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Vapor distribution above an evaporating sessile drop

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ABSTRACT

An experimental technique was developed that uses infrared tomography to measure the three-dimensional vapor distribution above an evaporating sessile drop. The technique was applied to measure the vapor distributions above evaporating drops of hexane and 3-methylpentane (3MP) at room temperature and pressure. The molecular masses of these two species are heavier than air and the vapor from the evaporating drop forms a flat, disk-shaped cloud. A Fourier transform infrared spectrometer (FTIR) was used to measure the spectral absorbance along a set of paths passing through the vapor cloud. From a set of path-averaged absorbance measurements, a two-dimensional spatial concentration distribution was determined using a computed tomography routine. A three-dimensional concentration distribution was obtained from multiple two-dimensional distributions obtained at different elevations above the drop.

The vapor distributions for both hexane and 3MP differ significantly from the values predicted by the solutions for diffusion-limited evaporation and indicate the effect of buoyancy-induced convection of the vapor. These measurements are the first quantitative measurements of the vapor distribution above a sessile drop and are important for advancing the understanding of the vapor phase transport mechanisms, and thus sessile drop evaporation.

1. Introduction

The understanding of sessile drop evaporation is important for many technical applications, including spray cooling [1,2], coating [3], ink-jet printing [4–6], DNA stretching and depositing [7,8], and self-assembly and surface patterning [9–11]. Analytical expressions for drop evaporation of various complexities have been developed for quasi-steady evaporation when the rate is limited by the rate of vapor diffusion from the drop surface [12–17]. Erbil has written a comprehensive review of the analytical models that have been developed over the past 120 years [18]. In addition, computational models have been developed to include complex phenomena not accounted for by the analytical models. For example, Dunn et al. developed a computational model to account for evaporative cooling and the pressure dependence of the vapor diffusivity [19], Semenov et al. computed the instantaneous flux distributions [20], and Widjaja and Harris studied the effects of motion inside the liquid drop [21].

The great majority of the published research on sessile drop evaporation pertains to conditions of quasi-steady, vapor diffusion-limited evaporation. Less work has been published for conditions in which buoyancy-induced convection of the vapor is significant. Recently, researchers have included vapor-phase natural convection in their models for the evaporation of sessile water drops [22,23]. Saada et al. computed a convective velocity distribution that is radially inward above the perimeter of the drop and turns vertically upward above the center of the drop due to the water vapor being less dense than the surrounding air. That result is qualitatively similar to the conclusions of O'Brien and Saville, who used interferometry to obtain images of the vapor above a diethyl ether drop and stated that the images are consistent with the presence of Bénard cell circulation with the vapor flow directed up along an axis above the center of the drop [24]. For the case of vapor that is heavier than air, schlieren videos show the convective flow of the vapor–air mixture to be horizontal and directed away from the drop surface in all radial directions [25]. Carle et al. investigated the effect of natural convection of vapor on the evaporation rates of ethanol drops by comparing the rates under conditions of normal and microgravity [26], and Vynnycky and Maeno considered the case of the water drop being colder than the surrounding air, and thus the water vapor being heavier than the air, but the results for the velocity and concentration distributions of the vapor were not presented [23].

Very little information is published on the distribution of the vapor concentration surrounding a sessile drop. For the case of diffusion-limited evaporation, the vapor is generally assumed to be distributed in the approximately hemispherical space above the

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Nomenclature

A	absorbance
l	path length through vapor
C	molar concentration
r	radial coordinate
x	horizontal coordinate
z	vertical coordinate

Greek symbols

α	molecular absorptivity
ν	spatial frequency

Subscripts

ν	spectral quantity
sat	saturation value

drop according to the solution of the steady Laplace equation [15,16,19,21,27]. A computational model that includes buoyancy-induced convection in the vapor phase for water vapor (lighter than air) indicates that convection draws the vapor toward a vertical axis above the center of the drop so that lines of constant concentration appear cone-shaped as opposed to hemispherical [22]. When the vapor is heavier than air, the vapor is contained in a flat, disk-shaped cloud surrounding the drop [25].

The distribution of the vapor is an important characteristic of the evaporation process. The local rate of diffusion is determined by the concentration gradient, and buoyancy-induced convection is determined by the density gradient. Since both convection and diffusion influence the vapor distribution, the two mechanisms are coupled so that the occurrence of convection affects the rate of diffusion, and vice versa. Thus, quantitative knowledge of the vapor distribution can lead to a more thorough understanding of the vapor transport. Furthermore, the conditions at the surface of the drop can influence the liquid phase behavior. For example, a shear stress induced by a convective flow of the vapor–air mixture at the surface of the drop will cause motion within the liquid drop. As mentioned above, the effects of various physical processes on the evaporation of sessile drops have been modeled, but there have not been any quantitative measurements of the vapor distribution, which are important for determining whether the models are accurately computing the vapor transport when both diffusion and convection are significant.

This paper presents a technique for obtaining quantitative measurements of the vapor distribution above a sessile drop using infrared spectroscopy and computed tomography. Computed tomography is a procedure to obtain a two-dimensional distribution (slice) from a series of one-dimensional measurements. By combining slices, a three-dimensional distribution can be obtained. The use of computed tomography is well known in medical applications, i.e. CT or CAT scans, but also it has been used in a variety of research applications, for example measuring combustion products in an internal combustion engine [28] or from a flat flame burner [29], measuring the structure of a hollow cone fuel spray [30], measuring nitrogen emissions from a swine waste lagoon [31], and various non-destructive testing applications [32].

We used computed tomography to determine the three-dimensional distributions of vapor concentration above sessile drops of hexane and 3-methylpentane (3MP) from a series of infrared absorbance measurements obtained using a Fourier transform infrared spectrometer (FTIR). A significant advantage of using an FTIR over a monochromatic source is the potential to simultaneously measure the vapor concentrations of different species, as occurs during the evaporation of multicomponent drops. That potential will be investigated in a future paper; for this paper the technique is applied to measure the vapor concentration surrounding single-component drops.

The measured vapor distributions for both hexane and 3MP are much different than the distributions that would be expected for diffusion-limited evaporation, and thus the measurements indicate the effect of buoyancy-induced convection.

2. Method

Fig. 1 is a schlieren image of the vapor cloud surrounding a pinned, sessile hexane drop of radius 6.5 mm and having an initial volume of 80 μl. The bright region indicates the presence of vapor. The drop is located at the center of the disk-shaped substrate, which has a radius of 22 mm. Since the vapor is heavier than air, the cloud flows away from the drop along the surface of the substrate and spills over the edge. As a result, the shape of the cloud is relatively flat with a thickness of approximately 5 mm.

To measure the vapor concentration, the infrared (IR) beam of an FTIR is passed horizontally through the vapor cloud at various locations above the evaporating drop. The arrow in Fig. 1 represents one pass of the IR beam. For each pass, the FTIR measures the absorption of the vapor–air mixture in the path of the beam, which is proportional to the average concentration along the beam path. To determine the two-dimensional vapor distribution in a planar slice through the cloud, multiple path-averaged absorption measurements are needed. For that purpose, a series of measurements are taken with the infrared beam passing through different secants of the vapor cloud in a given elevation plane, as shown in Fig. 2a. Constrained by the width of the sample compartment of the FTIR, not all regions of the cloud were probed but measurements were taken over more than half of the planar slice and extended beyond the edge of the cloud.

The distribution of path-averaged absorbance values, shown schematically in Fig. 2b, is the one-dimensional projection of the two-dimensional absorbance distribution in the given plane of the vapor cloud. To compute the vapor concentration distribution in an elevation plane, axial symmetry is assumed and computed tomography (CT) is used to compute the two-dimensional absorbance distribution from the measured one-dimensional projection. The vapor distribution, then, is obtained by multiplying the absorbance distribution by the molar absorptivity, which is measured by a separate series of experiments. Combining the distributions in

Fig. 1. Schlieren image of the vapor cloud surrounding a pinned, sessile hexane drop. The bright region indicates the presence of vapor and the arrow demonstrates a path of the infrared beam from the FTIR through the vapor cloud.