Experimental Thermal and Fluid Science 72 (2016) 59–66

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Effect of heat conduction on droplet life time and evaporation rate under forced convection at low temperatures

Hafiz Laiq-ur Rehman *, Julien Weiss, Patrice Seers

École de Technologie Supérieure, Montréal, H3C 1K3, Canada

ARTICLE INFO

Article history:
Received 9 June 2015
Received in revised form 23 October 2015
Accepted 28 October 2015
Available online 31 October 2015

Keywords:
Droplet evaporation
Heat and mass transfer
Heat conduction
Forced convection

ABSTRACT

Fuel droplet vaporization process involving heat and mass transfer holds key interest due to its application in wide range of energy systems. This manuscript presents the experimental and computational investigation of an isolated fuel droplet evaporation conducted in wind tunnel by suspending the droplet using supports of different sizes and materials. Different sizes of initial droplet diameter 1565–2775 μm, ambient temperature 303–403 K and varying ambient air velocity 0.4–2.7 m/s allowed the investigated Reynolds number to be varying between 30 and 275. K-type thermocouples (d_f = 76–812 μm) and glass fibers (d_f = 200–800 μm) are used for fuel droplet suspension. Use of thermocouples allowed acquiring the temporal variation of droplet temperature. Both experimental and computational investigations were carried out to quantify the heat conduction to fuel droplet through droplet support and its effects on the droplet evaporation rates. Gradients of droplet evaporation rates are found to be changing for very small support sizes while extrapolated to obtain values for pure convection cases. MATLAB code based on mathematical model is developed to see the outcome of varying support size, support material, ambient temperature, ambient velocity and droplet size on the droplet evaporation process. The average over estimation of mean droplet evaporation rates in the absence of heat conduction for linear extrapolation are found to be 30% and 8% for thermocouples and glass fibers respectively at U_∞ = 1.4 m/s and varying ambient temperatures while using $0.008 \leq d_f^2/d_o^2 \leq 0.035$ for linear extrapolation.

1. Introduction

Fuel spray injection systems are intensively used in gas turbines and internal combustion engines. Droplet evaporation is a key process between proper air–fuel mixture and its combustion. The simultaneous presence of both heat and mass transport phenomena in fuel droplet evaporation made it an attractive area of study for researchers over the last few decades. Extensive experimental, analytical and numerical research [1–13] have been conducted on single droplet evaporation due to its relative simplicity in comparison to complex spray systems. Isolated droplets better resemble the far field dilute region in the air–fuel mixture where aerodynamic transport is more dominant [14]. These studies have accounted for different factors affecting droplet evaporation process such as ambient temperature, pressure, gravity, transport properties of air surrounding the droplet, the droplet properties, the ambient air velocity and whether the air flow is laminar or turbulent.

Typically droplets are physically suspended from the smallest possible support of low thermal conductivity value materials to minimize the effect of heat conduction on droplet evaporation. This is done to simplify the experimental exercise while maintaining fixed test environment and obtaining high resolution pictures. Researchers performed investigations by using fine glass suspension filaments [2,3,9], silica fiber [10,11,15], quartz fiber [8,10,11] or capillaries [2,3] with low thermal conductivity values for droplet suspension while investigating the transport rates of evaporating fuel droplet. Thermo-elements [2,3] and thermocouples [1,16,17] are used to acquire the temporal variation of the droplet temperature while the latter are also used to support the droplet.

Despite its possible significance, conduction is not incorporated in most of the studies causing some serious deviations from the actual transport and evaporation rates. More recently the influence of this mode of heat transfer has got attention and researchers [1,8,10,11] started to quantify the amount of heat transported to droplet through its support.

Yang and Wong [8] quantified the effect of conduction through the support fiber in a weak convective flow and at temperatures (220–480 °C). It was concluded based on their one dimensional transient analytical evaporating model that heat conduction enhanced evaporation rate and this effect became stronger for lower gas temperatures and thicker fiber [8]. Chauveau et al.

---

* Corresponding author.

http://dx.doi.org/10.1016/j.expthermflusci.2015.10.030
0894-1777/

Nomenclature

d	droplet diameter varying with time
d_o	initial droplet diameter
d_f	support diameter
t_{evap}	droplet evaporation time
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
Sh	Sherwood number
Sc	Schmidt number
Le	Lewis number
h_f	convection heat transfer coefficient
U_∞	ambient air velocity
Δh_{vap}	latent heat of vaporization
Q_{cond}	heat transfer through conduction
$Y_{vap,air}$	mass fraction of air at reference temperature
m_d	droplet mass
K_o	droplet evaporation rate in the absence of support
K	droplet evaporation rate
ρ_{air}	density of air
D_{ab}	Diffusivity
B_M	mass transfer number
B_T	heat transfer number
T_∞	ambient air temperature
T_s	droplet surface temperature
T_{drop}	droplet temperature
$C_{p,liq}$	specific heat capacity of fuel
$C_{p,air,ref}$	specific heat capacity of air at reference temperature
$C_{p,vap}$	specific heat capacity of fuel vapor
k_f	thermal conductivity of support
k_{air}	thermal conductivity of air
$Y_{vap,s}$	mass fraction of vapor at surface temperature

[10,11] worked under hot quiescent environment at elevated temperatures (200–700 °C) for very small size fibers ($d_f^2 < 0.035$ mm^2) and estimated the mean droplet evaporation rate (K). They plotted the mean droplet evaporation rate against the square of the fiber diameter and tried to estimate through linear extrapolation the mean droplet evaporation rate in the absence of fiber and hence conduction. It was concluded that quartz fiber of very small sizes might not influence the evaporation process under quiescent environment. Chauveau et al. [10] mentioned that the studies performed to investigate the effects of ambient pressure on droplet vaporization rates might need to be revisited courtesy of the droplet support sizes used. They further concluded that there is a "possibility of a systematic over-estimation of the vaporization rates".

Seers et al. [1] used K-type thermocouples ($d_f^2 = 0.065$–0.67 mm^2) at lower temperatures (308–333 K) and atmospheric pressure under forced convection to obtain the mean evaporation rate values. An attempt was made to estimate the vaporization rate for pure convection cases through linear extrapolation.

The range and material of support sizes used in the last two studies are quite different from each other along with their droplet evaporation rate gradients. This variation in gradients while approaching toward pure convection case suggests the presence of non-linearity and hence raised some concerns about linear extrapolation.

Thus, the primary objective of this study is to investigate experimentally and numerically the non-linear behavior in droplet evaporation rate curves under the forced convection. We also provide experimental data allowing to validate a numerical model with respect to droplet diameter and temperature. This model is validated over a range of velocities (0.4–2.7 m/s) with butanol and ethanol. It is also important to see whether the assumption of linear extrapolation to obtain mean droplet evaporation rate in the absence of conduction (K_o) is correct. Finally, the d^2-law is investigated under warm forced convection environment to quantify the influence of heat transported through conduction by varying support sizes and materials.

2. Experimental set-up and test conditions

The experimental set-up presented in Fig. 1, consists of a vertical 10 cm-diameter, 1.5 m-long pipe at the base of which a variable speed fan is installed to generate a laminar hot air flow field. The ambient temperature (303–403 K) is maintained at the desired value by using a heater controlled by a PID controller to give an accuracy of up to 0.1 K. The fan generates the air speed ranging from 0.4 m/s to 2.7 m/s. The air speed is measured by using a hot wire probe which is connected to a mini CTA (DANTEC 54T30) and through to the oscilloscope.

Horizontal fine wire K-type thermocouples ($d_f = 76$–812 μm) with a maximum reading error of 2.2 K and single glass fibers ($d_f = 200$–800 μm) are used for fuel droplet suspension. The actual size of the thermocouples and glass fibers was checked by using the Clemex Captiva software and micrometer and errors of ±3% and ±2% were found in thermocouples and glass fibers respectively. The bead (junction) to prong (wire) ratio of thermocouple was found to be from 1.35 to 1.65.

Different volumes of fuel (2–20 μL) vary the fuel initial droplet diameter between $d_o = 1565$ μm and 2775 μm. A micro scale, accurate up to four decimal of a gram was used to ensure the repeatability of the precision syringe used to dispense the fuel droplet. The average initial droplet mass values were established over the 50 droplets and their uncertainty for different fuel volumes at 293 K are presented in Table 1. Fuels such as ethanol and n-butanol were used to investigate the effects of conduction on different fuels.

Reynolds number was varied from 30 to 275 by changing the flow characteristics and droplet sizes. The rate of evaporation is measured by making visual observations of the droplet appearance

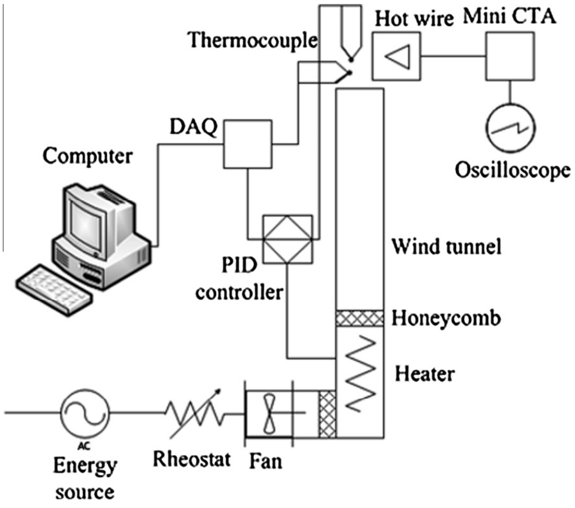

Fig. 1. Schematic of the experimental setup.