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NUSSELT CONDENSATION OF *n*-BUTYL ALCOHOL

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NOMENCLATURE

f,	condensation coefficient;
g,	acceleration of gravity;
h_{fg},	latent heat of vaporization;
h_{if},	interfacial heat transfer coefficient;
k,	thermal conductivity;
L,	height of condensing surface;
P,	pressure
R,	universal gas constant;
q,	heat flux;
T,	temperature;
u,	velocity in liquid film;
V,	specific volume;
y,	coordinate normal to condensation surface;
δ,	liquid film thickness;
ρ,	density;
μ,	dynamic viscosity.

Subscripts

s,	liquid surface at liquid-vapor interface;
v,	vapor;
w,	wall;
csate,	condensate measurement;
cond,	conduction measurement;
Nu,	Nusselt solution.

INTRODUCTION

Heat flux measurements were made of the laminar film condensation of *n*-butyl alcohol on a vertical surface. The measurements were compared with the Nusselt solution in an attempt to ascribe any difference between predicted and measured heat flux values to interfacial resistance, and thus to obtain a value for the condensation coefficient. The lowest vapor pressure obtainable in the present experiment was 9·4 mmHg (85 degF). At this pressure and above, the results indicate that the condensation coefficient is larger than 0·25. This is substantially larger than values reported for this class of liquids by previous experimenters. Kicska and Smith [1] obtained a most probable value for *sec*-butyl alcohol of 0·025. Measurements performed on methanol by Delaney [2] have yielded values of 0·017 at 7 degC and 0·030 at −27 degC while similarly low values are quoted in [2] from other literature.

DISCUSSION

The apparatus was a rebuilt version of that described by Mills [3], in which the condensation surface was the vertical face of a thick copper block 2-in. wide by 5-in. high, and was cooled on the opposite face with a refrigerated coolant. The lateral faces of the block were insulated by the nature of the block containment. In the block were embedded two columns of six thermocouples each; the columns being located at 1 and 2 in. from the condensing surface. These temperature measurements enabled a heat flux determination and the surface temperature was obtained by forward extrapolation. A further heat flux measurement was made by collecting condensate. Vapor temperature was measured with a thermocouple, and verified with a pressure measurement through available saturation pressure information [6]. Saturation conditions were at all times maintained.

Careful precaution was taken against the presence of noncondensable gases in the vapor. The apparatus was assembled using high vacuum components and soldered connections only. Upon assembly extensive tests for leaks

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were made with a helium leak detector. To eliminate the gases that are initially dissolved in the liquid, the apparatus was run for at least one hour with a fraction of the vapor continuously withdrawn before any data was taken. It was found in the course of the experimentation that non-condensables would build up in spite of all precaution. This could only be attributed to decomposition of alcohol in the evaporation–condensation cycle. The evidences of non-condensable gases were eliminated when the liquid was exposed to moderately heated metal surfaces only, and 25 per cent of the generated vapor was continuously withdrawn from the apparatus. The film was inspected visually and always appeared complete and uniform. Satisfactory operation was achieved at pressures above 9 mm Hg; at lower pressures the system became unsteady because of unsteady boiling in the vapor generator.

The experimental results are presented in Table 1. T_w was obtained by extrapolating the temperatures in the block forward to the surface and taking an average. To obtain q_{cond} the six temperature differences were averaged, and the thermal conductivity of the copper was taken at 220 Btu/h ft°F. The value for h_{fg} used to compute q_{csate} was the one corrected for liquid subcooling.

Table 1. *Experimental results*

	T_v (°F)	T_w (°F)	$T_v - T_w$ (degF)	P_v (mm Hg)	q_{cond} $\frac{\text{Btu}}{\text{h ft}^2}$	q_{csate} $\frac{\text{Btu}}{\text{h ft}^2}$	q_{Nu} $\frac{\text{Btu}}{\text{h ft}^2}$
1.	85·00	39·30	45·70	9·4	8337	8193	8401
2.	88·00	39·48	48·52	10·6	8910	8786	8842
3.	91·25	39·42	51·83	11·9	9327	9164	9326
4.	94·75	39·63	55·12	13·5	9591	9620	9814
5.	97·55	40·89	56·66	15·0	10185	10100	10102
6.	100·60	42·16	58·44	16·5	10647	10473	10416

Theoretical heat flux values q_{Nu} based on the Nusselt solution were computed using available property data. Values for μ, h_{fg} and ρ were taken from [4], and have since been confirmed in more recent sources. The value for k was taken from [5]. To account for property variation over the substantial temperature difference across the liquid film, the weakly temperature dependent properties ρ and k were taken at T_w. The solution was then developed for the case of the viscosity varying inversely with temperature as:

$$\mu = \frac{\mu_w}{1 + K(y/\delta)} \quad \text{since} \quad \frac{y}{\delta} = \frac{T - T_w}{T_s - T_w} \quad \text{and} \quad K = \frac{\mu_w}{\mu_s} - 1.$$

This gives the velocity profile

$$u = \frac{\rho g \delta^2}{\mu_w}\left[\frac{y}{\delta} - \frac{1-K}{2}\left(\frac{y}{\delta}\right)^2 - \frac{K}{3}\left(\frac{y}{\delta}\right)^3\right]$$

and the average heat flux

$$q_{Nu} \quad \left[\frac{g h'_{fg}\,\rho^2\,k^3\,(T_s - T_w)^3}{N\,\mu_w\,L}\right]^{\frac{1}{4}}; \quad N = \frac{16}{4 + K}$$

where $h'_{fg} = h_{fg} + 0{\cdot}68\ C_p(T_s - T_w)$ is the effective latent heat corrected for the condensate subcooling as in the constant property case, and the density of the vapor is neglected.

Good agreement of the measured heat flux values with q_{Nu} is shown in Table 1. For the six runs recorded it is noted that $0{\cdot}992 < q_{cond}/q_{Nu} < 1{\cdot}022$ and $0{\cdot}975 < q_{csate}/q_{Nu} < 1{\cdot}006$. These heat flux values permit a determination of the presence of interfacial resistance since a significant resistance would yield measured heat fluxes below the ones predicted by q_{Nu}. It remains to compute how much the heat flux would be reduced by interfacial resistance.

From the Hertz–Knudsen theory a sufficiently accurate expression for interfacial heat transfer coefficient is given by [3]

$$h_{if} = 778\,\frac{2f}{2-f}\left(\frac{g}{2\pi\,R\,T_s}\right)^{\frac{1}{2}}\frac{h_{fg}}{T_s\,V_v}\,.$$

Using the fact that the wall temperature was kept nearly constant in the experiments, heat fluxes with interfacial resistance were computed for a constant wall temperature of 40°F over a range of $T_v - T_w$ and various condensation coefficients. These values are plotted in Fig. 1 together with q_{Nu} for no interfacial resistance as the bold trace, and the experimental points. The dashed line indicates the predicted heat flux for measured wall temperature and no interfacial resistance. This trace coincides with the one for constant wall temperature except for the runs with the largest temperature difference. Figure 1 illustrates the insensitivity of heat flux to interfacial resistance for condensation coefficients moderately below unity.

CONCLUSION

In the present experiments agreement with the Nusselt theory for heat flux was obtained within 2 per cent. Figure 1 shows that within this accuracy no specific value for the condensation coefficient can be concluded. However, values as low as $f = 0{\cdot}10$ can be excluded, and for the present range of vapor pressures the condensation coefficient is indicated to lie in the range $0{\cdot}25 < f < 1{\cdot}00$. A narrower range could have been determined if operation at lower vapor pressures had succeeded.

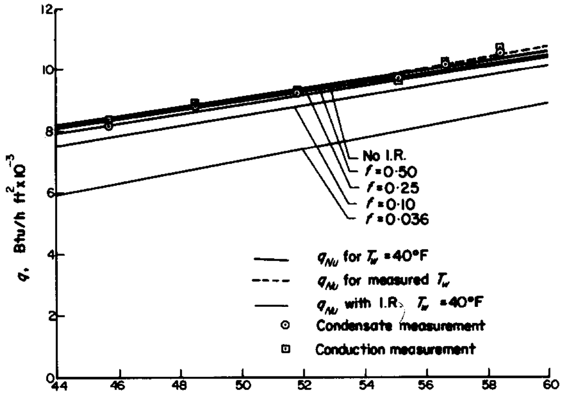

FIG. 1. Heat flux vs. temperature difference (I.R. = interfacial resistance).

It has been found in the course of the experimentations that noncondensable gases are continuously generated. It is therefore felt that some of the low condensation coefficients quoted in the literature for this class of liquids may be attributed to the presence of noncondensable gas.

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A NOTE ON NATURAL CONVECTION AT HIGH PRANDTL NUMBERS

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NOMENCLATURE

x, y,	distances along and perpendicular to the plate;
u, v,	velocity components along x and y directions;
Gr_x,	local Grashof number;
g,	acceleration due to gravity;
t,	temperature;
f,	non-dimensional stream function;
F,	transformed stream function in the inner layer;
G,	transformed stream function in the outer layer;
c_p,	specific heat at constant pressure.

Greek symbols

γ,	a constant;
ψ,	stream function;
σ,	Prandtl number; ν/α;
ε,	local dissipation number defined by (2);
β,	co-efficient of volume expansion of the fluid;
η,	similarity variable;
ρ,	density;
μ,	viscosity;
ν,	kinematic viscosity;
α,	thermal diffusivity;
θ,	temperature excess;
ϕ,	non-dimensional temperature function;

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