplet at the constant atmospheric pressure, the surrounding gas assumes ideal which is confirmed by Long et al. [23] and Ebrahimian and Habchi [24]. It is also assumed that droplet and environment are motionless and droplet retains its spherical shape during the evaporation process, and there is no gravity. For this purpose, the species and energy equations in the liquid phase and species, momentum, and energy equations in the gas phase should be solved together. Due to spherical symmetry, the one-dimensional form of these equations are solved and spatial and temporal variations of gas and liquid properties with the temperature and composition are considered.

The complete description of the physical model, governing equations, initial and boundary conditions, properties, and solution method were described in our previous works in details [20,21], and in this section are reported briefly.

2.1. Governing equations

There are two different regions: liquid and gas phase and for each region, it is necessary to solve specific equations. For the liquid phase, the governing equations include species and energy equations [25]:

$$\frac{\partial \rho_{kL}}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho_L D_L \frac{\partial Y_{kL}}{\partial r}\right), \quad k = 1, ..., N_L \tag{1}$$

$$\frac{\partial}{\partial t}(\rho_L C_{PL} T_L) = \frac{1}{r^2}\frac{\partial}{\partial r}\left(k_L r^2 \frac{\partial T_L}{\partial r}\right) + \frac{\partial}{\partial r}\left(r^2 \sum_{k=1}^{N_L} \rho_L D_{kL} h_k \frac{\partial Y_{kL}}{\partial r}\right) \tag{2}$$

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