Simple Model for Turbulence Effects on the Vaporization of Liquid Single Droplets in Forced Convective Conditions

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ABSTRACT

This paper presents a semi-analytical analysis for modeling effects of moderate turbulence flows on the vaporization of an isolated fuel droplet at ambient room temperature and atmospheric pressure conditions. The turbulent Nusselt and Sherwood numbers used in this model are purely empirical. Four different hydrocarbon fuels were tested, i.e. *n*-hexane, *n*-heptane, *n*-octane and *n*-decane each has an initial diameter of 1.5 mm. The droplet Reynolds number, Re_d, is changed in the range (60–1000), and turbulence intensity varied between 0 % and 11 %. The major findings of this study showed that the droplet's vaporization rate, which is deduced from the steady-state linear variation of the droplet squared diameter, increases with increasing turbulence intensity. Also, the results from using several liquid fuels, i.e. *n*-hexane, *n*-heptane, *n*-octane, *n*-nonane, and *n*-decane, show that the vaporization Damköhler number, D_{av}, is correlated to non-dimensional turbulence evaporation rate, K/K_L, by an exponential correlation. This correlation was generalized to be applicable at a wide range of Reynolds number ($60 \leq Re \leq 1000$).

INTRODUCTION

The evaporation of fuel droplets is fundamentally and practically important for many engineering systems powered by liquid fuels such as internal combustion engines. In these systems, fuel is injected into combustion chamber as a spray/jet. This spray/jet breaks down intro droplets that evaporate due to the surrounding atmosphere forming a combustible mixture that ignites once appropriate conditions are achieved. The evaporation process controls the combustion process that is eventually controls the performance of engine, pollution and design of combustion chamber.

Vaporization of single droplets is necessary in spray modeling. Detailed studying of the vaporization of a single liquid fuel droplet is based on solving complete Navier-Stokes equations and provides useful information on the evaporation history and parameters that affect on this process. These studies cannot be in practical use for complex spray models because of time consuming but it can be used to develop such correlations for heat and mass transfer to develop simple models to simulate the evaporation process in spray modelling.

A liquid droplet evaporating in free and forced convective flows received a great attention in the last century, which resulted in the establishment of well-accepted correlations of the heat and mass transport rates from a liquid droplet. Much of the credits of this great progress go to the pioneering research work undertaken by Frössling in the late nineteen thirty's [1] and, Ranz and Marchall in the late nineteen fifty's [2]. However, these correlations are applicable only to a droplet evaporating in a laminar convective flow. In the contrary, the evaporation process of a liquid droplet in turbulent flow conditions received a little interest, and consequently it is still less understood. Early and recent experimental, theoretical and numerical studies on turbulence effects on the transport rates from spheres and liquid droplets are reviewed in [3] and, therefore, are not discussed in this article. The review carried out in [3] showed that most of the available published work on turbulence effects on droplet vaporization in forced convective flows [4-8] or in zero-mean velocity turbulent flows [9-10] is experimental. Some numerical studies are available in the open literature [11-16]. The main conclusion is that turbulence enhances the evaporation process of droplets. The main objective of the present study is to propose a simple model for predicting the turbulent vaporization rate of a liquid fuel droplet subjected to moderate turbulence convective flows at ambient room temperature and atmospheric pressure.

TURBULENT EVAPORATION MODEL

The present model is an extension to the model developed in [17]. The model developed in [17] is capable of predicting the vaporization rate of a liquid droplet in stagnant or laminar convective flows. The main novelty of the present model is that the laminar Nusselt and Sherwood numbers employed in [17] are replaced by turbulent ones. Hence, the applicability of the present model extends to predict also the turbulent vaporization rate of a liquid droplet exposed to forced convective flows with moderate turbulence. Models assumption, governing equations are presented in the full paper due to space limitation.

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SOLUTION PROCEDURE

Calculations of droplet temperature and instantaneous droplet diameter are based on iterative method proposed by Chen et Lefebvre [18] for the model presented in this study. Starting from t = 0, $d = d_o$ and $T_s = T_{so}$, and time interval Δt. The heating up period is terminated if the rate of heat penetrating the droplet is zero or negative and all the heat transfer from gas used to evaporate fuel. The evaporation process is terminated, also, when the ratio between the droplet diameter and initial diameter less than 0.3, which means that more than 97 % of the droplet is evaporated.

SAMPLES OF RESULTS AND DISSCUSIONS

The evaporation of a droplet of *n*-hexane, *n*-heptane, *n*-octane and *n*-decane subjected of a turbulent air flow is considered. The initial droplet temperature is 253 K and its initial diameter is 1.5 mm. The turbulent air around the droplet is at room temperature and atmospheric pressure (300 K, 1 atm), turbulence intensity up to 11 % and mean flow velocities were changed between (0.6 – 10 m/s).

Figure 1 shows the time history of normalized square droplet diameter for of *n*-heptane at stagnant, laminar and at different turbulence intensities. Here a droplet life time is ended when 97.3 % of the droplet has evaporated. It is clearly that the droplet life time decreases with increasing turbulence intensity. This figure shows that the d^2 law is hold for all cases with different slops (evaporation rate). The evaporation rate increases with increasing turbulence intensity. This happens as turbulent is capable to transmit large shear stresses and to diffuse heat and matter more rapidly than corresponding laminar flow. The overall effect of turbulent is equivalent to increasing greatly the effective coefficients of viscosity, heat conductivity and diffusion. Also, the same trend obtained for *n*-decane with a long droplet life time, i.e. low evaporation rate, as shown in Figure 2.

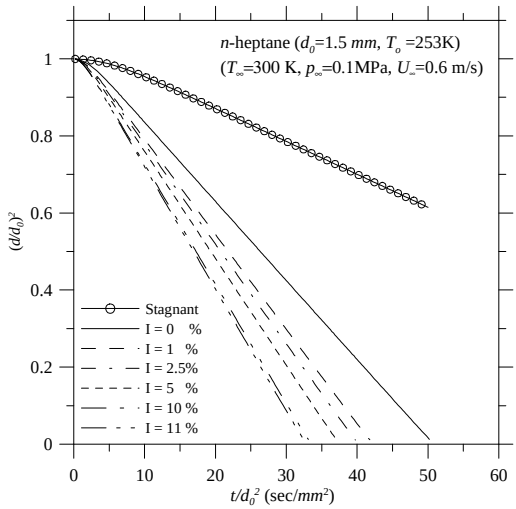

Figure 1. Time history of normalized diameter of *n*-heptane at stagnant, laminar and turbulent conditions

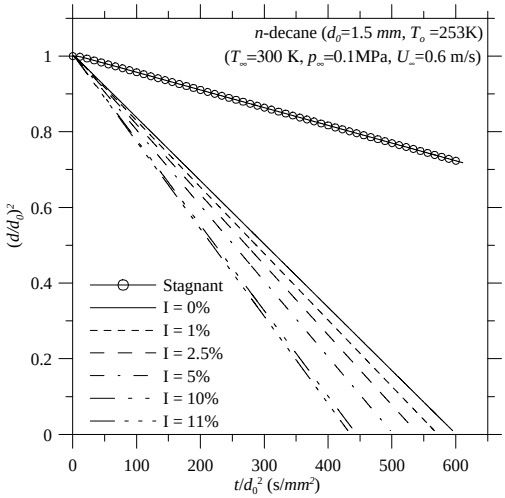

Figure 2. Time history of normalized diameter of *n*-decane at stagnant, laminar and turbulent conditions

The effective vaporization Damköhler number (D_{av}= T_{ed} / T_v), proposed by Gökalp *et al*. [4], which is defines as a completion between turbulence integral time scale and evaporation time scale has been used to correlate the evaporation rate normalized by laminar case. The present data are obtained by employing a droplet Reynolds number of 60, a freestream turbulence intensity in the range between 0 and 11%, and a turbulent integral length scale assumed equal 5 times the initial droplet diameter, which is the measured average value used by Wu et *al*. [7, 8]. As shown in Figure 3 the present numerical data collapse on a single line having the following expression $K/K_L = 0.9115 Da_v^{-0.1212}$. Wu *et al*. [7, 8] correlation is expressed as $K/K_L = 0.771 Da_v^{-0.111}$. The two correlations are slightly different. Correlation of Wu *et al* is held in the region $D_{av} \le 0.1$. At $D_{av} > 0.1$ there is no effect for turbulence as $K/K_L \cong 1$. Whileas the present study suggests that

turbulence still has an effect till $Da_v \leq 0.47$. The slight difference might be contributed to the assumption made for the turbulence integral length scale needed to calculate Da_v. This comparison suggests that the vaporization Damköhler number can be used to correlate the effects of freestream turbulence on the droplet evaporation rate at ambient room temperature.

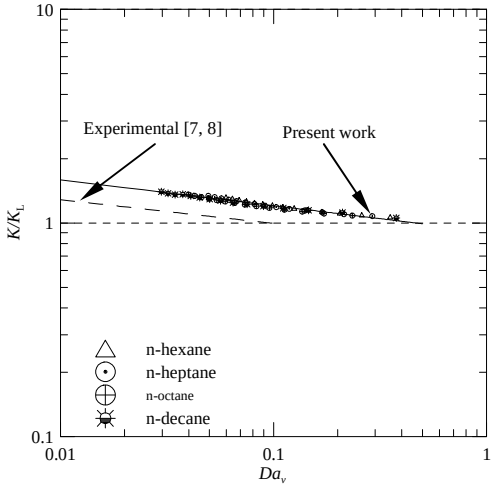

Figure 3. Normalized evaporation rate versus D_{av}

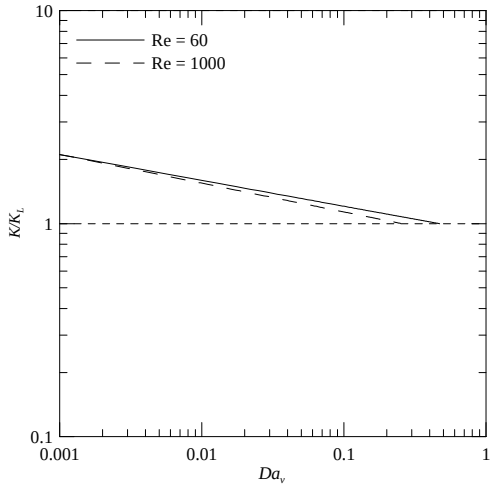

Figure 4. Normalized evaporation rate versus D_{av} at low and high Re

The effect of Reynolds number on the correlation between normalized evaporation rate and Damköhler number has been studied. Reynolds numbers in the range 60 to1000 have been used for test and only two identical numbers, i.e. 60 and 1000, are presented in Figure 4. This figure shows that the effect of Re on the correlation is negligible at low to moderate Reynolds number and slightly increases at high Reynolds number. This conclusion agree with Wu *et al.* [8] who proved experimentally that low to moderate Reynolds numbers have no effects on their correlation. The present study suggests the correlation $K / K_L = \ln(2.882\,\mathrm{Re}^{-0.027}) Da_v^{\ln(0.9033\mathrm{Re}^{-0.0448})}$ to generalize the previous correlation to include the effect of Reynolds number especially the higher values. More details about this generalized correlation and Results are presented in the full paper.

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