



A new experiment for investigating evaporation and condensation of cryogenic propellants



K. Bellur^a, E.F. Médici^a, M. Kulshreshtha^a, V. Konduru^a, D. Tyrewala^a, A. Tamilarasan^b, J. McQuillen^c, J.B. Leão^d, D.S. Hussey^d, D.L. Jacobson^d, J. Scherschligt^d, J.C. Hermanson^b, C.K. Choi^a, J.S. Allen^{a,*}

^a Michigan Technological University, 1400 Townsend Drive, Houghton, MI, USA

^b University of Washington, Seattle, WA, USA

^c NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, OH, USA

^d National Institutes of Standards and Technology, Gaithersburg, MD, USA

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ABSTRACT

Passive and active technologies have been used to control propellant boil-off, but the current state of understanding of cryogenic evaporation and condensation in microgravity is insufficient for designing large cryogenic depots critical to the long-term space exploration missions. One of the key factors limiting the ability to design such systems is the uncertainty in the accommodation coefficients (evaporation and condensation), which are inputs for kinetic modeling of phase change.

A novel, combined experimental and computational approach is being used to determine the accommodation coefficients for liquid hydrogen and liquid methane. The experimental effort utilizes the Neutron Imaging Facility located at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland to image evaporation and condensation of hydrogenated propellants inside of metallic containers. The computational effort includes numerical solution of a model for phase change in the contact line and thin film regions as well as an CFD effort for determining the appropriate thermal boundary conditions for the numerical solution of the evaporating and condensing liquid. Using all three methods, there is the possibility of extracting the accommodation coefficients from the experimental observations. The experiments are the first known observation of a liquid hydrogen menisci condensing and evaporating inside aluminum and stainless steel cylinders. The experimental technique, complimentary computational thermal model and meniscus shape determination are reported. The computational thermal model has been shown to accurately track the transient thermal response of the test cells. The meniscus shape determination suggests the presence of a finite contact angle, albeit very small, between liquid hydrogen and aluminum oxide.

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1. Introduction and background

Passive and active thermal and fluid control systems are routinely used to manipulate cryogenic liquids in microgravity and to mitigate boil off. Computational fluid dynamics (CFD) modeling of the propellant coupled with a lumped thermodynamic treatment of the vapor phase has been used to study pressurization within cryogen tanks [1–5]. From these models, a thin (approximately 1 mm) liquid layer separating the vapor phase from the wall was shown to form. Accurately predicting the stability of the liquid layer and evaporation/condensation remains a challenge due to the absence of reliable values of evaporation and

condensation coefficients and the ability to computationally capture the local thermodynamics [1,5,6].

Additional experimental evidence that suggests understanding local thermodynamic states is critical to predicting phase change of liquid hydrogen and methane were found during recent tests conducted at National Aeronautics and Space Administration (NASA) Glenn Research Center located in Cleveland, Ohio. These experiments focused on determination of bubble-point pressure, i.e. vapor break through, for liquid oxygen, methane, and hydrogen in liquid acquisition screens. The uncertainty in the experimental data was largely attributed to uncertainty in the evaporation at the screen surface [6–8]. Meniscus phase change is significantly different than that of pool boiling, where vapor pressure and wall temperature are generally sufficient to predict heat flux. Two additional factors affect phase change at a meniscus, such as those

* Corresponding author.

E-mail address: jstallen@mtu.edu (J.S. Allen).

present in a screen. The first is curvature, which gives rise to a pressure jump across the liquid–vapor interface due to surface tension. The second factor is the presence of the contact line, which results in non-uniform evaporation over the liquid surface due to anisotropy in the liquid stresses within the thin liquid film due to disjoining pressure effects [9]. Curvature and disjoining pressure effects have been incorporated into evaporation and condensation models [9–12], but accurate measures of the evaporation and condensation coefficients remains a challenge, especially for cryogenic liquids.

Liquid–vapor (evaporation or condensation) phase change is a complex, multiscale, conjugate problem. Different phase change models have been proposed to quantify the rate of mass transfer from one state to the other. These models can be classified as diffusive or kinetic models. Diffusive models rely upon relative partial pressure for triggering phase change. Diffusive evaporation or condensation models are material independent, generating the same mass flux regardless of the contact angle or liquid phase curvature. These models have been applied to study phase change in liquid reservoirs with large open surface area. In contrast, models traditionally used for investigating phase change in smaller liquid reservoirs where the exposed surface is comparable to the meniscus size, such as in porous media, are kinetics based. Kinetic models are dependent upon the material properties, the location of liquid phase within the material and may take into account the effect of disjoining pressure, meniscus curvature, and non-equilibrium interface temperature [13].

When evaporation is diffusion limited, the rate of phase change is proportional to the interfacial area and to the concentration difference between the vapor and the liquid–vapor interface, which for the modeling purposes is considered to be saturated vapor. A change in substrate material has no effect on the rate of phase change. As the interfacial area decreases with respect to contact line length, the rate of evaporation is no longer proportional to the area and a different model is needed to predict the mass flux based on the molecular dynamics taking place at the contact line region.

The contact line is an apparent intersection of three phases – vapor, liquid and solid. This intersection is commonly described using the static contact angle, θ , which refers to the apparent angle between the liquid and the solid (as measured through the liquid). The contact line is a continuum region and is often described for wetting liquids as a continuously thinning film that terminates in an adsorbed layer. Fig. 1 delineates regions of interest along a wetting evaporating meniscus according to the component of normal stress most affecting the thermo-fluid dynamics. The normal stress in the bulk liquid is mostly affected by capillarity, or interface curvature. The adsorbed film region is characterized by intermolecular forces and is not optically accessible. Both intermolecular forces and curvature affect the normal stress in the contact line region. A typical value of the maximum thickness of the contact line region where intermolecular forces begin to affect the liquid interface shape is 1 μm .

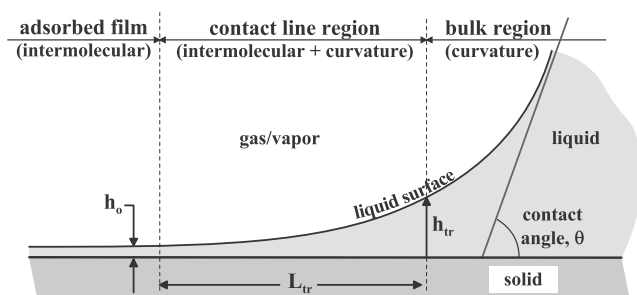


Fig. 1. Extended meniscus with regions delineated by normal stress components.

The contact line region has a dramatic effect on evaporation (and condensation). Typically during phase change a relatively large temperature gradient is setup in the contact line region both parallel and perpendicular to the solid surface that may result in thermocapillary stresses. For non-polar and/or wetting liquids, the result is that 60–90% of the total evaporation occurs in the contact line region [9,14–28]. Though specific experiments have been empirically analyzed and numerical models validated against these experiments [9,16,22], the effect of contact angle and contact line length on total evaporation is not quantitatively predictable in a general sense.

A kinetic model depends upon the local interface conditions in the contact line region, specifically in the contact line region. The amount of mass undergoing phase change is proportional to the size of the contact line region as well as the local properties such as partial pressure of vapor, temperature, and relative humidity. The mass undergoing phase change can be expressed in the form of the Hertz–Knudsen–Schrage equation [9,11,29]. Originally developed from kinetic theory for planar evaporation, this model has been expanded to include the effects of surface tension [10] and surface curvature [12] through the use of the Clapeyron equation:

$$J = \frac{2\alpha}{2 - \alpha} \left(\frac{M}{2\pi RT_{lv}} \right)^{1/2} \left[\frac{p_v M h_{fg}}{RT_v T_{lv}} (T_{lv} - T_v) - \frac{v_l p_v}{RT_{lv}} (\Pi + \sigma\kappa) + \frac{Mgp_v \chi}{RT_v} \right], \quad (1)$$

where J is the evaporative flux, α is the evaporation or condensation coefficient (often referred to as the accommodation coefficient), T_{lv} is interfacial temperature, Π is the disjoining pressure (the net pressure reduction within the film due to the solid–liquid intermolecular forces), σ is surface tension, and κ is the surface curvature. Other parameters are standard thermodynamic properties [12].

Evaporation and condensation coefficients, often referred to as accommodation coefficients, are derived from kinetic theory and represent the fraction of molecules striking the liquid surface [11]. The accommodation coefficient is considered to be a thermodynamic property of kinetic models of evaporation and condensation. Accurate prediction of the rate of phase change typically requires a measured value of the accommodation coefficient.

Unfortunately, there is significant discrepancy in reported values of the accommodation coefficient. For water alone the values have varied by two to three orders of magnitude depending on the researcher or the method used to determine this coefficient. An indication of why there is such a large discrepancy in the mass accommodation coefficient can be inferred from experiment details described by Cammenga et al. [30] and reiterated in Marek and Straub [31]. An evaporation coefficient of 0.002 was found for water in a glass vessel, but when the glass vessel was replaced with a copper vessel the evaporation coefficients increased two orders of magnitude to values between 0.25 and 0.38. With the exception of the vessel wall material, both experiments were conducted in the same apparatus. Thus, the reported values of the accommodation coefficient do not reflect the local conditions nor the non-uniform evaporation that occurs due to the presence of a contact line.

To solve for the mass flux undergoing phase change the temperature in the liquid phase is required. The liquid temperature depends on the adjacent solid surface temperature. Liquid and solid temperature profiles can be obtained from a conjugate heat transfer model that incorporates representative boundary conditions of the system under observation. For this research, a computational thermal model of the test cell and sample well developed in ANSYS/Fluent is used to obtain the temperature profile on the interior solid surface of the test cell. The liquid temperature profile is obtained through integration of a lubrication

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