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SOME EFFECTS OF BOILING ON HYDRODYNAMIC DRAG

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Abstract—Experiments at velocities up to 20 ft/s on a hemisphere–cylinder model heated to high temperature demonstrate a large reduction in friction drag. The drag reduction is due to formation of a stable vapor layer at the solid surface by film boiling of the liquid. An analysis of the phenomenon predicts the effect of surface temperature and water temperature on the drag reduction. Comparative measurements for nucleate boiling, subliming, and non-wetting surfaces are presented.

NOMENCLATURE

C_f, local friction coefficient defined by equation (26);
c_p, specific heat at constant pressure; without subscript refers to vapor layer;
D, function of β_0 defined by equation (21);
F, function of β_0 defined by equation (17);
G, function of β_0 defined by equation (25);
h, $q_w/(t_w - t_i)$;
k, thermal conductivity;
Nu_x, Nusselt's number (based on vapor-layer properties) $Nu_x = hx/k$;
Pr, Prandtl number $Pr = c_p\mu/k$;
q, local heat flux, Btu/h ft²;
R_v, vaporization Reynolds number $v\delta_v/u$;
R_x, flow Reynolds number $u_s x/u_l$;
t_l^*, liquid-layer reference temperature $t_l^* = (t_i + t_s)/2$;
t_v^*, vapor-layer reference temperature $t_v^* = t_w + t_i/2$;
u, velocity in x-direction;
u_i/u_l, slip-velocity ratio;
v, velocity in y-direction;
x, distance downstream from vapor-layer origin parallel to heated surface;
y, direction perpendicular to heated surface.

Greek symbols

β_0, vaporization parameter $c_p(t_w - t_i)/\lambda$;
β_{0_l}, subcooling parameter $c_{p_l}(t_s - t_i)/\lambda$;
δ, over-all velocity boundary-layer thickness ($\delta = \delta_v + \delta_l$);
δ_l, liquid velocity boundary-layer thickness;
δ_t, liquid thermal boundary-layer thickness;
δ_T, over-all thermal boundary-layer thickness ($\delta = \delta_v + \delta_t$);
δ_v, vapor-layer thickness;
δ_L, thickness of liquid boundary layer with *no* boiling;
θ, dimensionless dependent variable $\theta = t - t_w)/(t_s - t_w)$;
λ, latent heat of vaporization, Btu/lb;
μ, viscosity;
ν, kinematic viscosity μ/ρ;
ξ, dimensionless independent variable y/δ;
ξ', dimensionless independent variable y/δ_T;
ρ, density.

Subscripts

i, conditions at interface;
l, bulk liquid, or liquid boundary layer with film boiling;
L, liquid boundary layer with no boiling;
s, conditions outside boundary layer ("stream" conditions);
t, liquid thermal boundary layer (see δ_t);
T, see δ_T;
v, vapor layer;
w, conditions at heated wall.

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INTRODUCTION

FORCED-CONVECTION film boiling is established when the temperature of the heating surface is sufficiently high relative to the liquid temperature that a stable vapor layer exists between the heating surface and the moving liquids. It would appear that, in such a situation, the vapor would serve as a lubricating sheet, serving to reduce drag, as well as an insulating blanket. The present investigation was intended to study the possibility of producing a stable, thin vapor layer at the surface of hydrodynamic bodies.

The vapor layers studied were produced in three ways: by film boiling, by sublimation of a solid surface, and by a heated, chemically reacting surface. The emphasis of the investigation was on film boiling.

The results show that there exists a thermodynamic region within which a stable vapor layer may be expected. Within this region, the anticipated friction-drag reduction occurred. The ultimate boundaries of the region remain to be established—probably by the inherent instabilities of the vapor layers produced. The instabilities referred to are primarily those which involve the transformation of a stable vapor layer into a hydrodynamic cavity and those which cause transition from film boiling to nucleate boiling.

THEORY

The theory proceeded from a postulated idealized film-boiling boundary layer. This is shown schematically in Fig. 1 for a hemisphere–cylinder in axial flow.

A stagnation-point flow is conceived to exist at the upstream origin of the vapor layer. Over the forepart of the body, the model consists of a laminar vapor layer (thick solid line) overlaid by laminar liquid velocity and thermal boundary layers. At a critical Reynolds number, transition to turbulence of the liquid layer with resulting "froth" flow occurs. The critical Reynolds number is based on liquid-layer properties and bulk-liquid velocity relative to the interface. The interface referred to separates the vapor boundary layer from the liquid boundary layer (Fig. 1). Motion pictures of the phenomenon show this interface to be clearly defined for stable laminar flow.

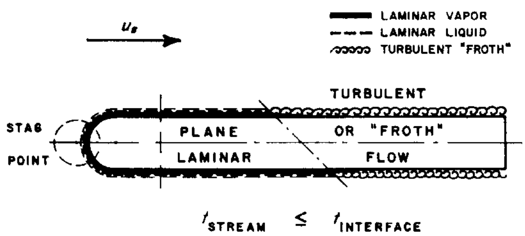


FIG. 1. Proposed physical model.

The present analysis was restricted to laminar axial flow on cylinders where the boundary-layer thickness is small relative to the cylinder radius. In other words, plane laminar subcooled flow was analyzed. The following simplifying assumptions are made:

(i) The flow is steady, two-dimensional, and laminar in both vapor and liquid boundary layers;
(ii) the pressure is everywhere constant;
(iii) the heated surface temperature (t_w) is constant;
(iv) the temperature of the liquid–vapor interface (t_i) is equal to the saturated liquid temperature at ambient pressure;
(v) thermodynamic and transport properties of the liquid and of the vapor are constant;
(vi) these properties are evaluated at a reference temperature defined by $t_v^* = (t_w + t_i)/2$ for the vapor and by $t_l^* = (t_i + t_s)/2$ for the liquid;
(vii) thermal-radiation effect on the vapor and liquid layers is neglected;
(viii) buoyancy effect on the forced-convection boundary layers is neglected.

The velocity and temperature profiles are assumed linear in the vapor layer and parabolic in the liquid layer. The integral method of solution due to Pohlhausen is applied (see, for example, [1]). An alternative approach to this problem is presented in [2].

Under these assumptions, the vapor-layer velocity profile is

$$U = \frac{u_i}{u_s}\frac{\delta}{\delta_v}\xi, \quad 0 \leq \xi \leq \frac{\delta_v}{\delta} \tag{1}$$

where $U = u/u_s$, u being the vapor velocity parallel to the surface and u_s the velocity of the stream relative to the surface. u_i is the interface velocity. The over-all velocity boundary-layer thickness is $\delta = \delta_v + \delta_l$ where δ_v is the vapor-layer thickness and δ_l is the liquid-layer thickness. ξ is the dimensionless independent variable $\xi = y/\delta$.

The liquid-layer velocity profile ($\delta_v \leq y \leq \delta$) is described by the cubic parabola

$$U = \left\{\frac{3}{2}\left[\frac{y-\delta_v}{\delta-\delta_v}\right] - \frac{1}{2}\left[\frac{y-\delta_v}{\delta-\delta_v}\right]^3\right\} \times \left[1 - \frac{u_i}{u_s}\right] + \frac{u_i}{u_s} \quad (2)$$

where the coefficients were determined by the boundary conditions:

at

$$y = \delta_v, \quad u = u_i,$$

$$y = \delta, \quad u = u_s, \quad \left.\frac{\partial u}{\partial y}\right|_{y=\delta} = 0. \quad (3)$$

The vapor-layer temperature profile will be given by

$$\theta = \frac{t_i - t_w}{t_s - t_w}\frac{\delta}{\delta_v}\frac{\delta_T}{\delta}\xi'; \quad 0 \leq \xi' \leq \frac{\delta_v}{\delta_T} \quad (4)$$

where t_w is the wall temperature. The over-all thermal boundary-layer thickness is $\delta_T = \delta_v + \delta_t$, δ_t being the liquid thermal boundary-layer thickness and $\xi' = y/\delta_T$.

The liquid thermal boundary-layer is described by a cubic parabola

$$\theta = \left\{\frac{3}{2}\left[\frac{y-\delta_v}{\delta_T-\delta_v}\right] - \frac{1}{2}\left[\frac{y-\delta_v}{\delta_T-\delta_v}\right]^3\right\} \times \left[\frac{t_s - t_i}{t_s - t_w}\right] + \left[\frac{t_i - t_w}{t_s - t_w}\right]. \quad (5)$$

Sample velocity and temperature profiles (calculated for the conditions of the experiment) are shown as Fig. 2. The interface location is marked by discontinuity of slope in the velocity and temperature profiles. Across the interface, of course, the phase transition occurs.

The analysis is straightforward mathematically and, in the interest of brevity, the following outline emphasized the physical aspects of the theory.

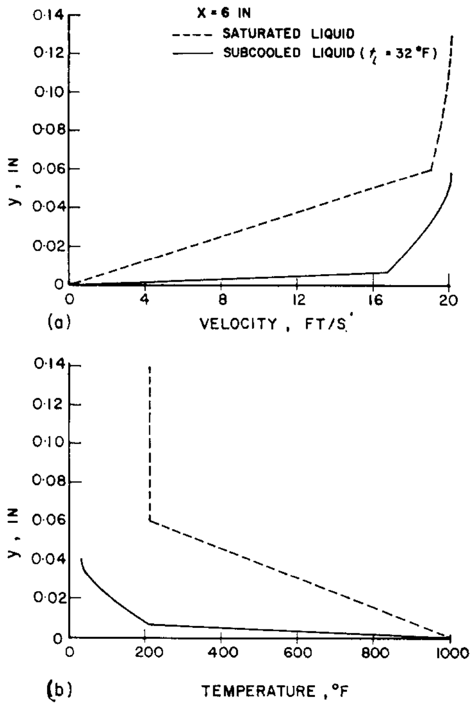


FIG. 2. Predicted effect of subcooling on velocity and temperature profiles.

In order to account for the latent heat of vaporization and the thermal transport between the two boundary layers, a heat and mass balance at the interface is required. This yields

$$[\rho v(i_l + \lambda) + q_l] - [\rho_l v_l i_l + q_v] = 0$$

where i_l is the enthalpy in the liquid layer at the interface. The heat conducted from the vapor to the interface and from the interface to liquid are represented by q_v and q_l respectively. It follows that

$$R_v = -\left[\frac{\beta_0}{Pr} + \frac{\beta_{0_l}}{Pr_l^{2/3}}\frac{u_i}{u_l}\right] \quad (6)$$

where

$$\frac{u_i}{u_l} = \frac{3}{2}\frac{\mu_\lambda}{\mu}\frac{\delta_v v}{\delta_l} \quad \text{and} \quad \frac{\delta_l}{\delta_t} = Pr_l^{1/3}.$$

The second term on the right-hand side of equation (6) shows the influence of subcooling. Here, R_v is the "vaporization Reynolds number" $v\delta_v/\nu$, ν being the vapor-layer kinematic viscosity.

β_0 is a vaporization parameter. The subscript l denotes quantities pertinent to the liquid layer. In the analysis leading to equation (6), radiation effects are neglected.

It is assumed that fluid elements at the interface are in dynamic equilibrium under the action of shear at the interface. This condition requires that

$$\frac{u_i}{u_l} = \frac{3}{2}\frac{\mu_l}{\mu}\frac{\delta_v}{\delta_l} \tag{7}$$

where u_l is the velocity of the stream relative to the interface and δ_l is the thickness of the liquid velocity boundary layer.

Assuming that the vapor-layer thickness increases slowly with x (Fig. 2), the liquid boundary layer develops along the interface as on a wedge of very small opening angle, and the variation of stream velocity is, therefore, neglected. The characteristic velocity, in this case, will be the velocity of the stream relative to the interface. It can be shown, for a laminar liquid layer, that

$$\frac{u_i}{u_l} = \left[\frac{1}{9{\cdot}4}\left(\frac{\mu_l}{\mu}\right)^2 \frac{\mu_l}{\nu_l}\frac{\delta_v^2}{x}\right]^{1/2} \tag{8}$$

continuity yields

$$\frac{d\delta_v}{dx} = -\frac{2v}{u_i}$$

where

$$-v = \frac{\nu}{\delta_v}\left[\frac{\beta_0}{Pr} \frac{\beta_{0_l}}{Pr_l^{2/3}}\frac{u_i}{u_l}\right]$$

from equation (6). Combining and integrating, we get

$$\frac{\delta_v^2}{x} = \frac{4\beta_0}{[u_i/\nu]Pr}\left[1 + \frac{\beta_{0_l}}{\beta_0}\frac{Pr}{Pr_l^{2/3}}\frac{u_i}{u_l}\right]. \tag{9}$$

Equations (8) and (9) together yield

$$\frac{u_i}{u_l} = \left\{\frac{1}{2{\cdot}35}\left[\frac{\mu_l}{\mu}\right]^2 \frac{\nu}{\nu_l}\frac{\beta_0}{Pr}\left[1 + \frac{\beta_{0_l}}{\beta_0}\frac{Pr}{Pr_l^{2/3}}\frac{u_i}{u_l}\right]\right\}^{1/3} \tag{10}$$

the "slip-velocity ratio", where

$$u_i + u_l = u_s. \tag{11}$$

The vapor-layer growth parameter $(\delta_v/x)(R_x)^{1/2}$ through equations (9–11) is expressible solely in terms of β_0 for parameters of β_{0_l}/β_0.

The vapor-layer velocity profile being given by equation (1)

$$\frac{u}{u_i} = y/\delta_v, \tag{12}$$

the surface viscous shear is simply

$$\tau_w = \mu \left.\frac{du}{dy}\right|_{y=0} = \mu\frac{u_i}{\delta_v}.$$

The ratio of frictional resistance coefficients is

$$\frac{C_f}{C_{f_L}} = \frac{2}{3}\frac{\mu}{\mu_l}\frac{\delta_L}{\delta_v}\frac{u_i}{u_s} \tag{13}$$

where $C_f = 2\tau_w/\rho_l u_s^2$ and δ_L is the thickness of the laminar liquid boundary layer with no boiling.

The heat-transfer coefficient will be defined

$$h = \frac{q_w}{t_w - t_i}$$

for convenience. By this definition, the expression for Nusselt number becomes

$$\frac{Nu_x}{R_x^{1/2}} = \frac{1}{(\delta_v/x)R_x^{1/2}}. \tag{14}$$

Thus, for this model of the flow, C_f/C_{f_L} and $Nu_x/R_x^{1/2}$ are expressible solely in terms of β_0 and β_{0_l} where $\beta_{0_l} = [C_{p_l}(t_s - t_i)]/\lambda$. These relationships calculated for water at 1 atm pressure are shown plotted on Fig. 3.

The predictions of the theory may be summarized with reference to Figs. 2 and 3. The theory predicts that skin friction will be drastically reduced by stable laminar film boiling. This is indicated qualitatively on the Fig. 2 velocity profiles by an effective "slippage" between the solid surface and the liquid. This slippage is essentially due to the large difference in viscosity between the vapor and liquid. The effect of subcooling is to reduce the vapor-layer thickness, thereby increasing the shear transmitted to the liquid. By this means, the slippage is reduced and the friction increased relative to that for a saturated liquid. Quantitative predictions are provided by Fig. 3. On Fig. 3 the effect of subcooling is shown to depend solely in the parameter $-\beta_{0_l}/\beta_0$. A corresponding effect on heat transfer is indicated by Figs. 2(b) and 3(b).

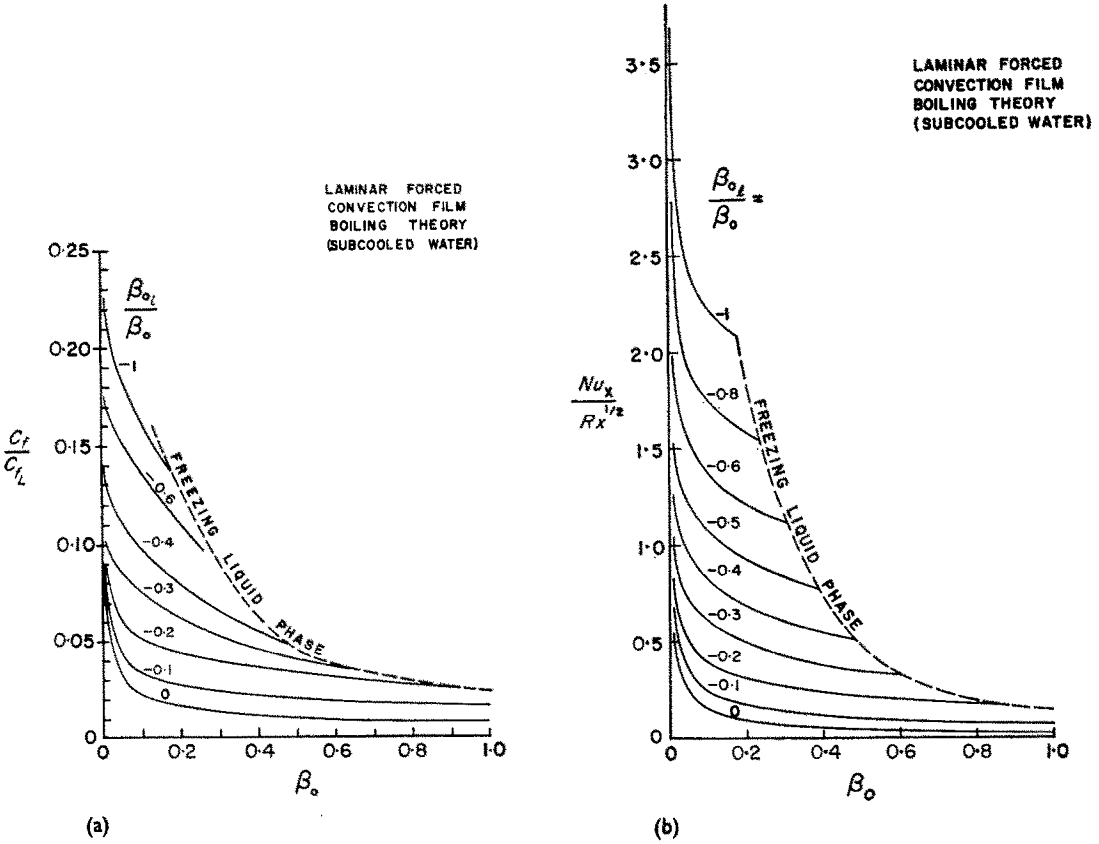


FIG. 3. Predicted effects of stable film boiling on friction drag and heat transfer.

EXPERIMENT

The forced-convection experimental investigation consisted of high-speed motion-picture observations and quantitative drag measurements. The high-speed motion pictures were made of models fabricated of dry ice, graphite, aluminum and Teflon, launched horizontally into water. The body shapes were hemisphere–cylinders. In addition to the results discussed here, heat-transfer studies in free and forced convection were made.

The temperature of the water could be raised from 60°F to saturation. Drag measurements were made by means of strain, base pressure, and accelerometer readings from the sting-mounted models. The output of these instruments as well as the thermocouples, velometer and position indicator were recorded on a multi-channel recording oscilloscope.

All film-boiling drag measurements were obtained from graphite hemisphere–cylinder models. The models were heated to approximately 2000°F before each run in an induction furnace in air. The models were then driven into the water through a weir-type gate. The carriage on which the models were mounted could be driven at constant acceleration to the desired predetermined velocity. For the data given here, accelerations never exceeded 0·2g. Corresponding virtual-mass effects were evaluated and found to be negligible. These runs were characterized by completely laminar flow; consequently, the model cooling rates did not exceed 20 degF/s.

The drag was determined as the sum: (axial-force reading) plus (model base drag) minus (model mass times acceleration). The accuracy of the balance and the base and acceleration corrections is 0·05, 0·004 and 0·02 lb, respectively, yielding an over-all estimated uncertainty of $\pm 0{\cdot}074$ lb.

Motion pictures were taken either at about 1500 or about 2300 frames/s depending on the nature of the experiment. All experiments were cai ied out at atmospheric pressure. Comparison of free- and forced-convection motion pictures indicadtethat relative motion between the heating surface and the liquid had a stabilizing effect on the interface at velocities up to about 20 ft/s. Transition to "froth flow" (Fig. 1) was observed for film-boiling models at speeds greater than 20 ft/s.

It was observed that systematic subcooling of liquid water greatly affected the vapor-layer stability. High-speed motion pictures showed the most stable vapor layers to occur with moderate subcooling. For temperatures near saturation the vapor–liquid interface was very "active" owing to the comparatively large rate of vapor generation and its tendency to "escape" from the surface. For intermediate subcooling temperature increments (from about 20–50 degF), a relatively stable interface was observed. As subcooling was increased further, "ripping" and "bumping" instabilities began to occur. These tendencies toward transition were presumed due to the thinning of the vapor layer in relation to the mean surface roughness.

The vapor-layer instabilities were dramatically illustrated by quenching experiments with solid graphite cylinders in subcooled water. For such experiments a "banging" instability occurred. In two instances this was of sufficient violence to destroy the glass quenching bath container. High-speed movies showed transition from a slick continuous film-boiling interface to violent nucleate boiling over the whole surface in less than 0·001 s. In several cases, multiple bangs were observed as film boiling re-established and the transition cycle repeated. In each case, a very thin layer of the cylinder surface was blown off almost uniformly. The cylinder was essentially undamaged and could be re-used, although the surface gradually roughened.

In Fig. 4 are shown sketches of the effect of subcooling on the interface configuration at 5 ft/s as observed from motion pictures. The water temperature was 200°F for Fig. 4(a) and 165°F for Fig. 4(b). The nose cap is cavitation-superimposed on the underlying vapor layer. This nose cap is not present under the same conditions for a source-shaped body.

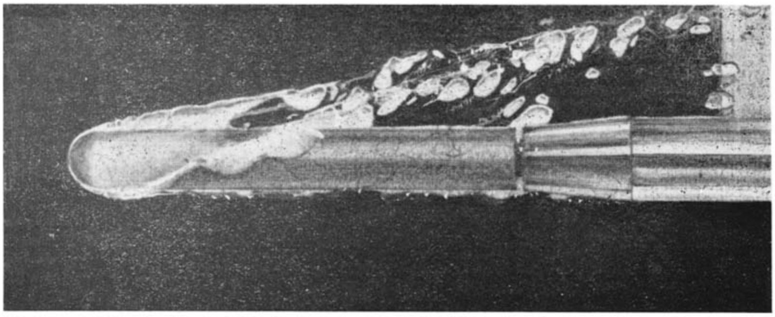
The effect of free convection on the nose-cap configuration in Fig. 4 is evident. A separate investigation of the relative contributions of free and forced convection indicated that approximately 80 per cent of the total heat loss was due to free convection at 15 ft/s with laminar flow and 15 degF subcooling.

Sketches were necessary for Fig. 4 owing to the loss in resolution which occurs when single-frame printing is attempted of 16 mm movies taken at about 2000 frames/s. However, the movies will be loaned upon request directed to the senior author.

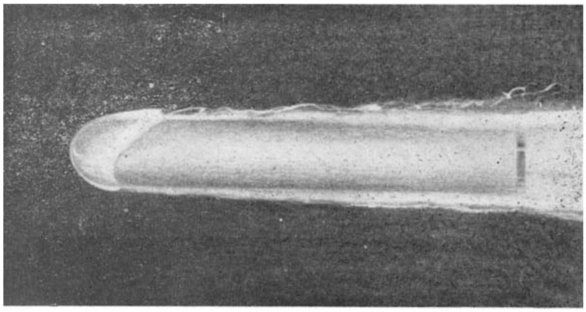
Results of drag measurements are shown on Figs. 5–7. Fig. 5 is a summary of skin-friction data taken from unheated bodies, i.e. with no vapor layer present. Shown for comparison with the flat plate theory are data from hemisphere–cylinder models of aluminum, Teflon and graphite. In each case, the model diameter was $1\frac{1}{2}$ in and the length was 12 in. The mean roughness of the aluminum and Teflon bodies is estimated at not more than 30 μin and that of the graphite at not less than 500 μin. The results indicate predominantly turbulent flow over the graphite surface. The non-wetting character of the unheated Teflon surface had no discernible effect on the friction drag, the data points intermingling with those from the aluminum model.

On Fig. 6, drag measurements with and without model heating are shown. The film-boiling data shown represent three different runs with water temperatures at 180°F and 193°F, within the subcooling range which gave the most stable vapor layers. Thus β_0 is roughly 0·6 and the corresponding value for β_{0l}/β_0 is $-$ 0·05. The results show that, within the accuracy of the measurements, the friction drag is eliminated. Comparison is made with the predicted film-boiling friction-drag values according to the theory.

Experiments were also made on hemisphere–cylinders with subliming surfaces. These models were machined from dry-ice blocks, and it was difficult to establish an exact shape. Neverthe-



(a)



(b)

FIG. 4. Observed effect of subcooling on vapor-layer configuration.

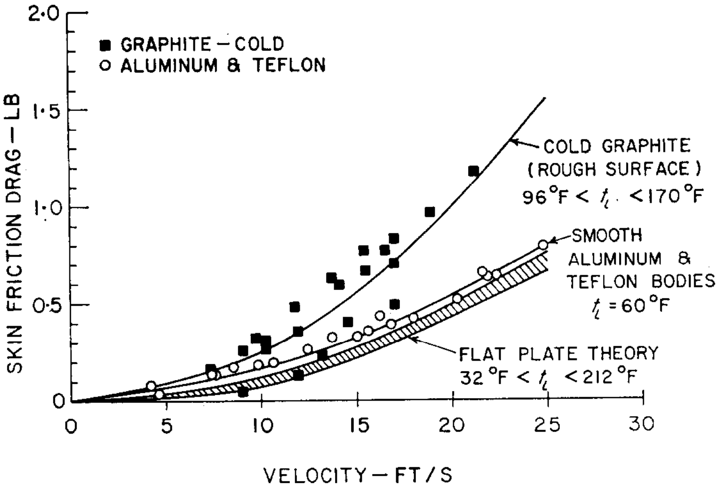


FIG. 5. Friction-drag data for unheated models.

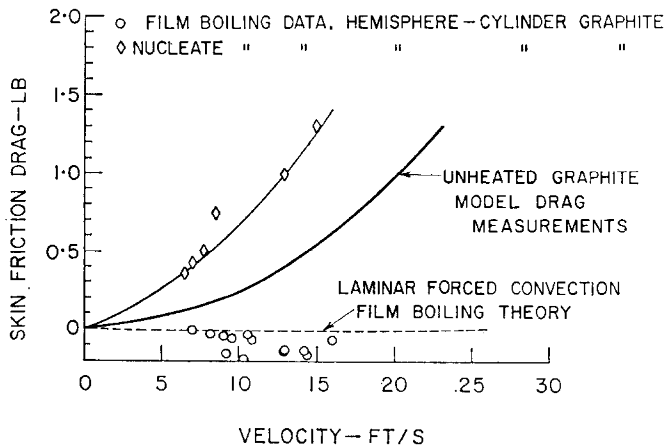


FIG. 6. Observed effects of boiling on friction drag.

less, motion picture and drag results of qualitative interest were obtained and will be reported. The motion pictures showed formation of a large, unruly, gas-filled cavity about the model nose which effectively changed the model shape. This phenomenon is due, it was concluded, to the extremely high rate of sublimation over the hemisphere. The shape of the nose changed from hemispheric to conical during these runs. The gas pocket collapsed downstream from the nose and the re-entering water gouged pockets out of the dry-ice cylinder. Under these circumstances, the large drags shown on Fig. 7 are not surprising. In order to produce a stable vapor layer by subliming, it would be necessary to vary the composition of the surface material in the direction of flow.

CONCLUSIONS

Producing a stable vapor layer between a hydrodynamic surface and the liquid drastically reduces friction drag. On the other hand, unstable two-phase flow (for example, nucleate boiling and uncontrolled sublimation) may cause large increases in drag.

The present experiments indicate the existence

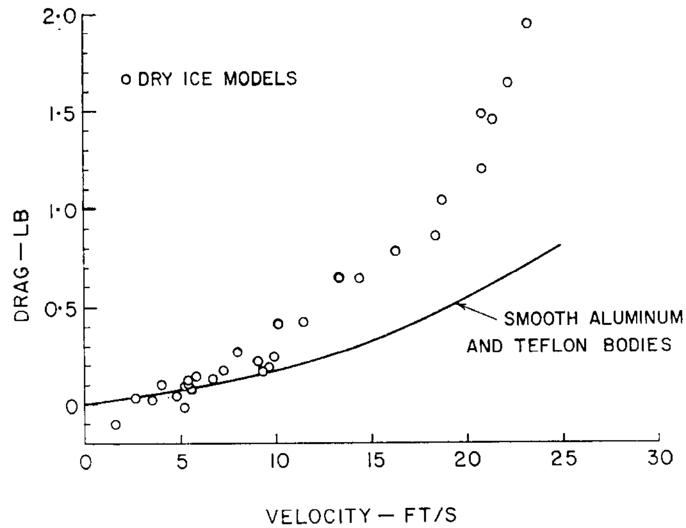


FIG. 7. Observed effect of surface sublimation on drag.

in forced convection of a thermodynamic region where a stable vapor layer exists. Herein, the momentum and heat exchanged between the body and the liquid are materially reduced without (it would appear) essentially changing the pressure distribution over the body. In this way the phenomenon seems fundamentally different from hydrodynamic cavitation. Experiments with vapor-layer generation and control, by combining suitable features of film boiling, and chemically reacting and subliming surfaces, should be undertaken. Bounds on the existence of the region are evidently established by subcooling, surface condition, hydrodynamic cavitation, and velocity. These bounds remain to be quantitatively established.

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Résumé—Des expériences faites avec une maquette sphéro-cylindrique chauffée à haute température ont mis en évidence, pour des vitesses allant jusqu'à 6 m/s, une grande diminution de la traînée. Celle-ci est due à la formation d'une couche de vapeur stable à la surface du solide lors de l'ébullition du liquide. Une étude du phénomène a permis de déterminer l'influence de la température de la surface et de la température de l'eau sur la réduction de la traînée. Les mesures faites dans le cas d'une ébullition nucléée, d'une sublimation et d'une surface non-mouillée sont comparées.

Zusammenfassung—Versuche an einem hocherhitzten Halbkugel-Zylinder-Modell bei Geschwindigkeiten bis 6 m/s zeigen eine starke Abnahme des Reibungswiderstandes. Diese Verminderung des Widerstandes beruht auf der Bildung einer stabilen Dampfschicht an der Körperoberfläche infolge Filmsiedens der Flüssigkeit. Die Analyse des Phänomens gibt Aufschluss über die Wirkung der Oberflächentemperatur und der Wassertemperatur auf die Widerstandsverminderung. Vergleichsunternehmungen wurden beim Blasenverdampfen angestellt für sublimierende und nicht-benetzbare Oberflächen.

Аннотация—Опыты при скоростях до 20 фут/сек на модели в виде полушарие-цилиндр, нагретой ло высокой температуры, показывают сильное уменьшение сопротивления трения. Уменьшение сопротивления вызвано образованием стабильного слоя пара на поверхности твёрдого тела благодаря плёночному кипению жидкости. Анализ явления позволяет определить влияние температуры поверхности и воды на уменьшение сопротивления. Приводятся сравнительные результаты измерений для сублимирующихся и несжимающихся поверхностей, а также для поверхностей при пузырьковом кипении.