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Oblate spheroidal droplet evaporation in an acoustic levitator

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ABSTRACT

The modelling of evaporation in which droplet geometry deviates from sphericity, i.e., oblate spheroid, when the droplet experiences high dynamic stresses or a high Weber number, is important in many applications. The validation of such theoretical models is often difficult to achieve experimentally. The acoustic levitation technique was used to investigate the evaporation of an oblate spheroid for different liquids. Evaporation of oblate droplet at constant aspect ratio is realized through the course of evaporation in the acoustic levitator by continuously adjusting the applied acoustic force on the droplet. A Two-dimensional axisymmetric computational model in oblate coordinate system is presented to predict droplet evaporation driven by the acoustic boundary layer, the model calculates the vapor flux at each grid point on droplet surface. The evaporation follows the d^2-law and a good agreement between model prediction and experiments is demonstrated. The acoustic levitator allows for the study of the evaporation of freely suspended deformed droplets and validates the theoretical model of oblate droplet evaporation.

1. Introduction

The evaporation of droplets is an essential step in various chemical engineering processes, such as spray drying, fuel combustion, the prevention of aircraft icing and nanomaterial fabrication. In these applications, multiple physical phenomena often occur, including droplet atomization, spray transport, droplet-wall interactions, collisions, coalescence, oscillations (including the instabilities of evaporating droplets) and, on the scale of single droplets, heating and subsequent evaporation of a liquid solvent.

Modelling of the diffusion process involved in vaporizing droplets has attracted many researchers. The simplest model for diffusion controlled evaporation was proposed by Maxwell [1]. Maxwell's model addressed stationary state evaporation and assumed that the concentration gradient of the solvent vapor between the droplet surface and the surrounding gaseous medium was the sole driving force behind the vapor's transport. Maxwell's equation ignores the gas convective flow effect, which limits its applicability. Fuchs [1] took Maxwell's model one step further by solving mass diffusion and heat flow simultaneously. Fuchs assumed that heat is transferred due to conduction and neglected the radiation and convection effects. It is worth noting that both models attempted to simulate the steady state evaporation of a non -moving droplet.

In most cases, droplets move relative to the gaseous medium, which results in convective transport of the evaporated solvent. Film theory [2] introduced the influence of convective flow. An empirical correlation [3,4] was proposed to account for the evaporation of a droplet by forced or natural convection. These correlations are usually written in terms of Sherwood/Nusselt numbers that relate the mass/heat transfer of moving droplets to that of a stationary one.

Abramzon and Sirignano [5] presented a theoretical model based on the concept of film theory. They studied the convective transport induced by droplet motion or the effects of gas blowing and employed the diffusion and thermal boundary layer thickness to compute the convective mass and heat transfer between the droplet's surface and the air stream.

Another implementation of the film theory concept [6] was similar to Abramzon and Sirignano's model but with a modified boundary condition that considers droplets' surface recession during evaporation and Stephan flow, resulting in a generalized form of mass and heat transfer coefficients.

Evaporation of multicomponent liquid droplets was investigated by many researchers [6–9], either using semi-analytical approach [10] or in case of spray evaporation; CFD models [11] were implemented to study different evaporation problems. Brenn et al. [7] developed a computational model based on Abramzon and Sirignano's model to simulate the evaporation of single droplet consisting of up to five liquid components, the influence of various liquid component activities was modeled using the UNIFAC approach. They used an empirical correlation for *Sh* number found by Ranz and Marshall [3] for convective mass transfer, even though the evaporation is driven by the acoustic boundary layer.

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Nomenclature

a	semi-major axis ratio, [m]
A_{os}	surface area of oblate spheroid, [m^2]
A_R	aspect ratio = b/a [–]
b	semi-minor axis ratio, [m]
C_p	heat capacity, [kj/(kg·K)]
c_s	sound velocity, [m/s]
e	oblate spheroid eccentricity, ($e^2 = 1 - A_R^2$)
f	focal length, [m]
h_g	heat transfer coefficient, [W/(m^2·K)]
h_ξ, h_θ, h_φ	metric coefficients
k_d	heat conductivity of droplet, [W/(m·K)]
L_c	characteristic length, [m]
L_{major}	equatorial diameter (L_{major} = 2a), [m]
L_{minor}	axial diameter (L_{minor} = 2b), [m]
Mw	molecular weight, [g/mol]
Nu	Nusselt number, [–]
P_*	vapor pressure, [atm]
P_{amt}	ambient gas pressure, [atm]
Sh	Sherwood number, [–]
T	temperature, [k]
x, y, z	cartesian coordinates system
y_s	vapor fraction at the surface, [–]

Greeks

ξ, θ and φ	oblate coordinates system
α	thermal diffusivity, [m/s^2]
ρ	density [kg/m^3]
λ	heat vaporization of liquid, [kj/kg]
$\mathfrak{D}_g$	diffusion coefficient, [m/s^2]
ω	angular frequency, [Hz]

Subscripts

os	Oblate spheroid
s	surface of droplet
d	droplet
g	gas
vap	vapour

Modelling of droplet evaporation was developed primarily for a simplified geometrical shape, i.e., a spherical droplet. Experimental studies showed that droplet geometry may have a significant shape deformation; a droplet moving in a gas medium is prone to dynamic stresses on the droplet's surface [12]; while the gas's dynamic stress forces the droplet to deform, the surface tension tends to retain the droplet's surface to an equilibrium surface energy which leads to a spherical shape [13]. At a Weber number much greater than unity, droplet shape deviates from sphericity [14], any change in liquid surface tension might cause the droplet shape to oscillate [15].

Many monographs have studied the heating of spheroid droplets in terms of the heat transfer coefficient. They addressed the energy and Navier-Stokes equations that describe the flow past the spheroid [16–19]. Spheroidal droplet evaporation has been investigated theoretically for oscillating spheroidal liquid drops [20]. A general 1-D mathematical approach was developed [21] and results in an analytical solution to steady-state evaporation from spheroidal droplets (oblate, prolate and triaxial ellipsoids). A theoretical study was conducted on deformed droplets under forced convection evaporation [22]; it sought to obtain an algebraic solution for the evaporation rate of an oblate droplet. The researchers validated their model for the spherical case only and assumed an empirical correlation for Sherwood/Nusselt numbers based on geometrical analysis instead of solving the Navier-Stokes equation that describes the flow around the oblate spheroid.

In recent work from our laboratory, Al Zaitone [23] investigated theoretically the evaporation of an oblate liquid droplet. The evaporation is driven by the forced convection of air stream past the droplet, the governing equations of energy, mass and momentum were solved numerically. The influence of droplet geometry i.e. aspect ratio on the resulting profiles of Sherwood/Nusselt numbers on droplet were calculated. Al Zaitone presented a quantitative analysis of the shape factor effect on evaporation rate of spheroidal droplets versus spherical droplets, the study shows that the maximum deviation of evaporation rate occurs as oblateness of the spheroid approaches disk-like shape for the same equivalent volume of spherical droplets.

Experimental observations revealed that spheroids are a good approximation of non-spherical particles [24]. A sphere is a special case of generalized spheroidal geometry; for example, most aerosols are not spherical in nature [25]. A recent review [26] shows that elongated particles are more efficient at enhancing targeted drug delivery, as they can easily pass through cell membranes.

In most studies involving the evaporation of spheroidal droplets, only a theoretical analysis has been presented. In sprays, droplets might deform due to the high aerodynamic forces exerted, which leads to droplet disintegration. Such phenomena happen in a very short time and it is difficult to observe this evaporation experimentally. The validation of theoretical models through experimental results is important.

Successful modelling tools for understanding transport processes are highly related to an accurate description of the drop's geometry. Therefore, the objective of the present study is to experimentally investigate the evaporation of oblate droplets using the acoustic levitation technique. The unique feature of acoustic levitation – holding up freely suspended droplets in the air – is used to generate an oblate droplet of a predefined droplet geometry, i.e., the aspect ratio during the evaporation process which allows the theoretical model predictions for an oblate spheroidal coordinate to be validated with experiments. The mathematical model of deformed droplet evaporation is first presented, then the acoustic levitator is described in the experimental method section followed by an analysis of acoustic field influence on evaporation of single droplet. Experimental results of deformed droplet evaporation at constant aspect ratio is discussed. The mathematical model is verified using experimental data acquired with an acoustic levitator, and a further study of deformed droplet evaporation at various aspect ratio from the computational model is discussed, finally the conclusions of the present work is drawn in the last section.

2. Oblate droplet evaporation model

Oblate spheroids droplets are formed by revolving an ellipse around its minor axis, the oblate orthogonal coordinates shown in Fig. 1 is related to the cartesian coordinates [28]:

$$\begin{aligned} X &= f \cdot \cosh\xi \cdot \sin\theta \cdot \cos\varphi \\ Y &= f \cdot \cosh\xi \cdot \sin\theta \cdot \sin\varphi \\ Z &= f \cdot \sinh\xi \cdot \cos\theta \end{aligned} \tag{1}$$