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**EFFECT OF ICE CONTAMINATION OF LIQUID-NITROGEN
DROPS IN FILM BOILING**

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TECHNICAL PAPER to be presented at the
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ABSTRACT

Previously reported vaporization time data of liquid nitrogen drops in film boiling on a flat plate are about 30 percent shorter than predicted from standard laminar film boiling theory. This theory, however, had been found to successfully correlate the data for conventional fluids such as water, ethanol, benzene, or carbon tetrachloride. This paper presents experimental evidence that some of the discrepancy for cryogenic fluids results from ice contamination due to condensation. The data indicate a fairly linear decrease in droplet evaporation time with the diameter of the ice crystal residue. After correcting the raw data for ice contamination along with convection, a comparison of theory with experiment shows good agreement.

INTRODUCTION

Leidenfrost film boiling data of discrete masses of a cryogenic fluid were first reported by Keshock and Bell (ref. 1 and 2). They attempted to correlate their cryogenic data using the equations developed in reference 3 from standard laminar film boiling theory. This theory had been found to successfully correlate data for conventional fluids such as water,

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ethanol, benzene, or carbon tetrachloride. However, Keshock and Bell found the measured drop vaporization times were as much as 30 percent shorter than predicted by the equations developed in reference 3, even after the contributions of heat transfer by radiation and free convection to the droplet's upper surface were considered. To account for this discrepancy, the effect of ice contamination and mass transfer from the upper surface of the drop were experimentally investigated in the present paper. In particular, ice formation in the drop from contamination was found to significantly affect the vaporization times of liquid nitrogen drops.

INITIAL EXPERIMENTS

Keshock and Bell (ref. 2) suggested that the difference between theory and experiment, particularly at large drop volumes, results from vapor break through beneath the drop, similar to that observed with pool film boiling. Later, Baumeister, Keshock and Pucci (ref. 4) used this hypothesis to develop a correlation based on a heat transfer coefficient which shifted from a droplet coefficient to a pool boiling coefficient when the drop volume was sufficiently large so that vapor break through occurred. This technique produces some improvement between theory and experiment for large nitrogen drops (see ref. 4, fig. 1); however, the measured evaporation times were still lower than those predicted by theory.

As part of this paper, a 5 cm diameter nitrogen cooled shield was placed above the tops of the drops (within 0.5 cm) to reduce (eliminate) radiation, convection and mass transfer from the upper drop surface, much the same as a nitrogen shield used in dewars for storage and transport of liquid hydrogen or helium. For liquid nitrogen drops on

a plate at 20° C, no significant change in the total vaporization times were seen, in comparison to the vaporization times without the shield. However, in special cases where radiation and convection could be important (moving drop) Keshock and Bell report (ref. 1) that even after correction for radiation and free convection are made, the experimental results are still substantially lower than theoretical predictions.

During these initial experiments, a problem was encountered with the absorption of water into the drop and the formation of a slight ice residue. Keshock, in his very exacting work (ref. 4), dehumidified the droplet environment with dessicants and still had problems with ice contamination in the droplets. There was therefore, the possibility that previous data taken for film boiling studies of nitrogen were effected by contamination. The experiments performed herein assess the magnitude of this effect on the vaporization times.

EXPERIMENTAL APPARATUS AND PROCEDURE

Leidenfrost boiling of drops was performed on a flat stainless steel plate (slightly concaved at center to prevent drop motion) and on a vertically mounted aluminum wheel (ref. 5) which could be spun to simulate the effect of drop velocity on Leidenfrost boiling. Thermocouples were used to monitor the surface temperature. The nitrogen was delivered by use of two metal cups with insulated handles to reduce heat loss. The cups were calibrated by a weighing procedure with distilled water (see ref. 6).

The diffusive and convection effects by different cover gases appear to be quite small (ref. 7). The initial experiments indicated that the vaporization times of liquid nitrogen drops in air agreed with Keshock's data (ref. 1) for a dry nitrogen atmosphere. Because of these observations, liquid nitrogen drop behavior was investigated in an ambient air

atmosphere since this would simplify the procedures and equipment requirements and allow close observation of the evaporation process. The nitrogen was simply delivered to the heat transfer surface using the delivery cup and a timer was started. Extreme care was taken to prevent drop fragmentation during delivery.

During these experiments, the size of the ice residue increased with subsequent data runs. However, when a new container of nitrogen was obtained, the ice residue size abruptly dropped. Careful observation of the liquid nitrogen handling and storage equipment indicated a possible source of the contamination was from frost formation on the storage flash spout and much of the handling equipment. By air drying all apparatus and cleaning the equipment periodically during an experiment, the amount of ice crystal impurity present could be held at a nearly constant low value but could not be completely eliminated. Some of the contamination was apparently coming from storage and possibly the manufacturing process itself.

To investigate the effect of ice contamination on evaporation time, frost was deliberately introduced into storage containers of nitrogen which were used in an experiment. In the following experiments, all the parameters were held constant except the contamination volume. To measure the residue ice volume, a micrometer was placed above the flat plate approximately $3/8$ inch above the droplet. Since the ice mass remaining did not melt for several seconds after the vapor film collapsed, there was time to measure (estimate) the diameter with the micrometer. The total vaporization time could then be related to the diameter of the ice residue, see figure 1. Next, earlier experiments were repeated taking care to measure the diameter of the ice residue.

RESULTS

The data indicated a fairly linear decrease in evaporation time with diameter of the ice residue over the range where the residue appears to be fairly spherical, as shown in figure 1. Next, the measured evaporation times of the earlier experiments were corrected for ice contamination using a linear least squares data fit. The complete procedure for correcting the raw data to account for ice formation is given in Appendix C of ref. 6. A comparison of the theory to the corrected vaporization times are shown in figure 2. The data were also corrected for free convection using the Keshock and Bell procedure (refs. 1 and 2). The data fall into the extended drop range shown in table I.

The theoretical relationship for the vaporization time, shown in figure 2, was developed in ref. 8 by first solving the Laplace capillary equation for the drop thickness and radius as a function of volume. A closed form analytical solution did not exist over the complete range of drop volume; however, by asymptotic approximations, closed form solutions were developed for three separate volume ranges - small, intermediate, large. Next, these solutions for drop shape were combined with the simultaneous solution of the continuity, momentum, and energy equations in the laminar vapor layer beneath the drop to obtain the heat transfer coefficient between the supporting plate and the drop. Finally, a time dependent energy balance on the droplet lead to expression for the total vaporization time of the drops. Because the drop shape was broken into three separate ranges, three separate solutions for the vaporization time are required. These final expressions are shown in table I.

As seen in figure 2, good agreement exists between experiment and theory. The correction for ice formation and convection is approximately

20 percent over a range of drop velocities of 0 to 3.7 m/sec. For larger drop volumes, the correction can be expected to be even larger, as pointed out in reference 2.

CONCLUSIONS

When convection, bubble break through, and ice contamination corrections are applied to vaporization time data of cryogenic nitrogen drops in Leidenfrost boiling, predictions of the drop vaporization times based on standard laminar film boiling theory are in reasonable agreement with experiment.

NOTATION

$B_{1,2}$	constants, see table I
C_p	specific heat at constant pressure of vapor
F	dimensionless function, defined in table I
g	coefficient of gravity
g_c	gravitational constant (conversion constant between mass and force units)
k	thermal conductivity of vapor beneath drop
l	average drop thickness, defined table I
l^*	dimensionless average drop thickness, see table I
P_r	Prandtl number of vapor, $C_p \mu/k$
ΔT	temperature difference, $T_w - T_s$
T_w	wall temperature
T_s	saturation temperature
t	time
t^*	dimensionless time, defined in table I
U	velocity of plate relative to drop
V	volume of drop




V^*	dimensionless volume of drop, see table I
Γ	see table I for definition
λ	latent heat of vaporization
λ^*	modified heat of vaporization $\lambda^* = \lambda \left(1 + \frac{7 C_p \Delta T}{20 \lambda} \right)^{-3}$
μ	viscosity of vapor
ρ_g	vapor density
ρ_L	liquid density
Φ	latent to sensible heat ratio, $\lambda^*/C_p \Delta T$

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TABLE I. - SUMMARY TABLE FOR MOVING DROP RESULTS

Volume range, $V^* = \frac{V}{\left(\frac{\rho_{Gc}}{\rho_L g}\right)^{3/2}}$	Drop shape	Drop thickness, $z^* = \frac{z}{\left(\frac{\sigma_{Gc}}{\rho_L g}\right)^{1/2}}$	Vaporization time, $t^* = \frac{t}{\left(\frac{\lambda^4 \rho_L^{3/2} \sigma^{5/2} g^{5/2} \mu}{k^3 \lambda^* g^{7/2} (\rho_L - \rho_G) \rho_G \Delta T^3}\right)^{1/4}}$	Pseudo velocity dependent volume, V^+
$V^* \lesssim 0.8$	Small spheroid 	$z^* = 0.83 V^{*1/3}$	$t^* = 1.21 V^{*5/12}$	$V^+ = V^* \Gamma\left(\frac{V^*}{2}\right)^{12/5}$
$0.8 < V^* \lesssim 155$	Large drop 	$z^* = 0.8 V^{*1/6}$	$t^* = 2.23 V^{*1/3} - 0.97$	$V^+ = V^* \left[\Gamma\left(\frac{V^* + 0.8}{2}\right) + \frac{B_1}{2.23 V^{*1/3}} \right]^3$
$V^* > 155$	Extended drop 	$z^* = 1.85$	$t^* = 4.52 V^{*1/4} - 5$	$V^+ = V^* \left(\Gamma(V) + \frac{B_2}{4.52 V^{*1/4}} \right)^4$

Constants resulting from integration

$$\Gamma = \left[\left(1 + \frac{2.56 P_r \Phi U^{0.8}}{\left[4 \left(\frac{\rho_L}{\rho_G} - 1 \right) g z \right]^{-4}} \right)^{1/2} - \frac{1.6 (P_r \Phi)^{1/2} U^{0.4}}{\left[4 \left(\frac{\rho_L}{\rho_G} - 1 \right) g z \right]^2} \right]^{1/2}$$

$$B_1 = -2.07 \Gamma\left(\frac{V^* + 0.8}{2}\right) + 1.1 \Gamma(0.4) + 0.97$$

$$B_2 = -16 \Gamma(V) + 9.9 \Gamma(77.9) + 1.1 \Gamma(0.4) + 5$$

$\Gamma\left(\frac{V^*}{2}\right)$ means Γ evaluated at V^* equal to $\frac{V^*}{2}$
 $\Gamma\left(\frac{V^* + 0.8}{2}\right)$ means Γ evaluated at V^* equal to $\frac{V^* + 0.8}{2}$
 $\Gamma(0.4)$ and $\Gamma(77.9)$ means Γ evaluated at V^* equals 0.4 and 77.9 respectively

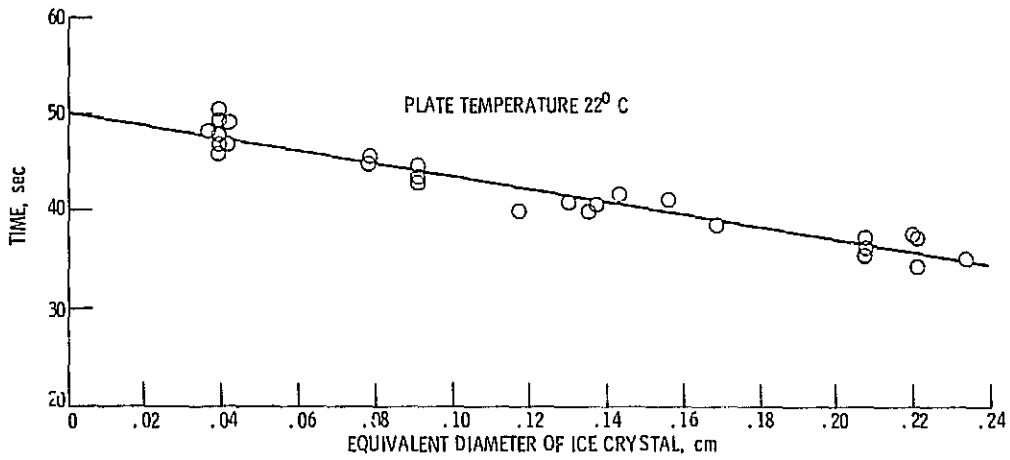


Figure 1. - Effect of ice crystal contamination on evaporation time of 0.47 ml stationary nitrogen droplets on a flat plate.

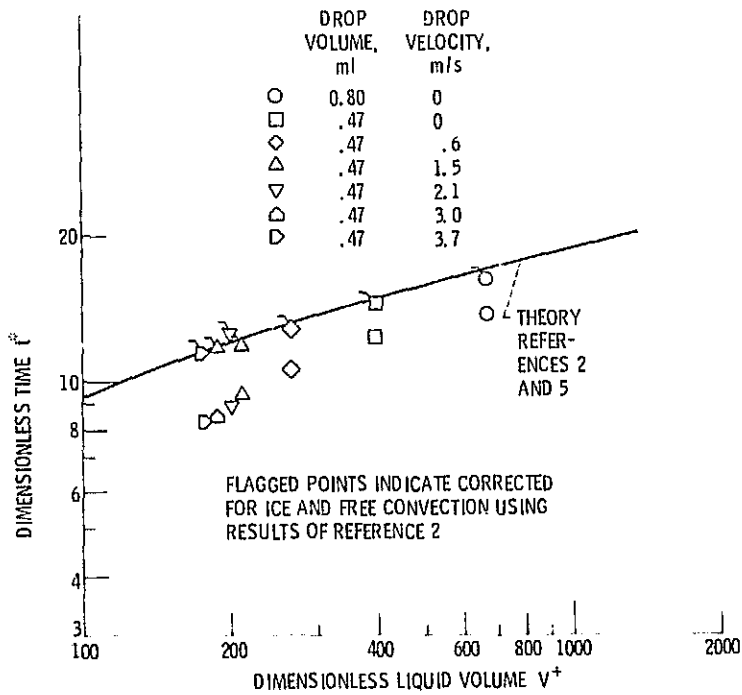


Figure 2. - Dimensionless total vaporization correlation of nitrogen data with ice and free convection corrections.