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Void fraction and pressure drop in two-phase liquid metal flows in channels†

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Abstract—Experimental results on void fraction and friction pressure drop in vapour–potassium flows in the high-vapour-quality region up to unity are presented. The experimental data obtained and the pertinent results of other authors are generalized, and empirical relationships are suggested to calculate void fraction and pressure drop in two-phase liquid metal flows for channels of various configurations and orientations. The relationships are valid within the range of vapour qualities from almost zero to unit. The experimental data prove the mass velocity to have no influence on the hydrodynamic characteristics within the range of the parameters investigated. It is found in the experiments with heat supply that friction pressure losses are smaller than those for adiabatic conditions. It is shown that this result is in good correspondence with the model of the effect of injection in a boundary layer on the value of shear stresses between cases.

1. INTRODUCTION

Determination of the hydraulic characteristics of liquid metal parallel-feed evaporators requires valid correlations for void fraction α and friction pressure drops Δp_f of two-phase liquid-metal flows in the whole range of vapour quality $x = 0, \ldots, 1$ in channels of various orientations and configurations.

In the well-known investigations of this problem with potassium and sodium, the major experimental data refer to $x < 0.5$. In the present work, the process of determining α and Δp_f in vapour–potassium flows for $x > 0.5$ was investigated.

2. EQUIPMENT AND TECHNIQUES

Experiments were carried out on a set-up at the Liquid Metal Boiling Laboratory of the Dnepropetrovsk State University. The set-up allows investigation of thermal and hydrodynamic characteristics (heat transfer limiting conditions, flow rate and pressure dynamics, pressure losses, wall liquid-film thickness) of potassium boiling under forced convection conditions in parallel-feed evaporators of various configurations and orientations in a wide range of regime parameters. The set-up consists of the following main parts:

(1) a closed circuit with an MHD-pump, preheater, cooler-condenser, locking and regulating fitting,
(2) an experimental evaporator (or section),
(3) a power supply system,
(4) an informing and measuring system,
(5) a supplying system.

A detailed description of the experimental set-up is given in ref. [1].

The experimental study was conducted in a series of runs. Every run included the following stages: determination of the potassium temperature at the working section inlet, and maintenance of fixed and constant inlet flow rate and pressure at the inlet and outlet. After the heater was energized, the supplied power was increased in small steps up to the incipience of boiling. The power level was then kept for several minutes. During that time the informing and measuring system recorded the potassium flow rate, its temperature and pressure at the section inlet and outlet, and the temperature regime of the outer wall along the channel. After boiling at constant G, p_s and x, the power was increased stepwise, with the above-mentioned parameters being recorded right up to the heat transfer crisis. Then, one of the parameters under study (mass, velocity or pressure) was changed and the experiment was repeated.

The details of determining void fraction and vapour–potassium two-phase flow pressure drops are given below in the appropriate parts of the paper.

3. VOID FRACTION

The value of α was determined with the aid of the wall liquid film fraction by measuring the electric resistance of the vapour–liquid mixture on the horizontal adiabatic test section with internal diameter d of 7 mm and wall thickness of 0.3 mm. The active length between two measuring electrodes was 150 mm.

The test section was placed after the section for

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NOMENCLATURE

B	injection parameter determined by equation (5)
d	inner diameter of channel [m]
D	diameter of coil [m]
G	mass velocity [kg m^{-2} s^{-1}]
l	length [m]
p	pressure [N m^{-2}]
q	specific heat flux [W m^{-2}]
T	temperature [K]
W	velocity [m s^{-1}]
x	vapour quality
X_{LM}	Lockhart–Martinelli parameter determined by equation (1).

Greek symbols

α	void fraction
δ	liquid film thickness [m]
Δ	addition of parameter, difference in meaning
λ	latent heat of vaporization [J kg^{-1}]
μ	dynamic viscosity [kg m^{-1} s^{-1}]
ρ	density [kg m^{-3}]
ϕ_l	relative pressure drops determined by equation (3)
ψ	relative friction coefficient.

Subscripts

f	film; friction
g	vapour phase
l	liquid phase
s	saturation
W	value parameter of the wall
W_0^*	liquid phase circulation velocity.

Superscripts

ad	adiabatic condition
h	condition with heating.

vapour–potassium mixture preparation. A coiled pipe with $d = 7$ mm, relative length $l/d = 182$ and curvature $d/D = 0.0357$ was used. The evaporator, fabricated in the form of a coiled pipe, made it possible to obtain a vapour quality of about 1 without attaining the heat transfer crisis, and to determine α (or the liquid film thickness δ_f) within the unknown range $0.5 < x < 1$.

The results obtained allowed us to trace the change of δ_f at the evaporator outlet in the regimes preceding and accompanying the heat transfer crisis in the evaporator.

Altogether, 16 runs were conducted and 104 experimental values of α (or δ_f) were obtained in the ranges of mass velocity $G = 51$–132 kg m^{-2} s^{-1}, pressure $p_s = 1.1$–1.4 bar and vapour quality $x = 0.5$–1. Figure 1 shows the dependence of δ_f on x at the evaporator outlet cross-section for one of the runs. The dependence is typical for the other runs too. It can be seen that, as x increases, the film thickness becomes increasingly smaller and approaches zero at the heat transfer crisis. The results obtained point to the fact that the heat transfer crisis during boiling of liquid metals in channels is the consequence of the wall liquid film drying-out.

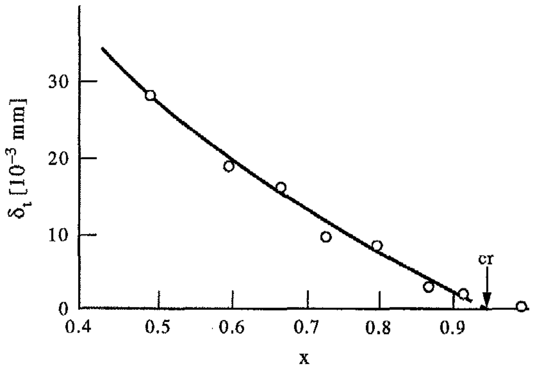

Fig. 1. Change in film mean thickness in the evaporator outlet cross-section; $p = 1.26$–1.33 bar; $G = 68$ kg m^{-2} s^{-1}; cr, heat transfer crisis.

The analysis showed that the measured values of α did not depend on G and were determined only by the Lockhart–Martinelli parameter [2]

$$X_{LM} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\mu_l}{\mu_g}\right)^{0.1}\left(\frac{\rho_g}{\rho_l}\right)^{0.5} \tag{1}$$

where ρ_l and ρ_g are the densities of the liquid and vapour phases, μ_l and μ_g are the dynamic viscosities of the liquid and vapour.

Comparison performed in the $(1-\alpha)$–X_{LM} coordinates shows that the data of the present work are in good agreement with the well-known similar results obtained in refs. [3–6] for potassium and in refs. [7–9] for sodium (Fig. 2). Summarizing the values of α yields the relationship

$$(1-\alpha) = (1+X_{LM}^{-0.552})^{-2.19} \tag{2}$$

which for $X_{LM} < 1$ gives the values of α coinciding with the Chen–Kalish formula [6], and for $X_{LM} > 1$ with the Lockhart–Martinelli relation [2]. Relation (2) is valid for $10^{-3} < X_{LM} < 10^2$.

4. TWO-PHASE PRESSURE DROPS

Friction pressure drops were determined experimentally in two-phase vapour–potassium flows in the test section having the form of helical pipes with inner diameters of 7 mm and 11 mm and relative curvature

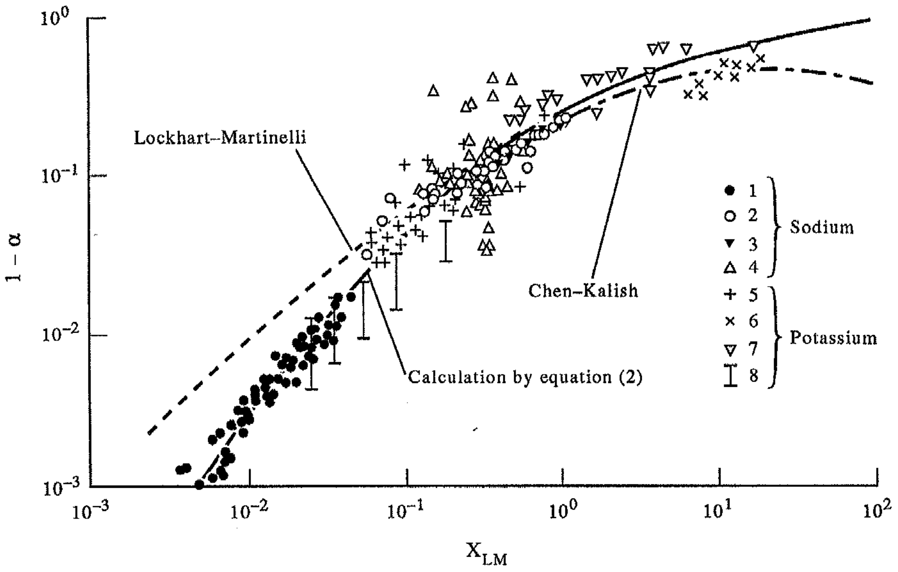

Fig. 2. Volume fraction of liquid in two-phase flow of alkali metals; 1, present paper; 2, experiments [4]; 3, data of ref. [6]; 4, data of ref. [5]; 5, experiments [10]; 6, experiments [7]; 7, experiments [3]; 8, evaluation of data [8].

$d/D = 0.0357$, 0.049, 0.062 (here D is the diameter of the coil). The experiments were made for adiabatic conditions in the ranges of mass velocity $G = 27$–320 kg m^{-2} s^{-1}, pressure $p_s = 1.2$–3.1 bar, and vapour quality $x = 0.07$–1.

The friction pressure drop of vapour–potassium flows was determined from the static pressure change over the small basic length (0.4 m) by measuring saturation temperatures in the vapour chambers joined with the channel and by converting these temperatures into pressure in accordance with the saturation curve.

The analysis of the results of the investigation was performed with the use of the Martinelli parameter in the form

$$\phi_l = (\Delta p_f/\Delta p_{W_0'})^{0.5} \tag{3}$$

where $\Delta p_{W_0'}$ is the pressure drop for the liquid phase alone flowing in the channel with the velocity $W_0' = (1-x)W_0$ (W_0 is the circulation velocity). The Lockhart–Martinelli parameter X_{LM} was also used.

5. ADIABATIC CONDITIONS

In the first stage, the friction pressure drop in vapour–potassium flow was studied in the absence of heat exchange with the environment. The results of the experiments carried out at $q_W = 0$ and various mass velocities on the coil pipe with $d/D = 0.0357$ are presented in Fig. 3. It can be seen that there is practically no deviation of experimental points along G. Similar results were obtained for two other geometries of test sections. Thus, it is possible to conclude that there is no influence of mass velocity on relative friction pressure drops during vapour–potassium mixture flow in the helical coil pipe channel for experiments performed in the range $G = 27$–320 kg m^{-2} s^{-1}.

Figure 4 represents the experimental data obtained for three test sections of varied relative curvature. It can be seen that there is no deviation of points for various geometries of test sections and the whole data file, represented in logarithmic coordinates, is located about a certain straight line (1) (the equation for line 1 will be given in what follows). The information given above allows us to infer that the relative pressure drops are independent of the test-section curvature for the range of geometric and regime parameters for the vapour–potassium flows studied. The result allowed an assumption that the experimental values

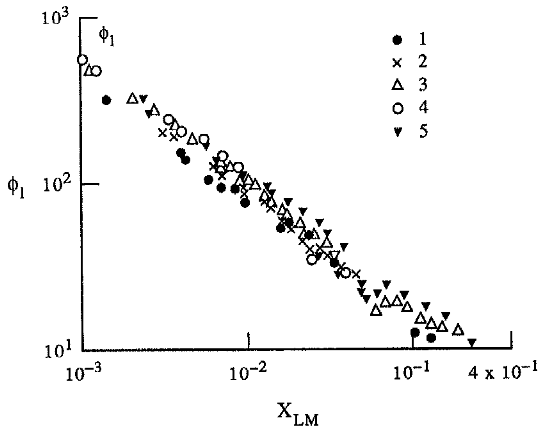

Fig. 3. Relative friction pressure drops of vapour-potassium flow ($d/D = 0.0357$), G (kg m^{-2} s^{-1}): 1, 68; 2, 84; 3, 102; 4, 116; 5, 134.

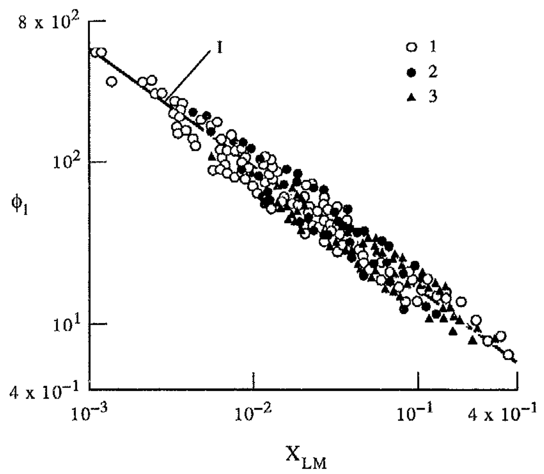

Fig. 4. Experimental data on relative friction pressure drop; D/d, 1, 0.0357; 2, 0.049; 3, 0.062; I, calculation by equation (4).

of ϕ_l for coil pipes have to coincide with similar data for straight pipe channels and evaporators of other geometries.

On the basis of the above consideration comparison was made between the data of the present work with the available data for liquid metals (potassium and sodium) in straight vertical [4, 6, 10] and horizontal [11] pipes, in coil pipes [12] and in bundle rods [13]. The results of the comparison are given in Fig. 5. Curve 8 in this figure was calculated by the Lockhart–Martinelli method [2]. It can be seen from Fig. 5 that the experimental values obtained for ϕ_l are in good agreement.

The comparison of all the available results with the Lockhart–Martinelli dependence shows that as a whole the experimental values of ϕ_l are lower than those calculated by the Lockhart–Martinelli method. Thus, while the divergence is not large in the range $0.02 < X_{LM} < 0.2$, which earlier allowed us to consider the Lockhart–Martinelli method applicable for determining Δp_f in liquid metal two-phase flows, with $X_{LM} < 0.02$ (approximately $x > 0.7$) this divergence becomes appreciable (50% and above).

The analyses of all the experimental data obtained for Δp_f and all the other available data on liquid metals in channels of various configurations and orientations showed that the data could be described by a unified dependence. The data generalization led to the following empirical relationship:

$$\phi_l = 2.75 X_{LM}^{-0.66} \tag{4}$$

which can be applied for calculations in the range $0.001 < X_{LM} < 1$.

6. CONDITIONS WITH HEAT INPUT

Investigation of the influence of the heat flux q on pressure drops Δp_f^h was carried out in the range of the parameters: $G = 115$–243 kg m^{-2} s^{-1}, $q = (0.58$–$2.85) \times 10^5$ W m^{-2}, $x = 0.146$–0.796, $T_s = 1045$–1176 K. In processing experimental results, the Δp_f^h values were related to the average saturation temperature determined as the arithmetic mean between the values corresponding to the inlet and outlet of the test section (the length of the test section was 0.4 m).

Figure 6 presents experimental data in the form of the dependence of the relative pressure drops ϕ_l in heating on X_{LM}. Curve 4 shows the corresponding friction pressure drops in adiabatic conditions calculated according to equation (4).

The analysis of the data shows that the parameter X_{LM} allows us to obtain close enough values of the relative friction pressure drops for regimes with inclusive heat input. This makes it possible to infer that, just as for sodium [10], the influence of the absolute value of pressure and void fraction ϕ_l for potassium is similar qualitatively, and to some extent quantitatively, to the influence typical for adiabatic conditions. No separation was noted when the results were processed this way. Finally, the set of the experimental values of ϕ_f^h as a whole were lower than those calculated for adiabatic conditions. That is, in the range $0.05 < X_{LM} < 0.2$ this decrease is not large and is within the limits of experimental accuracy.

Thus, it is possible to state that, just as for water, and as it was discovered in refs. [10, 14] for sodium, there is an influence of heating on friction pressure drop for potassium which shows itself in the decrease of relative pressure drops. To determine the degree of this influence and to formulate the quantitative laws that govern this influence, experimental data were analysed using the methods based on the model of injection in the problems of a boundary layer [15]. The fitness of these methods for forecasting Δp_f^h in a two-phase vapour–sodium flow is given in ref. [14].

According to the recommendation given in ref. [14], experimental data on Δp_f^h were processed in coordinates where the relative friction coefficient ψ and injection parameter B were defined as

$$\psi = \Delta p_f^h / \Delta p_f^{ad} \quad B = \frac{4qGx}{\rho_g \lambda \alpha^{1.5} (\Delta p_f^h / \Delta l)}. \tag{5}$$

Here λ is the specific heat of vapour formation and Δl is the length of the measured part of the test section.

Figure 7 shows the values of ψ as a function of B calculated from equation (5). The values were calculated from the experimental data of the present paper. Curve 4 in Fig. 7 is calculated from the formula

$$\psi = \frac{(1-0.19B)^2}{(1+0.25B)^{0.25}} \tag{6}$$

the suitability of which for vapour–sodium flows is shown in ref. [14].

It is seen from Fig. 7 that there is no considerable spread in experimental data about curve 4 and the behaviour of experimental points in the area $B > 0$ is in agreement with the trend of curve 4 and with the

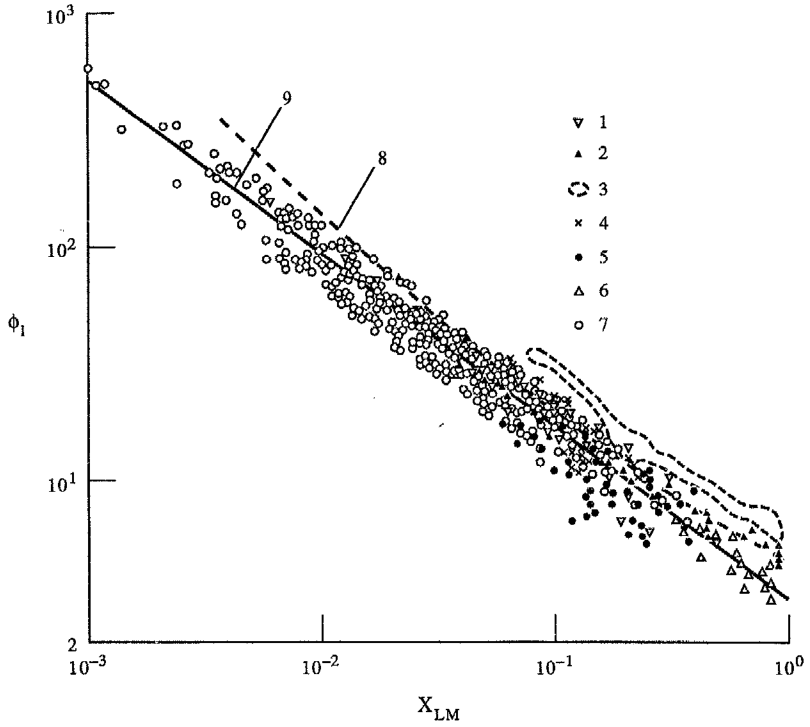

Fig. 5. Generalization of experimental data on friction pressure drop: 1, data of ref. [1]; 2, data of ref. [4]; 3, data of ref. [2]; 4, data of ref. [5]; 5, data of ref. [3]; 6, data of ref. [6]; 7, present paper; 8, Lockhart–Martinelli curve; 9, calculation by equation (4).

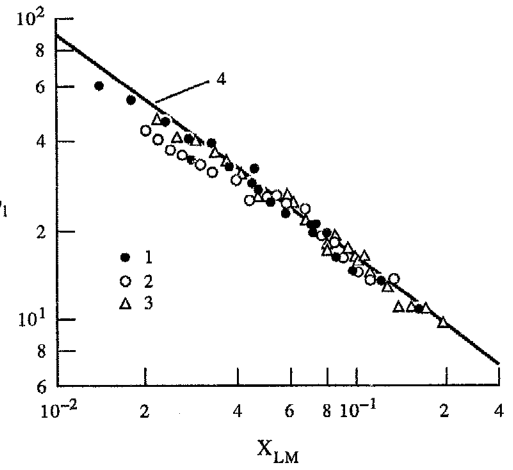

Fig. 6. Concerning the analysis of the influence of heat flux on relative pressure drops, G (kg m^{-2} s^{-1}): 1, 155; 2, 208; 3, 243; 4, calculation by equation (4).

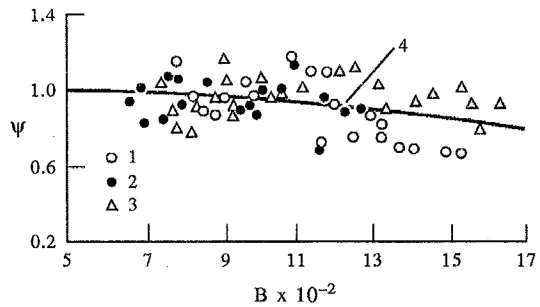

Fig. 7. Dependence of relative friction coefficient on injection parameter, G (kg m^{-2} s^{-1}): 1, 155; 2, 208; 3, 243; 4, calculation by equation (6).

general trend of the decrease in the ψ value with an increase in B. Experimental data on Δp_f^h in the area of the parameters under investigation agree well, in principle, with calculations by formulae (5) and (6).

7. CONCLUSIONS

Summarizing the studies described above, it is possible to arrive at the following conclusions.

(1) Void fractions and friction pressure drops of vapour–potassium flows are a poorly studied field for vapour qualities $0.5 < x < 1$.

(2) It is stated that, like for a low quality ($x < 0.5$) two-phase flow, the mass velocity in the area under study has practically no influence on the parameters investigated.

(3) On the basis of the present investigation data and of all similar experimental data given by other authors, calculation relationships for the following hydrodynamic characteristics of liquid metal two-phase flow are obtained;

—void fraction,

—friction pressure drop in the channels of various orientations and configurations (vertical, horizontal, ring, helical coil pipes, bundle rods), applicable for liquid metals (potassium, sodium and others) in the range of vapour qualities from several to near 100%.

(4) It is stated that supplying heat to vapour–potassium flow lowers the friction pressure drop in comparison with adiabatic conditions, as in the case with sodium. The results obtained are in good qualitative and quantitative agreement with the model of injection influence upon the value of shearing stress in the boundary layer.

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