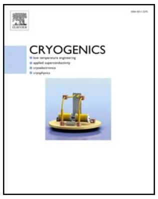
Cryogenics 91 (2018) 103–111

Contents lists available at ScienceDirect

Cryogenics

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



Determining solid-fluid interface temperature distribution during phase change of cryogenic propellants using transient thermal modeling

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ARTICLE INFO

Keywords:
Cryostat
Transient thermal model
Contact resistance
Wall temperature distribution
Contact line evaporation

ABSTRACT

Control of boil-off of cryogenic propellants is a continuing technical challenge for long duration space missions. Predicting phase change rates of cryogenic liquids requires an accurate estimation of solid-fluid interface temperature distributions in regions where a contact line or a thin liquid film exists. This paper described a methodology to predict inner wall temperature gradients with and without evaporation using discrete temperature measurements on the outer wall of a container. Phase change experiments with liquid hydrogen and methane in cylindrical test cells of various materials and sizes were conducted at the Neutron Imaging Facility at the National Institute of Standards and Technology. Two types of tests were conducted. The first type of testing involved thermal cycling of an evacuated cell (dry) and the second involved controlled phase change with cryogenic liquids (wet). During both types of tests, temperatures were measured using Si-diode sensors mounted on the exterior surface of the test cells. Heat is transferred to the test cell by conduction through a helium exchange gas and through the cryostat sample holder. Thermal conduction through the sample holder is shown to be the dominant mode with the rate of heat transfer limited by six independent contact resistances. An iterative methodology is employed to determine contact resistances between the various components of the cryostat stick insert, test cell and lid using the dry test data. After the contact resistances are established, inner wall temperature distributions during wet tests are calculated.

1. Introduction

One of the limiting factors in long duration space missions is the ability to maintain propellant storage depots. Computational Fluid Dynamics (CFD) along with a lumped parameter treatment of the vapor has been used to study pressurization in cryogen tanks and these have shown that a thin (≈1 mm) liquid layer separating the vapor phase from the wall is obtained [1–4]. Propellants exist as liquid-vapor mixtures that constantly undergo phase change. Liquid-vapor phase change is a complex, multi-scale problem and kinetic theory has provided the framework for modeling evaporation/condensation for over a century. Classical kinetic theory is a statistical description of the behavior of gases based on velocities of the constituent molecules. Although kinetic models have shown to be very effective in capturing phase change, the use of the models is still limited due to the fact that kinetic theory only describes the maximum phase change flux possible for a given thermodynamic situation [5]. In reality, the phase change flux may be lower than the maximum value depending on the molecular species under consideration [6]. Evaporation and condensation coefficients were introduced by Knudsen [7] in order to account for the deviation from the maximum phase change rate. Evaporation and condensation coefficients are often set equal to each other and referred to as the accommodation coefficient. CFD modeling of propellant behavior utilizes the accommodation coefficient as an input to capture phase change [1,8,9]. This is particularly challenging due to the lack of available evaporation/condensation coefficients and the inability to sufficiently resolve local thermodynamics at the liquid-vapor interface [10–13]. These coefficients must be determined experimentally [14].

At an evaporating or condensing meniscus, the normal stress in the bulk liquid is primarily influenced by interface curvature. Far from the meniscus, the adsorbed region consists of a nanoscale, non-evaporating layer of liquid molecules where intermolecular forces dominate. Between these two exists a transition film region in which the normal stress is affected by both intermolecular forces and interface curvature. For non-polar/wetting liquids, 60–90% of the evaporation occurs in the thin film region close to the wall [15–21].

Most thin film evaporation models use a constant wall temperature condition in the transition film region [16,18–20,22–27]. However, due

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https://doi.org/10.1016/j.cryogenics.2018.02.009
Received 12 July 2017; Received in revised form 26 January 2018; Accepted 27 February 2018

to non-uniform evaporation there exists temperature gradients along the wall near the transition region as demonstrated by Stephan and Busse [28]. The non-uniform wall temperature can generate thermocapillary stresses at the interface, which in turn affects the local normal stress in the liquid and subsequently the evaporation rate. In order to accurately capture the thermophysics of evaporation at a contact line, thermal boundary conditions should be representative of local temperature distributions along the solid-liquid interface. Accounting for the non-uniform wall temperature is a key factor to accurately model phase change and ultimately calculate the evaporation and condensation coefficients. Details of calculation of evaporation and condensation coefficients using kinetic theory are described elsewhere [12].

This paper represents one piece of the overall methodology; a thermal model that serves to bridge the macroscale experiment observations with the micro-scale phase change modeling. The goal of this thermal model is (1) determine the rate and mode of heat transfer to the cryogenic liquid in the test cell and (2) translate discrete exterior surface temperature measurements to an interior wall temperature distribution suitable for use in the microscale transport model.

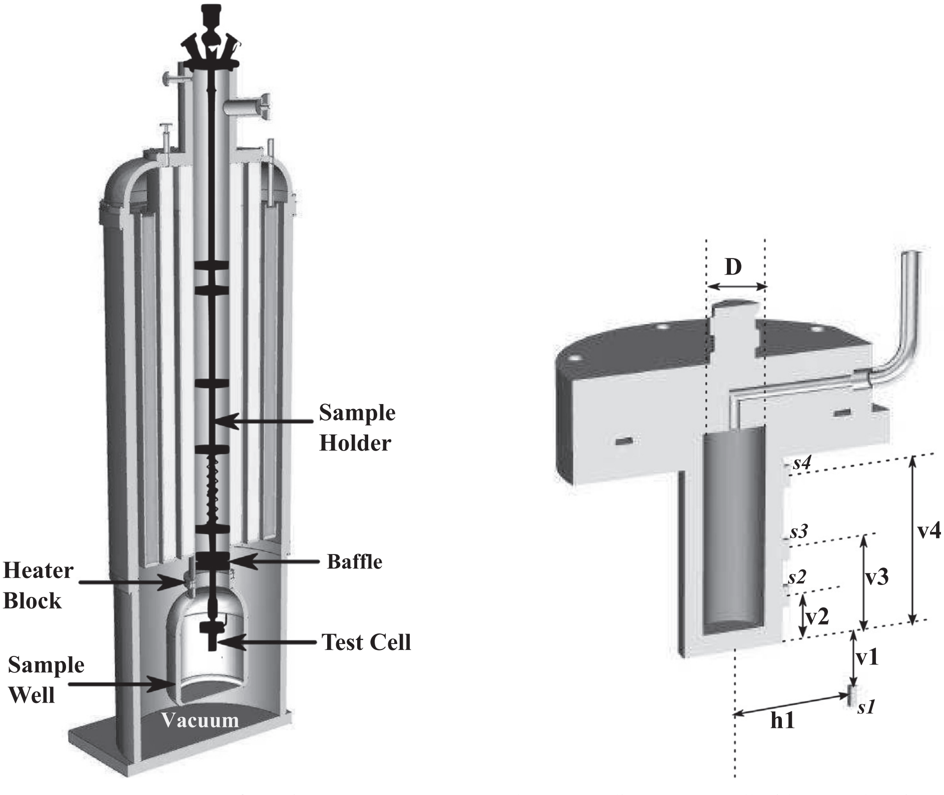
2. Cryogenic phase-change experiments

Cryogenic phase change experiments with hydrogen and methane were conducted, using a 70-mm-cryostat at the Neutron Imaging Facility at the National Institute of Standards and Technology (NIST). The experiments were conducted at absolute pressures between 100 and 210 kPa, corresponding to saturation temperatures between 15 K and 30 K for hydrogen and 100–120 K for methane.

Fig. 1(a) illustrates the components of the cryostat. Test cells are suspended in a sample well, below the cryostat using a 720-mm-long sample holder. The test cell is mounted to the bottom of the sample holder via a flange that includes a gas exchange port to allow hydrogen or methane vapor to be introduced into the test cell. The flange is attached to the test cell using an indium seal and secured in place with six screws. The sample holder is sealed at the top of the cryostat with ports for sensor leads and a cryogen vapor feed line. Radiation baffles on the sample holder minimize heat transfer from the top of the cryostat. The temperature in the sample well is controlled using a combination of an electric heater and liquid helium phase change passing through an expansion valve. Helium boiling occurs continuously and the heater is used to maintain sample well temperatures above the helium boiling point.

The cryostat heater is attached to a copper annulus that is in contact with the bottom radiation baffle. The heat path from the copper block to the test cell is through the bottom radiation baffle, sample holder, and flange. Low pressure helium gas introduced into the sample well provides a parallel conduction path between the heater block and the test cell. The annular contact between the copper heater block and the bottom radiation baffle is approximately 1 mm wide. The lower radiation baffles are spring loaded to allow for the test cell position to be adjusted within the sample well. As a result, the contact resistance between the lower radiation baffle and the copper heater block changes with each test configuration.

Fig. 1(b) illustrates one of the test cells that has a 10-mm-diameter bore. Four Lakeshore silicon diode DT-670 sensors were used to record temperature at various locations. One sensor (s1) was suspended in the helium exchange gas approximately 1 cm from the test cell wall. The remaining three sensors (s2–s4) were mounted on the external surface of the test cell. The sensors were secured to the outside of the test cell using 316 SS wire with spring-wire tensioners. The temperatures sensors were connected to a Lakeshore 340 temperature controller. The lower flange mount on the sample holder houses a fifth Si-diode temperature sensor (Scientific Instruments SI-410b). The copper heater block contains an NTC RTD X45720 sensor hereby referred to as the ‘heater sensor’. The heater and the sample holder sensors were connected to a Lakeshore 331 temperature controller. The heater



(a) Cryostat configuration

(b) 10-mm diameter test cell with sensor location

Fig. 1. Hardware configuration for cryogenic phase change experiments. (a) Cryostat with test cell suspended in sample well. (b) Illustration of the 10-mm diameter test cell. s1, s2, s3, and s4 are the temperature sensors. The location of each (v1, v2, v3, v4) are relative to the bottom exterior surface of the test cell.