Fuel xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Efficiency of the lumped parameter concept and the role of liquid properties in modelling micro droplet evaporation

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HIGHLIGHTS

- Evaporation study of alkane droplets <100 μm in increasing thermal load is done.
- Effective conductivity model variants are developed to predict droplet behaviour.
- Infinite conductivity model proves high efficiency in a number of conditions.
- Except for density, variations of liquid properties are unimportant in this work.

ARTICLE INFO

Article history:
Received 19 March 2015
Received in revised form 20 October 2015
Accepted 22 October 2015
Available online xxxx

Keywords:
Microdroplet evaporation
Infinite conductivity
Effective conductivity
Evaporation modelling
Alkanes

ABSTRACT

This paper presents a study of the micro-sized droplets of dodecane, decane and nonane undergoing evaporation under increasing thermal load through a laminar flow reactor. The objective is to use the effective conductivity concept for the liquid phase to explore the droplet internal state during its lifetime and to assess the efficiency of the infinite conductivity (lumped parameter) concept by comparing these concepts with each other and against the experimental data. Another objective of this work is to assess the sensitivity of the process on the liquid phase properties by developing the constant properties effective conductivity model to more enhanced versions and comparing them to the fully numerical one. Extension to higher Reynolds number and higher temperature conditions is also made. While the enhanced models give almost identical predictions to the full numerical version for all conditions examined, the lump model also found to yields close predictions. Examination of the liquid properties shows that relative to the other properties, accounting for variation in the liquid density is most important.

1. Introduction

This paper examines the ability of a variety of approaches to model evaporation of micro-sized droplets (<100 μm). This is prompted by moves toward reduced fuel droplet size as a means to improve efficiency and reduce pollutant formation in many combustion systems. One of the problems in undertaking such an investigation is the limited experimental data available (e.g. [1–5]), with even fewer studies providing high temporal and spatial resolution [6,7]). The difficulty in obtaining experimental data for the length and time scales necessary under the high temperature and pressure conditions found in combustion systems is the main reason behind the absence of a large body of data. Of the studies available, we have selected one previously published by the authors for the limited condition of droplets undergoing evaporation in an environment of increasing thermal heating load, such as might be found in a partially premixed compression ignition engine [7]. The advantage of this data set is that it contains almost the entire evaporation history of droplets <100 μm in diameter. The disadvantages are the long preheating period and low Reynolds number, which are not typical of many combustion systems.

In this series of studies, fuel droplet evaporation is investigated for droplets flowing through a laminar flow quartz glass reactor, described in [6,7]. The reactor's increasing convective heating load is created by the mixing of the cooler carrier gas used to transport droplets into the reactor with the flow produced by the reactor's flat flame burner. The advantage of this approach over other methods is that it provides precise control of the droplet conditions (initial size, temperature and velocity), and once created, the droplet contacts only gases, rather than filaments or similar droplet suspension devices. The setup is characterised by a prolonged preheating time that the droplet experiences as the carrier gas heats

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http://dx.doi.org/10.1016/j.fuel.2015.10.097
0016-2361/

Nomenclature

1D, 2D	one or two-dimensional
B_H, B_Y	heat and mass transfer (Spalding) numbers
C_{pl}, C_{pf}, C_{pg}	specific heat of the fuel liquid, fuel vapour and reactor gases (J/kg K)
C_F	droplet skin friction coefficient
D, D_o	droplet diameter, initial droplet diameter (μm)
F_D, F_B	drag force, buoyancy (N)
F_H, F_Y	heat and mass transfer number correction factors
g	gravitational acceleration (m^2/s)
H	fuel latent heat of vaporisation (J/kg)
k_{fg}	binary diffusion coefficient (m^2/s)
K_v, K_{vs}	evaporation rate, steady evaporation rate (mm^2/s)
Le	lewis number
m, $\dot{m}_d$	droplet mass (kg), droplet mass flow rate (kg/s)
Nu	Nusselt number
p, p_v	pressure, fuel vapour pressure (Pa)
Pe_l	Peclet number in the liquid phase
Pr, Pr_l	Prandtl numbers in the gas and liquid phases
q	total heat flux to the droplet (W/m^2)
Q, Q_l	total and sensible heat transfer rates to the droplet (W)
r_s, r_o, $\bar{r}_s$	droplet radius (μm), initial radius (μm) and non-dimensional radius
Re, Re_l	droplet and liquid phase Reynolds numbers
Sh	Sherwood number
T_d, T_s, T_g	droplet temperature, droplet surface temperature, gas temperature (K)
$T_{d\max}$	maximum attained (steady state) droplet temperature (K)
T_{ave}	average droplet temperature (K)
T_o, $\overline{T}$	droplet initial temperature (K) and non-dimensional temperature
T_{ref}	reference temperature for estimating gas properties (K)
T_H	high temperature condition
t	time (s or ms)
u, u_{rel}	droplet velocity, relative velocity between droplet and gas (m/s)
u_s	maximum velocity at the droplet surface (m/s)
x	axial coordinate (m)
Y_s	vapour mass fraction at the droplet surface
α_l	liquid thermal diffusivity (mm^2/s)
ρ_l, ρ_g	droplet and gas densities (kg/m^3)
δ_M, δ_T	thicknesses of the gas films for mass and heat transfers
λ_g, λ_l	thermal conductivities of gas and liquid fuel (W/m K)
λ_{eff}	effective liquid conductivity (W/m K
ν_g	kinematic viscosity of gas (m^2/s)
μ_g, μ_l	dynamic viscosities of gas and liquid (N s/m^2)
ζ	correction factor for liquid reference temperature
η	non-dimensional radial coordinate within the droplet
τ	non-dimensional time
χ	liquid phase effective heat transport factor

up to the much higher reactor temperature. Accounting for the heating up effect is thus important in modelling the present droplet behaviour. In addition to this, and common to many studies, droplet Reynolds number is less than unity; the droplet velocity is low and close to that of the reactor flow. Dodecane, decane and nonane droplets were investigated with their sizes monitored over almost the entire trajectory as they pass through the reactor, thus creating entire evaporation histories from ensembles of individual droplets. The need to track the droplets until the end of their lifetimes poses a difficulty in practice, as does the need for repeatable behaviour under complex thermal loading conditions. Through the coupling of magnified digital inline holography and digital particle image correlation, simultaneous measurement of droplet size and velocity yields the evaporation rate time history of individual droplets in the reactor. A detailed description of the experimental technique can be found in [6].

There are a number of options to model droplets the choice of which depends on the strength of the convective heat transfer. Options range from the simple lump parameter approach as represented by the infinite conductivity method, to more complex models which include internal circulation thus enabling 2D descriptions of temperature and fluid properties. In this paper, a range of approaches with differing complexity will be used to model the data published in [7]. The temperature profile chosen for this paper is the high gas temperature condition T_H as described in [7] which has a peak of 680 K. While this temperature resembles the peak temperature in a naturally aspirated compression ignition engine, the use of atmospheric pressure with isolated droplets and the very low gas and droplet speeds used, render the conditions different to those found in an engine [8].

Despite its relative simplicity, the infinite conductivity concept [9–11] which treats the liquid phase as a lump model of unique parameters unvarying in space but varying with time, has been shown to be efficient in predicting the near steady droplet evaporation rates in the weak convective conditions studied here, although with some small difference in evaporation times [7]. One of the aims of this work is to enhance the treatment of the liquid phase to explore the internal state of the present droplets in relation to their behaviour to explain the efficiency of the lump model.

In general, for convective conditions 2D modelling approaches enable a more detailed description of the droplet internal transport which is generated by the slip effect between the droplet and the surrounding gas. The internal process can be visualised by showing the isothermal streamlines which, for strong convective case, can take the form typical of Hill vortices [12,13]. However, for weak convection it is more efficient to approximate the process by the effective conductivity approach introduced in [9], which treats the liquid phase as a diffusion-limited process with an enhanced coefficient representative of the improved heat transport. Furthermore, while essential for multicomponent fuels, such a detailed 2D description is not essential when modelling for a single component liquid. Another consideration is the possibility of internal transport being caused by the thermo-capillary (Marangoni) effect. This effect is due to an uneven distribution of temperature dependant droplet surface tension. This effect only becomes significant for conditions of high relative speed and/or where variation of the surrounding environment is large (see e.g. [14–16]), which is not the case in this work. For this work, the implementation is simplified to a 1D approach as represented by the choice of the effective conductivity concept.

The simplest form of effective conductivity model used in this study makes use of average liquid properties estimated from a reference temperature that is kept constant during the whole process. The aim is then to improve this model in planned steps to assess the importance of liquid phase properties. These models are compared to the more complete model which numerically solves the liquid heat transfer equation with variable properties. Assessments are finally made for some extended, more realistic conditions which are difficult to study experimentally.

Please cite this article in press as: Nguyen D et al. Efficiency of the lumped parameter concept and the role of liquid properties in modelling micro droplet evaporation. Fuel (2015), http://dx.doi.org/10.1016/j.fuel.2015.10.097