THE INFLUENCE OF WALL-CONDENSATE INTERFACE RESISTANCE ON MEASUREMENTS OF LIQUID METAL CONDENSATION COEFFICIENT

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NOMENCLATURE

g,	gravitational acceleration [m s^{-2}];
h,	laminar film condensation heat transfer coefficient [W m^{-2} K^{-1}];
h_A,	apparent interphase heat transfer coefficient [W m^{-2} K^{-1}];
h_c,	heat transfer coefficient at liquid–wall interface;
h_i,	interphase heat transfer coefficient [W m^{-2} K^{-1}];
h_{fg},	latent heat of vapourisation [J kg^{-1}];
k_l,	thermal conductivity of liquid [W m^{-1} K^{-1}];
L,	vertical length of condenser surface [m];
P_s,	saturation pressure [Pa];
R,	gas constant [J kg^{-1} K^{-1}];
T_i,	liquid surface temperature [K];
T_s,	saturation temperature [K];
T_w,	condenser wall temperature [K];
v_{fg},	spes. volume of vapour − spes. volume of liquid [m^3 kg^{-1}];
q/A,	heat flux [W m^{-2}].

Greek symbols

α,	coefficient in saturation equation;
β,	coefficient in saturation equation [K];
ρ_l,	liquid density [kg m^{-3}];
ρ_v,	vapour density [kg m^{-3}];
μ_l,	liquid viscosity [kg m^{-1} s^{-1}];
σ,	condensation coefficient.

1. INTRODUCTION

THE RATE of heat and mass transfer during condensation of liquid metal vapours has been the subject of numerous theoretical and experimental investigations over the past few decades. Most of this work, the results of which have been adequately summarised [1], has been focussed on the interphase resistance which is given by the following well known equation:

$$[(T_s - T_i)/(q/A)] = 1/h_i$$

$$= [(2-\sigma)/2\sigma][(2\pi R T_s)^{1/2}/h_{fg}]\left(\frac{dT_s}{dP_s}\right) \quad (1)$$

where the condensation coefficient, σ, must be determined experimentally.

More recent theoretical studies by Cipolla *et al.* [2] and Labuntsov and Kryukov [3] have resulted in a slightly improved equation,

$$1/h_i = [(2-0.8\sigma)/2\sigma][(2\pi R T_s)^{1/2}/h_{fg}]\left(\frac{dT_s}{dP_s}\right). \quad (2)$$

Whether equation (1) or (2) is used to determine the condensation coefficient, σ is found to have a value which is near or equal to unity below a saturation pressure of about 5 kPa but which decreases exponentially with a further increase in pressure.

2. THERMAL RESISTANCE DURING FILM CONDENSATION

In the determination of the condensation coefficient it is necessary to account for the various thermal resistances involved. These have been summarized as follows [4, 5]:

(i) Wall–condensate interface thermal resistance;
(ii) Condensate film resistance;
(iii) Liquid–vapour interphase resistance;
(iv) Diffusional resistance due to non-condensable gases;
(v) Effect of vapour superheat.

In the various experiments to determine the condensation coefficient, or interphase resistance, the abovementioned thermal resistances, except for (i), were either accounted for or effectively eliminated. The wall to condensate film resistance has generally been either ignored completely or argued to be extremely small and of no significance. It has been generally accepted that the resistance due to the liquid condensate film can be accounted for by means of the modified Nusselt equation suggested by Rohsenow [1],

$$h = 0.943\{g\rho_l(\rho_l - \rho_v)k_l^3[h_{fg} + 0.68(T_i - T_w)]/ $$

$$[L\mu_l(T_i - T_w)]\}^{1/4}. \quad (3)$$

Many experiments with liquid metals have been plagued by problems with non-condensable gases. However, various techniques, using secondary condensers with repeated system evacuation, have largely eliminated this problem.

A second category of pseudo-non-condensables is possibly the presence of dimer-molecules in the vapour. The effects of dimerisation have been investigated by the authors (unpublished results) and were found to be negligible.

In the case of most measurements of condensation coefficient, equation (1) was used. In the event of T_s being the true saturation temperature corresponding to the system pressure this equation is entirely satisfactory. However, very small amounts of superheat at the higher temperatures could lead to erroneous results. Were it possible to measure the vapour pressure with sufficient accuracy this problem would be eliminated. In most of the experiments reported, temperature measurements alone were used to determine the condensation coefficients. However, Sakhuja and Rohsenow [6] were able to eliminate this problem by using two condensers with greatly differing condensation rates. Unfortunately, these measurements were restricted to pressures below 5 kPa. Their technique also made it possible to determine the degree of superheat in the vapour without actually measuring the system pressure.

The only factor influencing the measurement of the condensation coefficient which has been given little consideration is that of the wall–condensate interface thermal resistance. It will be shown below that such a resistance, if unaccounted for, will produce values of the condensation coefficient similar to those already obtained in the event of the actual condensation coefficient having a value near or equal to unity. The conclusions arrived at here are further strongly

upported by some preliminary experimental measurements
if the liquid–nickel contact resistance using sodium.

3. THE EFFECT OF WALL–CONDENSATE INTERFACE RESISTANCE

For the purpose of the exercise carried out below, equation
2) has been employed. The results using this equation would
differ insignificantly from those obtained with equation (1),
particularly at the higher pressures.

Using the Clausius–Clapeyron relationship,

$$h_{f_g} = T_s v_{f_g} \left(\frac{dP_s}{dT_s} \right) \qquad (4)$$

ind the relationship between saturation pressure and
temperature

$$\ln P_s = \alpha - (\beta / T_s) \qquad (5)$$

:quation (2) can be written as

$$1/h_i = [(2 - 0.8\sigma)/2\sigma](2\pi/R)^{1/2}[T_s^{5/2}/(\beta^2 P_s)] \qquad (6)$$

aking $v_{f_g} \simeq v_g$.
With $\sigma = 1$ this becomes

$$1/h_i = 0.6(2\pi/R)^{1/2}[T_s^{5/2}/(\beta^2 P_s)]. \qquad (7)$$

n the experiments where the wall–condensate interface
·esistance was not accounted for an apparent vapour–liquid
nterphase resistance, $1/h_A$, would have been measured such
hat

$$1/h_A = 0.6(2\pi/R)^{1/2}[T_s^{5/2}/(\beta^2 P_s)] + 1/h_c \qquad (8)$$

where $1/h_c$ is the wall–condensate interface resistance.

An apparent condensation coefficient can now be derived
using equation (8), so that

$$[(2 - 0.8\sigma_A/2\sigma_A](2\pi/R)^{1/2}[T_s^{5/2}/(\beta^2 P_s)]$$
$$= 0.6(2\pi/R)^{1/2}[T_s^{5/2}/(\beta^2 P_s)] + 1/h_c. \qquad (9)$$

Therefore

$$\sigma_A = 2/(2\zeta + 0.8) \qquad (10)$$

where

$$\zeta = 0.6 + (R/2\pi)^{1/2}[(\beta^2 P_s)/T_s^{5/2}](1/h_c). \qquad (11)$$

Values of apparent condensation coefficient were determined
for sodium and potassium in the range 0.1–100 kPa for
different values of $1/h_c$ using equations (10) and (11) and are
plotted in Fig. 1. It can clearly be seen from these curves that a
wall–condensate interface resistance of relatively small
magnitude would impose the trend in measured values of
condensation coefficient if unaccounted for when the actual
condensation coefficient is near or equal to unity.

In the case of Kröger [8] and Labuntsov [9] a value
of $1/h_c = 10^{-5}$ K m^2 W^{-1} would have been appropriate
while in the case of Wilcox and Rohsenow [10] it would be
1.25×10^{-6} K m^2 W^{-1} and with Bakulin [7] $1/h_c = 6.25$–
12.5×10^{-7} K m^2 W^{-1} would have applied. Sakhuja's [6]
results also indicate a wall–condensate thermal resistance of
approximately 1.25×10^{-6} K m^2 W^{-1}.

4. EXPERIMENTAL MEASUREMENT OF THE THERMAL RESISTANCE BETWEEN LIQUID SODIUM AND A NICKEL SURFACE

An experiment, briefly described below, was conducted in
order to verify the order of magnitude of the wall–condensate
interface resistance.

A nickel-plated 25 μm brass-shim, folded back and forth 20
times, was placed between two nickel-plated copper
conduction blocks (Fig. 2). The void around the shim was
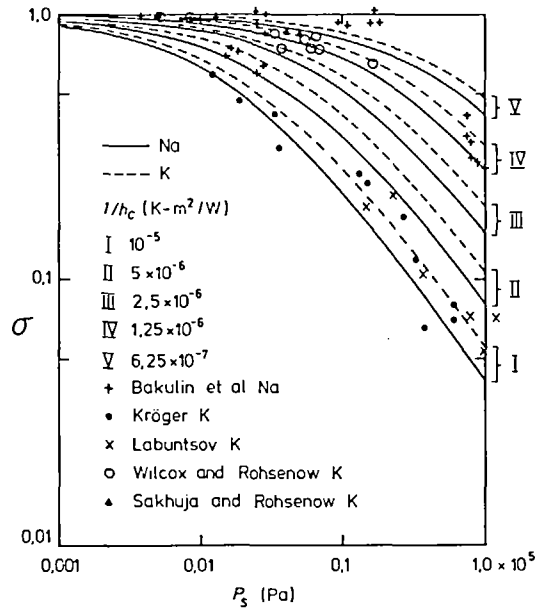subsequently filled with sodium under argon cover gas. With

FIG. 1. Predicted apparent condensation coefficients assuming
the indicated wall–condensate resistances and $\sigma = 1$.

the blocks initially separated by a gap of about 8 mm the
system was allowed to soak at 200°C for several h so that
sodium could enter the gaps between the shim layers. The
blocks were then moved towards each other and held together
with the shim compressed in between by means of the spring
and lever system illustrated. With heating at one end and
cooling at the other a steady state heat conduction experiment
could be carried out. The temperatures on the copper block
surfaces in contact with the shim as well as the heat flux could
be determined by measuring the thermal gradient, by means of
three thermocouples, in each of the two blocks. By using the 20
layers of shim the liquid–nickel interface resistance to be
measured was amplified by a factor of 42 thus greatly
increasing the accuracy. When determining the liquid–nickel
resistance of the shim material was subtracted from the total
resistance measured.

After several h it was found that the resistance stabilised at
5.11×10^{-7} K m^2 W^{-1} at 445°C. Further measurements at
567°C showed a slight increase of resistance to 6.46×10^{-7} K
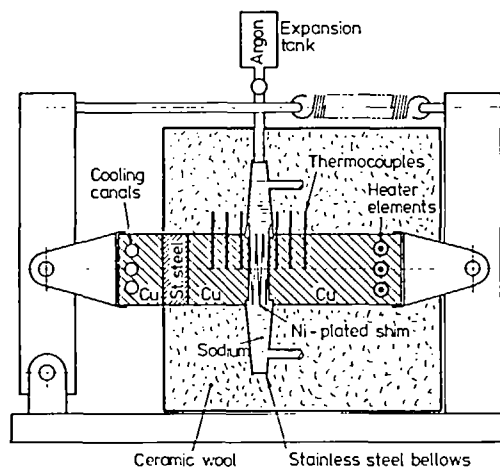

FIG. 2. Apparatus for the measurement of wall–liquid
resistance between sodium and nickel.

$m^2 W^{-1}$. It is interesting to note that the final values measured were of the same order of magnitude as the corresponding values suggested by the results of Bakulin, *et al.* [7], Sakhuja and Rohsenow [6] and Wilcox and Rohsenow [10].

5. CONCLUSIONS

The above theory points strongly to the presence of a wall–condensate interface resistance or resistive layer on the nickel condenser surfaces during experiments with condensing liquid metals. Further, preliminary experimental measurements of this resistance tend to support this theory. The authors at this stage make no attempt to explain why such a resistance, or possibly a resistive layer, should exist but merely suggest that all the facts point to the presence of such a phenomenon in liquid metal condensation experiments.

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A THEORY FOR TRANSIENT MASS TRANSFER WITH SUCTION AT THE PHASE BOUNDARY—APPLICATION TO BUBBLES IN FLUIDIZED BEDS

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NOMENCLATURE

a,	concentration of diffusing species;
a_0,	concentration of diffusing species far from interface;
D,	gas diffusivity;
D_s,	diameter of slug;
E,	enhancement of diffusive flux due to crossflow;
E_{tr},	as E but for transpiration;
F,	fraction of additive flux contributed by diffusion only;
$k_G S$,	transfer coefficient for slugs due to diffusion only;
L_s,	length of slug;
N,	instantaneous flux of diffusing species across interface;
N_a(cross),	average flux of diffusing species across interface due to crossflow only;
N_a(diff+cross),	average flux of diffusing species across interface accounting for interaction between diffusion and crossflow;
N'_a(diff),	purely diffusive average flux with random surface renewal, $a_0(Ds)^{1/2}$;
N'_a(diff+cross),	average flux at the interface with random surface renewal, accounting for interaction between diffusion and crossflow;
p,	variable of the Laplace transform domain;

Q,	overall transfer coefficient between slug and dense phase;
R,	ratio between exact value of average flux and the sum of fluxes due to diffusion only and crossflow only;
R',	as R but with random surface renewal;
s,	rate of surface renewal;
t,	time;
T,	dimensionless time, $v^2 t/D$;
u,	component of gas velocity tangent to bubble surface;
U_{mf},	minimum fluidizing velocity;
v,	fluid velocity perpendicular to the interface;
X,	dimensionless distance from interface, xv/D;
w,	dummy variable;
z,	dummy variable.

Greek symbols

α,	dimensionless concentration, $(a-a_0)/a_0$;
$\bar{\alpha}$,	Laplace transform of α;
θ,	dimensionless time of contact, $v^2/(Ds)$.

Subscripts

av,	average;
0,	far from interface;
s,	refers to slug.