



Computational modeling of the effects of support fibers on evaporation of fiber-supported droplets in reduced gravity



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ABSTRACT

A detailed numerical investigation of the effects of support fibers on the vaporization of a fiber-supported droplet in reduced gravity is presented. The volume-of-fluid (VOF) method was employed to capture the liquid–gas interface while allowing for time-dependent two-phase multidimensional flows. The calculations allowed for the inclusion of thermocapillary stresses at the liquid–gas interface. The study also investigated the effects of the thickness of fiber, ambient pressure, and ambient temperature on droplet evaporation. The present computational results agree well with experimental results.

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1. Introduction

Evaporation of droplets has been the subject of numerous investigations over the last few decades because of its importance in the liquid fuel combustion process. Almost all practical combustion processes involve non-premixed combustion where liquid fuels are converted into sprays comprising a large number of droplets. The combustion of single, isolated droplets has been of great interest for fundamental understanding of the combustion process [1,2]. In order for comparison of experimental data with simplified analytical and numerical results, many droplet experiments have been conducted in reduced gravity conditions. Over the last 50–60 years there have been many experimental studies on liquid fuel droplet evaporation and combustion which include drop tower experiments, fiber supported droplet combustion experiments, unsupported droplet combustion experiments, and Flame Extinction (FLEX) experiments in the International Space Station (ISS).

Many droplet evaporation and combustion experiments have been conducted with droplets supported by a fiber to avoid experimental difficulties associated with free-falling, such as droplet drift. Despite years of analytical and numerical studies in isolated droplet evaporation and combustion, only a few studies on the effects of fibers are available in the literature [3–6]. A fiber

supporting the droplet introduces additional heat conducted to the droplets that changes flow fields inside the droplets and their surroundings and the droplet evaporation rate [7,8]. The heat conducted by the fiber introduces temperature gradients along the droplet surface causing variations in the surface tension which causes the flow field inside a droplet to change [8,9].

Nomura et al. [10] have done an experimental study of n-heptane droplet evaporation for a wide range of pressure (0.1 to 5 MPa) and temperature (400 to 800 K) in microgravity conditions. Their work is useful in estimating n-heptane evaporation rates or droplet diameters as a function of time, but they have not done any study on the effect of the supporting fiber. Chauveau et al. [3] have done some experimental investigation of effect of heat conduction through supporting fibers for n-heptane droplets both in micro-gravity and normal gravity, but they have not done any study on the effect of surface tension on the evaporation rates. Yang and Wong [6] have done some analytical and experimental studies on the effect of the supporting fiber for n-heptane and n-hexadecane droplets in weakly convective flow in microgravity environments. However, their modeling is based on some major simplifying assumptions like the model is simple one-dimensional, all thermo-physical properties are constant and there are no effects of surface tension. Dwyer et al. [4] have done some study on thermal Marangoni effect on the stability of fiber-supported methanol droplets in microgravity. Shaw and Harrison [5] have also done an analytical study on the effect of supporting fibers on the shapes of heptane-hexadecane droplets in reduced gravity. But none of the above mentioned studies have done detailed investigations on

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the effects of fibers and thermocapillary stresses on the flow and temperature fields inside and outside of the droplet, temperature variations at the droplet surface and on the droplet shape. Shringi et al. [8] have done a numerical investigation on the effect of fiber on methanol droplet in a convective flow, but they have not done any study in stagnant environment where a majority of microgravity experiments have been conducted. Their work also did not allow for variable droplet shapes from the surface tension variations.

The purpose of the current research is to study fiber supported droplet evaporation in detail, while relaxing the limitations of the prior studies that include the Marangoni effect caused by temperature gradient along the droplet surface, multi-dimensional flow, accurate interface tracking with the VOF method, variable thermo-physical properties of liquid and all species in the gas phase, and stagnant environments. In the present study, we investigate the effect of fiber and surface tension variations on the flow and temperature fields, vaporization rate and the shape of a droplet by employing a full multi-dimensional computational fluid dynamics solver with the volume of Fluid (VOF) method to track liquid–gas interface accurately. The study also includes the effects of variation of the ambient temperature and pressure on fiber supported droplet evaporation.

A commercial CFD package ANSYS FLUENT V14.0 has been employed for the numerical analysis. The current numerical investigation consists of the following cases: (1) fiber supported droplets with and without thermal Marangoni effects (2) droplets supported by fibers of different diameters (3) droplets exposed to different ambient temperatures (4) and droplets exposed to different ambient pressures. The numerical results are compared with the experimental study by Nomura et al. [10].

2. Mathematical formulation

2.1. Interface tracking

The volume of Fluid (VOF) method [11] has been employed to track the interface between the liquid and gas phases. In order to distinguish the two phases, an additional field variable (α) which represents the volume fraction of the liquid phase, is introduced in the VOF method:

$$\alpha(\vec{X}, t) = \begin{cases} 0 & \text{in gas phase,} \\ 0 < \alpha < 1 & \text{in the interface,} \\ 1 & \text{in liquid phase,} \end{cases}$$

where α is controlled by the following transport equation [12,13]

$$\frac{\partial}{\partial t}(\alpha) + \vec{v} \cdot \nabla(\alpha) = 0. \quad (1)$$

2.2. Species conservation in gas phase

The transport equation of species i is given by

$$\frac{\partial \rho Y_i}{\partial t} + \nabla \cdot (\rho Y_i \vec{v}) = \nabla \cdot (\rho D_i \nabla Y_i) + \dot{m}_i''' \quad (2)$$

where Y_i is the mass fraction of species i and the diffusivity, D_i , is given by [14–16]

$$D_i = \frac{1 - X_i}{\sum_{j \neq i} \frac{X_j}{D_{ij}}}, \quad (3)$$

where X_i denotes the mole fraction of species i . The mixture density, ρ , is defined as

$$\rho = \sum_j Y_j \rho_j, \quad (4)$$

where Y_j and ρ_j indicate mass fraction and density of species j . The source term \dot{m}_i''' in Eq. (2) is caused by the volumetric evaporation at the interface. This source term is non-zero at the interface and zero anywhere else in the computational domain. The variable D_{ij} is the binary diffusion coefficient of species i with respect to species j .

2.3. Continuity equation

The mass conservation equation is

$$\frac{\partial(\rho)}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_c. \quad (5)$$

The source term S_c in the continuity equation arises from evaporation of liquid phase at the interface and it exists only at the interface cells and ceases to exist at other cells in the computational domain.

2.4. Momentum equation

The momentum conservation equation is

$$\frac{\partial(\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot [\mu(\nabla \vec{v} + \nabla \vec{v}^T)] + \rho \vec{g} + f_\Gamma, \quad (6)$$

where the momentum source f_Γ at the interface is introduced because of the surface tension and \vec{g} is the gravitational acceleration. In the droplet evaporation experiment Nomura et al. [10] have achieved a gravity level less than 10^{-3} of normal earth gravity and in drop tower isolated droplet combustion experiments the gravity is less than 10^{-6} of the earth's normal gravity. The gravity is very small in micro-gravity experiments and its effect is negligible. As the current numerical study focuses on the evaporation in micro-gravity, the gravity term ($\rho \vec{g}$) is dropped from the momentum equation. The momentum source only exists in the interface cells and vanishes everywhere else in the computational domain.

2.5. Energy equation

The energy equation is given by

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot [\vec{v}(\rho E + p)] = \nabla \cdot \left(k \nabla T - \sum_j h_j \vec{J}_j + \vec{\tau} \cdot \vec{v} \right) + S_e, \quad (7)$$

where the energy density, E , is defined as

$$E = h - \frac{p}{\rho} + \frac{v^2}{2}. \quad (8)$$

The sensible enthalpy, h , in the gas phase is defined as

$$h = \sum_j Y_j h_j. \quad (9)$$

The specific enthalpy, h_j , for species/component j is computed as

$$h_j = \int_{T_{ref}}^T c_{p,j} dT, \quad (10)$$

where T_{ref} is 298.15 K and ρ_j , α_j and E_j indicate density, volume fraction and specific heat of phase j . The variable \vec{J}_j is the diffusion flux of species j and the term $\vec{\tau} \cdot \vec{v}$ in the energy equation Eq. (7) is the contribution of viscous dissipation. The source term S_e in the energy equation Eq. (7) arises from the energy associated with evaporation at the interface cells and it does not exist anywhere else in the computational domain.

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