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CONDENSATION OF LIQUID METALS

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EXPERIMEMTAL measurements of heat transfer during the condensation of liquid metals [1–10] have shown wide deviations from results predicted by the simple Nusselt theory. In all cases the observed heat-transfer rates are lower (in some cases by several orders of magnitude) than predicted. Most investigators have sought to explain this phenomenon in terms of an additional "resistance" arising from the non-equilibrium situation existing at the liquid–vapor interface during condensation or evaporation, and neglected in the Nusselt theory.

There is, at present, no established theory of interphase matter transfer. A significant contribution in this field is the work of Schrage [11]. Various experimenters have attempted to interpret their results in terms of Schrage's "simple theory". Less attention has been given to the more elaborate treatments of Schrage and others, a survey of which has been given by Wilhelm [5].

As well as providing design data, experiments on condensation of liquid metals offer an excellent opportunity for studying the interphase matter transfer problem since the thermal resistance offered by the condensate is small. There are however significant difficulties which must be overcome in order to obtain results of sufficient validity for this purpose. It is with one of these difficulties, namely errors arising from the presence of non-condensing gases in the vapour, that the present note is primarily concerned.

It has long been appreciated that the presence of non-condensing gases leads to an additional temperature drop in the vapour near to the interface and to a corresponding reduction in condensation rate. Though, in metal condensation experiments, attempts have generally been made to minimize the concentration of such gases, it has not been possible to say with certainty that the effect of any remaining gas was negligible.

Recently numerical boundary-layer solutions have been given [12, 13] for the case of condensation in the presence of a non-condensing gas and in the absence of forced convection. An approximate integral solution has also been given [14] for this problem and the closed-form result found to be in satisfactory agreement with numerical solutions for air-stream mixtures given in [12, 13]. The solutions mentioned above relate to plane vertical condensing surfaces when the non-condensing gas has the higher molecular weight.

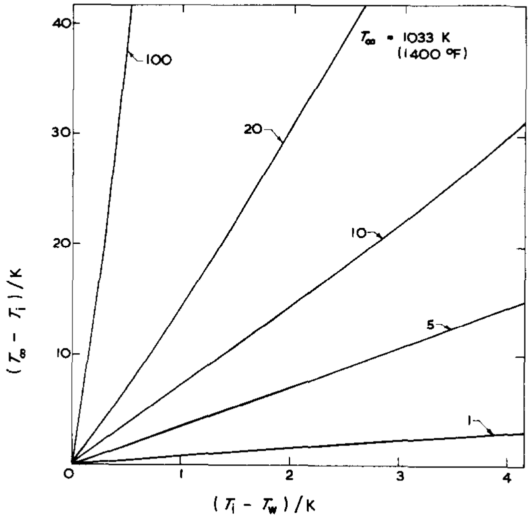

FIG. 1. Relative temperature drops in vapour and condensate for sodium condensing in the presence of nitrogen, based on equation (8) of [14]

T_∞ = temperature in remote gas–vapour mixture
T_i = temperature at vapour–condensate interface
T_w = temperature of condensing surface
(the number assigned to each curve is mass concentration of gas × 10^6).

By using the integral solution as a basis for estimating "errors" arising from the presence of a non-condensing gas in a condensing metal vapour, it has been found that significant temperature drops are caused by minute proportions of gas. For instance, Fig. 1 compares the magnitudes of temperature drops in sodium vapour resulting from the presence of nitrogen, with those in the condensate. In obtaining these results the temperature drop arising from interphase matter transfer was omitted. The mixture viscosity was found by the method of Wilke [15] and the diffusion coefficient by the method of Slattery and Bird [16]. It may be seen from Fig. 1 that concentrations of nitrogen a little in excess of 1 ppm give rise to temperature drops in the vapour of similar magnitude to those across the condensate film. For larger concentrations the resulting temperature drop in the vapour greatly exceeds that in the condensate.

Using a plate height equal to that of the vertical condenser tube used by Barry and Balzhiser [7, 8] it was found that nitrogen concentrations varying between 5 and 25 ppm would give rise to temperature drops of the magnitude found by these workers.

These examples serve to indicate the extreme sensitivity of liquid metal condensation experiments to very small amounts of non-condensing gases. In view of this fact it seems unlikely that significant error can be avoided simply by seeking to minimize the gas concentration. However, it should be possible to avoid, or at least greatly reduce this error, by arranging for forced convection of the vapour in the region of the condensing surface. Sparrow *et al.* has shown [17] that the influence of non-condensing gas is much reduced under forced convection conditions. It is probable that in the case of liquid metals and with small non-condensing gas concentrations, the error might be eliminated using velocities which are not sufficiently high to introduce significant error through their effect on the small temperature drop in the condensate film.

In support of the above suggestion, the similar situation with regard to dropwise condensation of steam may be cited. With this mode of condensation the vapour-side temperature difference is very small and, as in the case of liquid metals, its measurement is susceptible to errors arising from non-condensing gas. In recent tests [18, 19] using a simple apparatus, it was found impossible, even when operating above atmospheric pressure, to reduce the gas concentration to an insignificant level and that concentrations as little as 5 ppm introduced significant error. It was however found possible to eliminate this error by forced convection in the vapour near the condensing surface without introducing error through disturbance of the condensate.

Finally, should it prove to be the case that a significant proportion of the vapour-to-surface temperature drop in some earlier experiments has been due to non-condensing gas then, after removing this error, correspondingly greater accuracy will be required in the measurement of the much reduced temperature difference. When thermocouples are used special attention needs to be given to adequate isothermal immersion of the leads since, at the relatively high temperatures of the liquid metal experiments, measurements are particularly prone to this source of error.

The above comments are not intended as criticism of experimental work in this field which has provided valuable data, but rather to draw attention to the fact that caution should be exercised when interpreting results from the viewpoint of theories of interphase matter transfer.

REFERENCES

1. B. Misra and C. Bonilla, Heat transfer in the condensation of metal vapour: mercury and sodium up to atmospheric pressure, *Chem. Engng Prog. Symp. Ser.* **52** (18), 7 (1956).
2. J. A. Roth, Condensation of sodium and rubidium at low heat fluxes, *Report ASD-TDR*-62-738, Wright–Patterson AFB (1962).
3. S. P. Sukhatme and W. M. Rohsenow, Heat transfer during film condensation of liquid metal vapor, *M.I.T. report no.* 9167-27 (1964).
4. V. I. Subbotin, M. N. Ivanovsky, V. P. Sorokin and V. A. Chulkov, *Teplofiz. vysok. temp.* **4**, 616 (1964).
5. J. D. Wilhelm, Condensation of metal vapors: mercury and the kinetic theory of condensation, *Argonne National Lab. Report no. ANL*-6948 (1964).
6. I. T. Aladyev *et al.*, Thermal resistance of phase transition with condensation of potassium vapor, *Proc. Third Int. Heat Transfer Conf.* **2**, 313 (1966).
7. R. E. Barry and R. E. Balzhiser, Condensation of sodium at high heat fluxes, *Proc. Third Int. Heat Transfer Conf.* **2**, 318 (1966).
8. R. E. Barry, Condensation of sodium at high heat fluxes, Ph.D. Thesis, University of Michigan (1965).
9. D. A. Labunsov and S. I. Smornov, Heat transfer in condensation of liquid metal vapours, *Proc. Third Int. Heat Transfer Conf.* **2**, 329 (1966).
10. D. G. Kroger and W. M. Rohsenow, Film condensation of saturated potassium vapor, *Int. J. Heat Mass Transfer* **10**, 1891 (1967).
11. R. W. Schrage, *A Theoretical Study of Interphase Mass Transfer.* Columbia University Press, New York (1953).
12. E. M. Sparrow and S. H. Lin, Condensation heat transfer in the presence of a noncondensable gas, *J. Heat Transfer* **86C**, 430 (1964).
13. W. J. Minkowycz and E. M. Sparrow, Condensation heat transfer in the presence of noncondensables, interfacial resistance, superheating, variable properties and diffusion, *Int. J. Heat Mass Transfer* **9**, 1125 (1966).
14. J. W. Rose, Condensation of a vapour in the presence of a non-condensing gas, *Int. J. Heat Mass Transfer* **12**, 233 (1969).
15. C. R. Wilke, A viscosity equation for gas mixtures, *J. Chem. Phys.* **18**, 517 (1950).
16. J. C. Slattery and R. B. Bird, Calculation of the diffusion coefficient of dilute gases and of the self-diffusion coefficient of dense gases, *A.I.Ch.E. Jl* **4** (2), 137 (1958).
17. E. M. Sparrow, W. J. Minkowycz and M. Saddy, Forced convection condensation in the presence of noncondensables and interfacial resistance, *Int. J. Heat Mass Transfer* **10**, 1829 (1967).
18. E. J. Le Fevre and J. W. Rose, An experimental study of heat transfer by dropwise condensation, *Int. J. Heat Mass Transfer* **8**, 1117 (1965).
19. E. Citakoglu and J. W. Rose, Dropwise condensation—some factors influencing and validity of heat-transfer measurements, *Int. J. Heat Mass Transfer* **11**, 523 (1968).