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Effect of unsteadiness on droplet evaporation

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ABSTRACT

The aim of the present study is an investigation of the impact of gas phase unsteadiness in the evaporation of single component fuel droplets. For this purpose, the results of quasi-steady (QS) approach and Abramzon-Sirignano model (AS) are compared with the fully transient (FT) approach. In the FT and QS approaches, species, momentum and energy conservation equations in gas phase and energy equation in liquid phase have been solved in consideration of totally variable properties. The results of the FT approach at atmospheric pressure for fuels with different volatilities, show a very good agreement with experimental data which are available in the literature. The results of different approaches are obtained for three different fuels, heptane, decane, and hexadecane at temperatures of 500 K and 800 K. By using two measures of unsteadiness related to the mass fraction of fuel vapor and surface temperature, the amount of the steadiness of processes in the gas phase has been checked and deviation of the QS approach and AS model from FT approach has been justified. The results indicate that the temperature and type of fuel have significant effects on unsteadiness. Increasing temperature and decreasing the fuel volatility, increase the deviation of the two approaches from FT approach. Also it is found that the QS approach gives better results for small diameters while the AS model shows better lifetime estimation for large diameters.

1. Introduction

Study of spray vaporization and combustion processes in the combustion chamber, boilers with liquid fuels and many industrial equipment usually require calculation of evaporation rates of various single fuel droplets. The estimation of crucial engine parameters like pollutant emission and fuel consumption depends noticeably on the precision of the droplet vaporization model. For many decades, droplet evaporation has been studied numerically and experimentally in the broad range. The appearance of these models and their development, can be found in the review of Williams [1], Law [2], and Peng and Aggarwal [3]. Also classical droplet vaporization models have been given in detail in some books such as Kou [4], Sirignano [5], and Sazhin [6].

In the experimental background, Nomura et al. measured heptane droplet lifetime at various pressures and temperatures in the micro gravity condition [7]. The results of this study indicate that the slope of squared droplet diameter in the second half of the lifetime is constant at atmospheric pressure and reduces at elevated pressure. Ghassemi et al. studied single and multicomponent droplets evaporation of heptane and hexadecane at different pressures and temperatures under the normal gravity condition [8]. Chaveu et al. measured single component droplet evaporation in the absence of support fiber and discussed the effects of heat conducted through the support fiber on droplet vaporization [9].

Evaporation models can be divided into three different categories. The first, contains the models which study evaporation process based on the fixed temperature and properties assumptions that lead to d^2-law [10,11]. These models are suitable for small droplets and volatile fuels such as heptane.

The second category contains the models with quasi-steady assumption. Accordingly, analytical solutions for the gas phase variables are obtained and these results are used to determine the evaporation rate. The well-known model in this category is presented by Abramzon and Sirignano [12]. They considered the effects of variable properties, non-unity Lewis number in gas phase and Stefan flow on the droplet. Based on these assumptions, numerous studies are reported in the literature. Sazhin et al. by comparison of different kinds of thermal conductivities, observed the impact of the temperature gradient inside the fuel droplets on the evaporation process [13]. They reported that temperature

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gradient inside the droplet leads to an increment of surface temperature in the initial heating process. Tonini et al. presented a new analytical model for the liquid droplet evaporation in a gaseous environment in a radial coordinate system. This model relieves some inconsistencies of previous simplified models and it yields solutions also for the non-isothermal cases [14]. They also presented another model, including the effect of gas convection according to the film theory, by relating the thermal and diffusional film thicknesses to the gas stream Reynolds number [15]. Gavhane et al. showed the coupling influences of droplet constituent compositions and free stream vapor concentrations on evaporation characteristics [16]. They reported that the composition of component vapors for a fixed value of total vapor concentration in free stream has almost negligible influence on droplet lifetime. As mentioned above, although quasi-steady assumption leads to simpler equation and comfortable calculations, it gives an overestimated droplet lifetime due to ignoring the temperature and mass fraction variations in the gas phase. Another group of the second category solved the governing equations numerically such as Yang [17] and Aggarwal [18]. Due to the accuracy of analytical solutions and time consuming of the numerical solution, limited works have been done in this group.

The third category includes transient models. In this case plentiful studies have been done. Hubard et al. by studying the transient effects in the gas phase, reported one-third rule for properties determination [19]. Haywood et al. solved governing equation by considering internal circulation and effects of variable properties [20]. Birouk et al. by developing a three-dimensional numerical model, investigated the effect of turbulence on the mass transfer from a single droplet exposed to a free stream of air [21,22]. The result of this study revealed that the free stream turbulence intensity has an effect on the droplet vaporization even at significantly high-pressure and high-temperature conditions. Mitchel et al. extended a model for the purpose of solving a moving boundary problem for the transient heating of an evaporating spherical droplet [23]. Yin et al. presented a complete description of a model for transient heating and evaporation of moving monocomponent liquid fuel droplets [24].

Although numerous studies have done on the droplet evaporation, limited studies carried on the effects of unsteadiness term. Law et al. studied the effect of unsteadiness in the gas phase. It is reported that by using the quasi-steady assumption which includes fuel vapor accumulation in the inner region, results of transient state could be obtained. In this study the effect of transience is added to steady equations by considering temporal variations of upper bound of integration [25]. Matalon et al. by using perturbation method showed that gas phase unsteadiness leads to change droplet evaporation rate in order of $O[(\rho_g/\rho_l)^{1/2}]$ [26]. Application of the gas phase quasi-steady assumption in droplet ignition by Wong et al. showed that without considering the fuel vapor accumulation which have been widely used in droplet ignition studies, leads to inappropriate prediction for spray delays [27]. Aggarwal et al. studied gas phase unsteadiness effects on the droplet evaporation in sub- and super-critical environment, quantitatively [18]. In this study, two models of transient and quasi-steady state, at different pressures and temperatures are compared. The unsteadiness impact by introducing two time scale ratios is evaluated, quantitatively. It is shown that the gas phase unsteadiness has a great impact on the first period of the evaporation process. Unsteadiness reaches its maximum value near the droplet surface and away from the surface downs to a steady approach. Also by increasing pressure and temperature, the unsteadiness will grow. In addition, they reported that compared to the transient model, the quasi-steady model predicts a smaller regression rate initially and a larger rate during the later period. Aggarwal's work presented results for heptane which is a volatile fuel and spends almost all of droplet lifetime in steady mode. It is not clear what will happen for less volatile fuels and large droplets in which unsteadiness effects appear severely.

Models based on gas phase quasi-steadiness sacrifice the unsteady features of the problem which has a strong presence in the case of heavy fuels and large droplets. To what extent these models for predicting the droplet lifetime as well as evaporation rate of different fuels are appropriate? How much accurate are these models in different droplet sizes and different ambient temperatures? The present paper by presenting the fully transient model and considering temporal and spatial variations in all properties, tries to find the answers of these questions. For this reason, evaporation of different fuels droplet, in various sizes and at different temperatures are studied in three approaches. Quasi-steady (QS), Abramzon and Sirignano model (AS), and fully transient (FT) approaches have been applied and their range of validation are recognized. Also the effects of ambient temperature, type of fuel, and droplet size on the unsteadiness of the evaporation process are assessed.

2. Physical model

Consider a liquid hydrocarbon fuel droplet, with an initial radius r_0 and an initial uniform temperature T_0, immersed (float) into a homogeneous hot nitrogen environment. The gas-phase is prescribed by its pressure, P_∞, temperature, T_∞ (greater than T_0), fuel mass fraction, $Y_{F\infty}$.The gas phase is extended to r_∞ which is enough far from droplet surface. The droplet is heated by conduction and radiation, and is cooled down due to evaporation.

The following assumptions are employed in the present model:

(i) The droplet and surrounding gas are stationary and there is no drag force on the droplet surface, therefore, there will not be any internal flow within the droplet.
(ii) The droplet shape remains spherical. Because its diameter is chosen enough smaller than capillary length of fuels which is reported less than 1.8 mm for alkanes [28],
(iii) The droplet evaporates in a chemically inert atmosphere,
(iv) The gas–liquid interface is at a phase equilibrium,
(v) The effects of gravity, as well as Dufour (energy flux due to mass concentration) and Soret (mass diffusion due to temperature) are assumed negligible. These effects are insignificant in very small droplet.
(vi) The pressure is constant. Although, pressure changes due to vapor flow from droplet surface, but it is not too much because of incompressible nature of problem and its open boundary at r_∞,

Governing equations includes species, momentum and energy conservation equations for gas phase and energy equation for liquid phase. These equations are solved in spherically symmetric one-dimensional coordinate system.

Two approaches are used for solving the governing equations in the present study, Fully transient, and Quasi-steady. In addition, the widely used model presented by Abramson and Sirignano [12] will be used for comparison. It should be noted that, in all mentioned models, the transient governing equations of liquid phase (mass and energy) are solved, which leads to temporal variation of droplet radius, evaporation rate, and droplet temperature. However, only in the fully transient approach, the gas phase governing equations (mass, energy, and momentum) are solved in their transient form.

These three different approaches are described in the following sections: