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FILM BOILING ON A HORIZONTAL PLATE— A SUPPLEMENTARY COMMUNICATION

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NOMENCLATURE

Ar,	Archimedes number, $Ga(\rho'/\rho - 1)$;
B,	Laplace constant, $\{\sigma/[g(\rho' - \rho)]\}^{1/2}$;
Bi,	Biot number, $(\alpha\delta)/\lambda_w$;
c_p,	specific heat at constant pressure;
g,	acceleration of body forces;
Ga,	Galileo number, $(gl_{cr}^3)/(\nu^2)$;
F,	heat transfer surface area;
l_{cr},	critical wave length of 2-dim. Taylor instability, $2\pi\{\sigma/[g(\rho' - \rho)]\}^{1/2}$;
K,	phase change number, $r/(c_p\Delta T)$;
Nu,	Nusselt number, $(\alpha l_{cr})/\lambda$;
P,	pressure;
Pr,	Prandtl number, ν/a;
V,	specimen volume;
q,	heat flux density;
r,	latent heat of vaporization;
ΔT,	temperture difference, $T_w - T$.

Greek symbols

α,	heat transfer coefficient;
δ,	specimen thickness;
λ,	thermal conductivity;
μ,	dynamic viscosity;
ν,	kinematic viscosity;
ρ,	density;
σ,	surface tension;
τ,	time.

Superscripts

$'$,	refers to liquid.

Subscripts

cr,	critical;
w,	wall;
0,	normal.

INTRODUCTION

IN OUR recent paper [1], we suggested a relationship to calculate the heat transfer coefficient in film boiling from different-sized flat horizontal surfaces which was valid for a wide range of the dimensionless number *Ar* that defines the vapour flow regime. A comparative analysis of various relations also presented in that paper supported a higher accuracy of the heat transfer coefficient calculated by the proposed equation.

It should be noted, however, that up to now the region of small values of the *Ar* number (less than 10^5) has virtually not been studied at all. Very scarce also are data for high values of the phase change number *K* (above 5), and, worse yet, they lack consistent agreement [2, 3].

Investigations conducted in the above regions are of particular value as they provide for further testing of the potentialities of our theory.

EXPERIMENTS

One of the most accessible ways of obtaining the film boiling data in the region of low Archimedes numbers is that of conducting heat transfer experiments in liquid helium, on a surface heated to room temperature. According to our preliminary estimates, the phase change number may be appreciably larger for liquid argon in the region of low wall superheats close to the crisis of film boiling. The experimental specimens were 20 mm thick copper discs, with all sides being styrofoam-insulated, except the upward facing horizontal flat one which served as a heat transfer surface. The disc thickness was dictated by the demand for sufficient experimental duration (several minutes) and simultaneous compliance with the condition that $Bi < 0.1$, which when plotting the boiling curve, allows the use of Newton's simple law of cooling

$$q = -(\rho c_p)_w \frac{V}{F}\frac{dT_w}{d\tau}. \tag{1}$$

The disc diameter was made sufficiently large to exclude the effect of the heat transfer surface size on the intensity of the process. According to ref. [1], a flat horizontal surface can be regarded as 'large' if its minimum size surpasses about thirty Laplace constants.

Taking into account that at atmospheric pressure $b_{He} = 0.31$ mm and $b_{Ar} = 0.96$ mm, the disc diameter was taken to be 10 mm for helium and 40 mm for argon. In the latter case the same specimen was used as in earlier experiments with nitrogen [3]. Heat losses in experiments with argon amounted to a few percent and were not taken into consideration in the treatment of experimental data. Heat losses in the experiments with helium amounted to 30% of the total heat flux magnitude at the maximum temperature difference of 300 K. It should be noted that the effective thermal conductivity of insulation was refined by special experiments, since the values tabulated in ref. [4] entailed large errors.

The temperature sensors were small-sized copper–constantan thermocouples, with an electrode diameter of 0.1 mm. These were fitted into three radial holes in each disc. Since the sensitivity of these thermocouples drops markedly with temperature the readings for helium were not taken at ΔT below 30 K.

The heat transfer intensity vs the temperature difference, along with the results on film boiling in nitrogen [3] and helium [8, 9], are presented in Fig. 1.

DISCUSSION

The results we have obtained on helium film boiling are found to be in good agreement with our previous data [8] for the range of temperature differences up to 100 K and with the experimental results for lower temperature differences [9].

It is easy to notice that the data on film boiling in argon and nitrogen practically coincide, yet the helium boiling curves are almost twice as high at $\Delta T > 60$ K. This is mainly due to an appreciable thermal conductivity of the helium vapour. In our opinion, the experimental data presented herein suggest

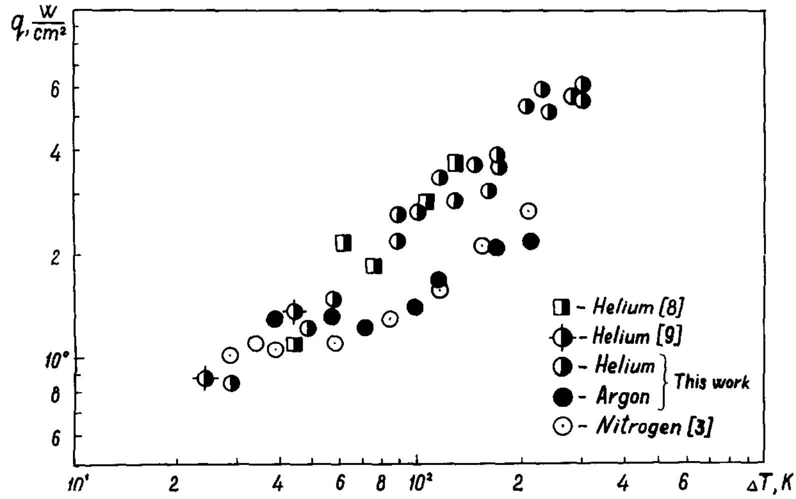

FIG. 1. Experimental data on film boiling on a horizontal surface.

that the film boiling heat transfer rate is very dependent on the interface friction, which is characterized by the phase change number K. It follows from Fig. 1 that the character of the dependence q vs ΔT changes markedly with increasing temperature difference. Thus, for nitrogen and argon in the region of wall superheats not surpassing 70 K, the heat flux density depends only slightly on ΔT. However, as the temperature difference increases, q becomes almost directly proportional to ΔT.

Conversely, the function $q(\Delta T)$ for helium, which is characterized by $K \ll 1$ in the whole range of temperature differences investigated, does not show any discontinuity. Thus, at small K, Nu should be independent of K for any kind of liquid, while at large K the interface friction exhibits a marked effect on the heat transfer process.

Converting to generalized coordinates, we must regretably admit that there were some vexing misprints in the figures in our previous work [1]. It therefore seems worthwhile to present these plots here corrected and supplied with newly obtained results.

Figure 2 shows in generalized coordinates the data on boiling of ten various liquids obtained by sixteen research groups. It is evident that the experimental data on film boiling in the region of Archimedes numbers down to 10^4 are well described by the relations proposed previously [1]. Figures 3 and 4 contain the same set of results given separately for laminar and turbulent regions in the form of $Nu/(Ar^n Pr^{1/3})$ as a function of the phase change number. It can be easily seen that the correlation suggested gives a good agreement with experimental results up to the values of the phase change number $K = 8$ (obtained in the experiments with argon). About 95% of the points lie within the interval ±25% of the approximating lines and more than 98%, within ±30%.

CONCLUSION

To calculate the heat transfer rate in film boiling on flat horizontal surfaces, the following correlations given in ref. [1] can be recommended:

at $Ar < 1 \times 10^8$

$$Nu = 0.19\, Ar^{1/3} Pr^{1/3} f_1(K), \tag{2}$$

where

$$f_1 = \begin{cases} 1 & \text{at } K < 1.4, \\ 0.89\, K^{1/3} & \text{at } K > 1.4; \end{cases} \tag{3}$$

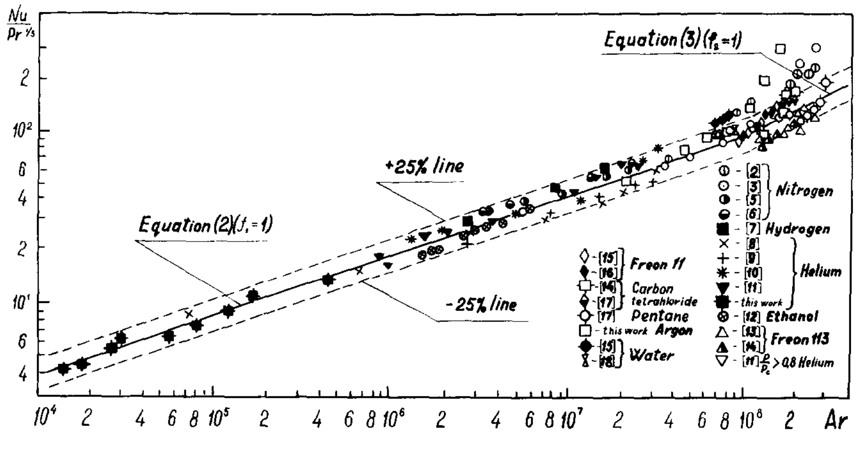

FIG. 2. Comparison of predictions by proposed relations with experimental data on film boiling on a horizontal surface.

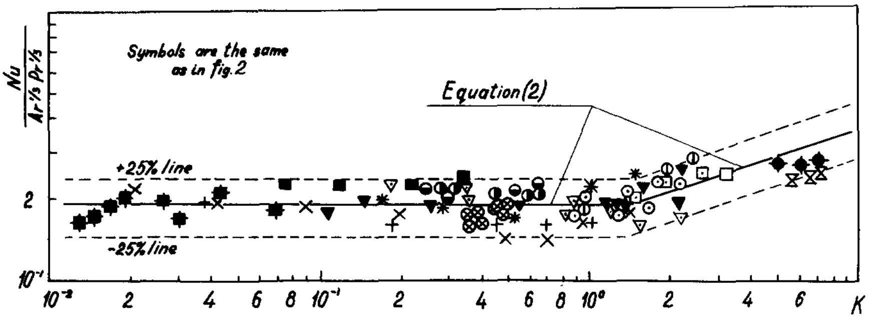

FIG. 3. Correlation of data on laminar film boiling.

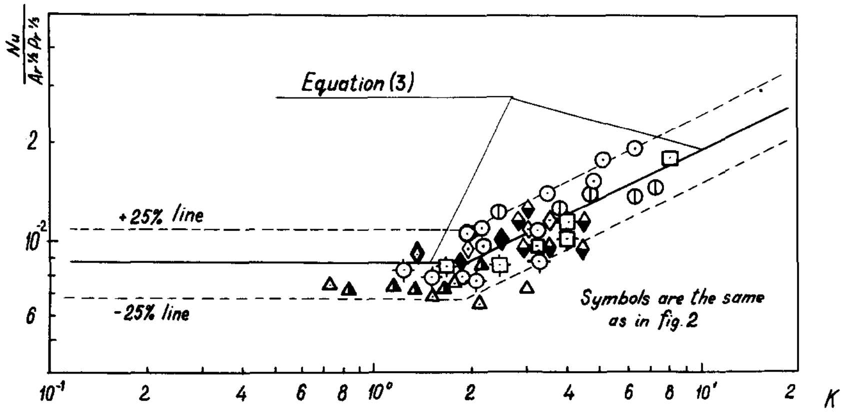

FIG. 4. Correlation of data on turbulent film boiling.

at $Ar > 1 \times 10^8$

$$Nu = 0.0086\, Ar^{1/2} Pr^{1/3} f_2(K), \qquad (4)$$

where

$$f_2 = \begin{cases} 1 & \text{at } K < 2.0 \\ 0.71\, K^{1/2} & \text{at } K > 2.0 \end{cases}$$

all the above being valid in the following ranges of parameters

$Ar = 10^4$–3×10^8, $Pr = 0.69$–3.45, $K = 0.013$–8.0,

$P/P_c = 0.0045$–0.98, $g/g_0 = 1$–21.7.

REFERENCES

1. V. V. Klimenko, Film boiling on a horizontal plate—new correlation, *Int. J. Heat Mass Transfer* **24**, 69–79 (1981).
2. W. Peyayopanakul and J. W. Westwater, Evaluation of the unsteady-state quenching method for determining boiling curves, *Int. J. Heat Mass Transfer* **21**, 1437–1445 (1978).
3. A. G. Shelepen and V. V. Klimenko, Film boiling of cryogens from flat surfaces, in *Transactions of Moscow Power Engineering Institute*, No. 478, pp. 15–25. Moscow (1980).
4. L. A. Novitsky and I. G. Kozhevnikov, *Thermal Properties of Materials at Low Temperatures*. Izd. Mashinostroenie, Moscow (1975).
5. H. J. Sauer Jr. and K. M. Ragsdell, Film pool boiling of nitrogen from flat surfaces, *Adv. Cryogen. Engng* **17**, 412–415 (1972).
6. P. C. Wayner Jr. and S. C. Bankoff, Film boiling of nitrogen with suction on an electrically heated porous plate, *A.I.Ch.E. Jl* **11**, 59–64 (1965).
7. C. R. Class, J. R. De Haan, M. Piccone and R. B. Cost, Boiling heat transfer to liquid hydrogen, *Adv. Cryogen. Engng* **5**, 254–261 (1960).
8. V. A. Grigoriev, V. V. Klimenko, Yu. M. Pavlov, Ye. V. Ametistov and A. V. Klimenko, Characteristic curve of helium pool boiling, *Cryogenics* **17**, 155–156 (1977).
9. R. D. Cummings and J. L. Smith, Boiling heat transfer to liquid helium, in *Liquid Helium Technology*, pp. 85–95. Pergamon Press, Oxford (1966).
10. V. A. Grigoriev, Yu. M. Pavlov and S. A. Potekhin, Heat transfer mechanism and crisis of helium nucleate pool boiling, 15th International Congress of Refrigeration, Venice, Italy, 23–29 September 1979; see also Yu. M. Pavlov, S. A. Potekhin and A. V. Paramonov, Heat transfer and crisis of helium pool boiling, in *Transactions of Moscow Power Engineering Institute* No. 427, pp. 10–15. Moscow (1979).
11. V. I. Deev, V. E. Keilin, I. A. Kovalev, A. K. Kondratenko and V. I. Petrovichev, Nucleate and film pool boiling heat transfer to saturated liquid helium, *Cryogenics* **17**, 557–562 (1977).
12. C. A. Heath and C. P. Costello, Some effects of geometry, orientation, and acceleration on pool film boiling of organic fluids, *J. Engng Ind.* **88**, 17–23 (1966).
13. V. M. Zhukov, G. M. Kazakov, S. A. Kovalev and Yu. A. Kuzma-Kichta, Boiling heat transfer from surfaces with coatings of low thermal conductivity, in *Heat Transfer and Physical Gas Dynamics* pp. 116–129. Izd. Nauka, Moscow (1974).
14. D. E. Kautzky and J. W. Westwater, Film boiling of a mixture on a horizontal plate, *Int. J. Heat Mass Transfer* **10**, 253–256 (1967).
15. E. R. Hosler and J. W. Westwarer, Film boiling on a horizontal plate, *ARS J.* **32**, 553–560 (1962).
16. Y. J. Lao, R. E. Barry and R. E. Balzhiser, Study of film boiling on a horizontal plate, in *Proc. 4th Int. Heat Transfer Conf.* B.3 10, pp. 1–10, Paris (1970).
17. P. J. Berenson, Experiments on pool-boiling heat transfer, *Int. J. Heat Mass Transfer* **5**, 985–999 (1962).
18. J. L. Olinger and C. P. Colver, A study of effect of an uniform electric field on nucleate and film boiling, *Chem. Engng Prog. Symp. Ser.* **67**, 19–29 (1972).