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BOILING OF LIQUID NITROGEN AND METHANE ON WATER. THE EFFECT OF INITIAL WATER TEMPERATURE

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DRAKE *et al.* [1] recently reported the rates of vaporization of liquefied cryogens spilled on a water surface. Primary emphasis was placed on the determination of boiling rates. Vapor temperatures were also monitored but few measurements were made in the bulk water. Mapping of liquid water temperatures must, however, be carried out before realistic heat-transfer models can be developed.

The purpose of the present note is, therefore, to report the results of additional boiling studies that were carried out in a vessel equipped to measure the temperature–time history at a number of locations in the bulk water phase.

The apparatus employed was similar to that described in [1] and consisted of an insulated container about 10 cm in diameter. The major change, as noted above, was the deployment of six fast-response thermocouples in the water. As before, one was placed so that it was close to the cryogen–water interface. The thermocouple locations were varied to sample a number of sites. The spill procedure was identical to that described in [1]; however, the data were recorded with a NOVA 840 real-time computer so rapid sampling ($10\,s^{-1}$) could be achieved. Values averaged over a 1-s period were recorded.

Boil-off rates were also determined and these agreed well with those reported previously [1]. Also, as noted in this earlier study, nitrogen vapor was significantly superheated whereas, for liquid methane, boil-off vapors were close to the expected saturation temperatures. Quantitative data are given elsewhere [2].

Of more interest here are the liquid water temperatures. For spills of both liquid nitrogen and liquid methane, it was verified that the vaporization rates were independent of initial water temperature—at least over the range of 6–42°C studied here. However, there was a significant difference in the pattern of water temperatures depending upon whether the water, initially, was warm or cool.

In experiments where the initial water temperature was below 20°C, coherent ice formed almost immediately on the surface and water temperatures beneath this sheet changed but little during a test. In Fig. 1, we show temperature–time traces for the six thermocouples during a spill of liquid nitrogen on 6.6°C water. There is a significant drop in temperature for the thermocouple 0.4 cm below the interface but at all other locations little variation is noted. An energy balance for this run indicated that the ice layer thickness at the end of the test was greater than 0.5 cm.

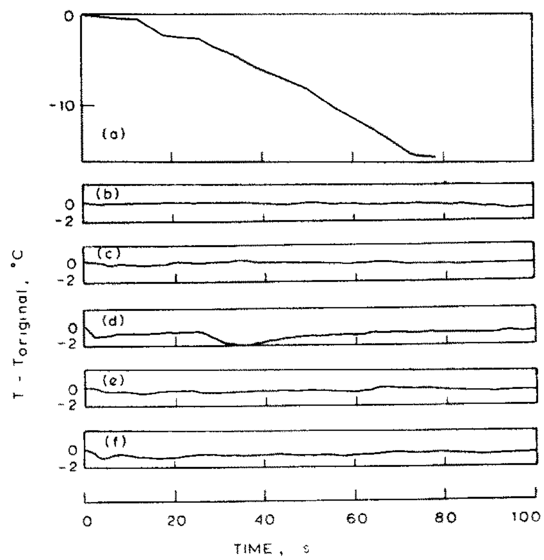

FIG. 1. Water temperatures after a spill of liquid nitrogen on 6.6°C water. 0.94 g/cm² of nitrogen was spilled. Thermocouple locations measured below the interface were as follows: (a) 0.4 cm, center; (b) 5.5 cm, center; (c) 3.2 cm, center; (d) 1.4 cm, side; (e) 3.5 cm, side; (f) 4.2 cm, side.

If the initial water temperature exceeded about 25°C, surface ice formed, but quite slowly. The water temperature in all locations decreased almost uniformly, although the largest decrease always occurred in the immediate vicinity of the interface. In Fig. 2, temperature–time traces are shown for a liquid nitrogen spill on 42.5°C water. For the tests shown in Figs. 1 and 2, the amount of liquid nitrogen spilled was the same and the boil-off rates were virtually identical. Similar water temperature observations were noted in other experiments with both liquid nitrogen and liquid methane.

From these experiments it is concluded that if the initial water temperature is low, heat transfer to the cryogen occurs through a growing ice shield with little effect on the underlying water. On the other hand, if the water is initially warm, ice forms more slowly and cool surface water convectively

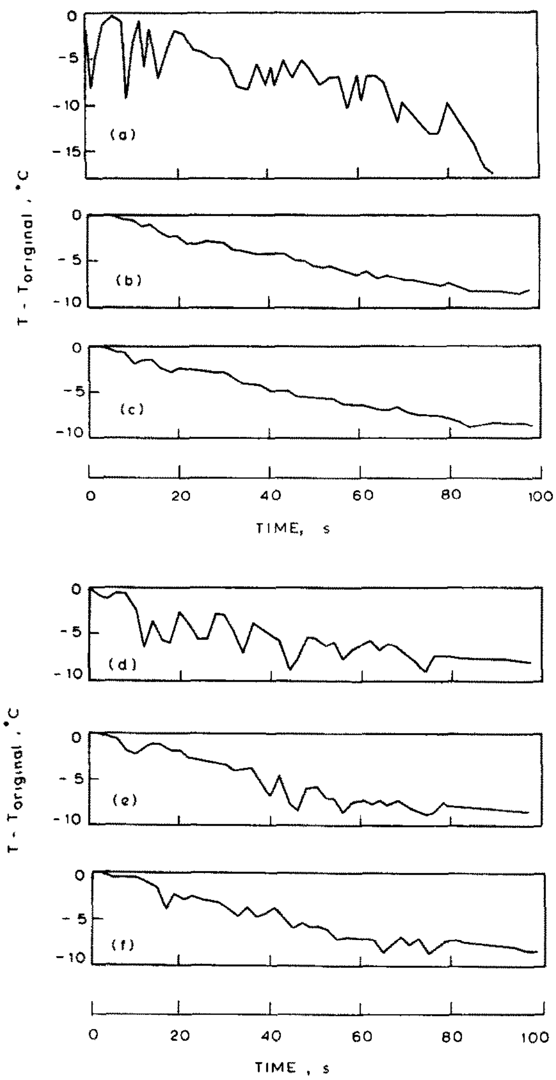

FIG. 2. Water temperatures after a spill of liquid nitrogen on 42.5°C water. 0.95 g/cm² of nitrogen was spilled. Thermocouple locations measured below the interface were as follows: (a) 0.3 cm, center; (b) 5.4 cm, center; (c) 3.1 cm, center; (d) 1.3 cm, side; (e) 3.4 cm, side; (f) 4.1 cm, side.

descends and mixes surprisingly thoroughly with the bulk—at least to depths of 6–6.5 cm as employed in these tests. The fluctuations noted in Fig. 2 attest to these thermals.

Although the energy transfer process in the water phase appears to depend upon the initial water temperature, the actual boil-off rate of cryogen is not affected. These findings cast some doubt on earlier theories [1, 3] which postulate that, for liquid methane, the boil-off increases with time due to ice formation which encourages a change in the boiling regime from film (on liquid water) to nucleate (on surface ice).

It is now established [1] that the boiling rate of liquid nitrogen on water decreases with time whereas, as noted above, for liquid methane the rate increases. But, the experiments reported herein indicate that there is no significant difference in the temperature response of the water between nitrogen and methane spills if the initial water temperatures are the same.

It is also interesting to note that even in the case of cool water with a growing ice film, it was not possible to correlate the heat transfer rate with theory using a conduction model with a moving ice boundary. The conduction model overestimates the boil-off rate and also predicts a time dependence different from that observed experimentally.

In general, the mechanism by which the water phase supplies energy to evaporate the cryogen is dependent on initial water temperature. At higher temperatures, the energy is supplied primarily by convection and homogeneous cooling of water. For low water temperatures, most of the energy is supplied by the heat of formation of ice. However, the change in the mechanism of heat transfer in the water phase was not found to affect the transient boiling rate for either liquid methane or nitrogen on water. These conclusions pertain only to early transient boiling phenomena—during about the first 100 s—after a spill. At longer times than those studied, ice buildup would be expected to limit and decrease boiling rates.

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LAMINAR HYPERSONIC BOUNDARY-LAYER FLOW AT A THREE-DIMENSIONAL STAGNATION POINT WITH SLIP AND MASS TRANSFER

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NOMENCLATURE

a, b, velocity gradients in x and y directions respectively;

c, ratio of velocity gradients, b/a;

C_{fx}, C_{fy}, skin-friction coefficients along x and y directions respectively;

f, F, dimensionless stream functions such that $f' = u/u_e$ and $F' = v/v_e$;

f_w, mass-transfer parameter, $-(\rho w)_w/(\rho_e \mu_e a)^{1/2}$;

g, dimensionless enthalpy, h/h_e;

g_w, cooling parameter for the wall, h_w/h_e;

$g(0)$, cooling parameter for the gas defined by (2c);