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TECHNICAL PAPER proposed for presentation at
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Abstract

The effect of helical-flow-promoting inserts on boiling pressure drop is correlated for water and alkali metals at relatively low pressures. A constant-slip model is used. The slip ratio (mean gas velocity divided by mean liquid velocity) is approximated by the square root of the liquid-to-gas density ratio. For boilers with no inserts, the two-phase friction factor has previously been correlated as a function of mean superficial liquid and gas Reynolds numbers. It is assumed that inserts affect pressure drop through an increase in friction factor and reduction in flow area. The two-phase friction factor is correlated herein as a function of mean superficial liquid and gas Reynolds numbers and the ratio of insert pitch to tube diameter.

INTRODUCTION

Helical-flow-promoting inserts are often used in boilers to improve separation of the phases, increase heat-transfer coefficients (thereby reducing the required heat-transfer area), and produce a more stable and reliable system. However, these benefits are accompanied by a larger pressure drop across the boiler than with no inserts. Thus, it is necessary to know the pressure-drop penalties imposed by helical-flow inserts, as well as the performance improvements obtained in order to achieve an optimum design. This paper deals with the pressure drop in water and alkali metal boilers with and without helical-flow inserts.

Some experiments have been reported (refs. 1-3) on the boiling of alkali metals in heat exchangers with and without inserts. Lewis, Groesbeck, and Christenson (ref. 1) report data for sodium boiling in a single tube-in-shell heat exchanger with no inserts at temperatures from 1211 to 1355 K (liquid-to-gas density ratio from about 650 to about 1650); in some cases high exit quality could be obtained stably, even though no inserts were used. Peterson (ref. 2) presents results for potassium boiling in a single-tube-in-shell heat exchanger at temperatures from about 1090 to 1230 K (liquid-to-gas density ratio, ~330 to ~850); results are given with and without helical-vane inserts. Collins, Boppart, and Berenson (ref. 3) report data for potassium boiling in curved, multiple-tube heat exchangers with twisted-tape inserts; tests are reported at temperatures from about 980 to 1170 K (liquid-to-gas density ratio, ~470 to ~2200).

Since experiments with the alkali metals are difficult and expensive to perform, a series of experiments have been made at Lewis Research Center on water-boiling heat exchangers (refs. 4-6). Alkali-metal properties at temperatures of interest for space power systems are approximated by water near atmospheric pressure, except for liquid thermal conductivity. A correlation of pressure drop in boilers with no inserts has been obtained in reference 4; a constant-slip model similar to that of Thom (ref. 7) is used. In reference 6, it is shown that pressure-drop data for water boiling with a helical-wire insert (ratio of wire pitch to tube diameter, 1.9) can be correlated by the model of reference 4 with an increased friction factor.

The purpose of this report is to give a simple method of predicting pressure drop in boilers with and without helical-flow-promoting inserts, applicable to alkali metals. It is desired to avoid the necessity of knowing details of heat flux and void distribution within the boiler and to avoid any trial-and-error or iterative calculations. Since the model used is approximate, data taken over a wide range of test conditions are used to determine the empirical correlation of the two-phase friction factor. The model of reference 4 is used, and all swirl effects are lumped in the frictional pressure drop term. Data are correlated for insert-pitch-to-tube-diameter ratios of 1.9 and greater and over a range of liquid to gas density ratio from about 330 to about 6000 for water, sodium, and potassium.

ANALYSIS

Application of the laws of conservation of energy, mass, and momentum yields the pressure drop as the sum of three terms: inertial, gravitational, and frictional. From mass balance considerations,

$$u_l = \frac{G}{\rho_l}\left(\frac{1 - x}{1 - \alpha}\right) \tag{1}$$

and

$$u_g = \frac{G}{\rho_g}\left(\frac{x}{\alpha}\right) \tag{2}$$

Dividing equation (2) by equation (1) and solving for the void fraction α, the following results:

$$\alpha = \frac{x(u_l/u_g)(\rho_l/\rho_g)}{1 + x\left[(u_l/u_g)(\rho_l/\rho_g) - 1\right]} \tag{3}$$

Thom (ref. 7) fit void-fraction data for water boiling at pressures from 10^5 to 2×10^7 N/m^2 abs. and vapor qualities of 0.03 and greater by assuming that the slip ratio u_g/u_l is a function of pressure only. The boiling pressure-drop correlation of reference 4 showed that the approximation, $u_g/u_l = \sqrt{\rho_l/\rho_g}$, appears valid. Although this differs from the relationship used by Thom (ref. 7), it should be noted that Thom presents pressure-drop results only for water at pressures of 1.7×10^6 N/m^2abs. or greater $\rho_l/\rho_g < 100$), whereas this paper deals with data for $\rho_l/\rho_g > 300$. The assumption that velocity ratio is equal to the square root of the density ratio has often been utilized previously. The following analysis is otherwise similar to that of Thom (ref. 7), except for the treatment of the two-phase friction factor.

Inertial Pressure Drop

The inertial pressure drop for all-liquid flow at the inlet is obtained as follows:

$$\Delta P_I = G(1 - x_e)u_{le} + Gx_e u_{ge} - G^2/\rho_l \tag{4}$$

Substituting from equations (1), (2), and (3) and assuming constant flow area and physical properties, the following is obtained, as in reference 4:

$$\Delta P_I = (G^2/\rho_l)R_1 \tag{5}$$

where

$$R_1 = \left[1 + x_e(\sqrt{\rho_l/\rho_g} - 1)\right]^2 - 1 \tag{5a}$$

Gravitational Pressure Drop

The gravitational pressure drop for vertical-upward flow is given by

$$\Delta P_G = g \int_0^L \rho_{mean}\, d\ell \tag{6}$$

For constant heat flux and physical properties, Thom (ref. 7) obtained the following:

$$\Delta P_G = g\rho_l L R_2 \tag{7}$$

With the simplifying assumption, $u_g/u_l = \sqrt{\rho_l/\rho_g}$, R_2 is given by (ref. 4)

$$R_2 = \frac{\sqrt{\rho_g/\rho_l} - 1}{\sqrt{\rho_l/\rho_g} - 1} + \frac{(\sqrt{\rho_l/\rho_g} - \sqrt{\rho_g/\rho_l})}{x_e\left[(\sqrt{\rho_l/\rho_g}) - 1\right]^2} \ln\left[1 + x_e \sqrt{\rho_l/\rho_g} - 1)\right] \tag{7a}$$

Frictional Pressure Drop

By analogy to single-phase flow, the frictional pressure drop may be written

$$\Delta P_F = 4f\left(\frac{L}{D}\right)\left(\frac{G^2}{2}\right) v_{mean} \tag{8}$$

Thom (ref. 7) arbitrarily assumed the effective mean specific volume is given by the arithmetic average of inlet and exit specific volumes; thus,

$$\Delta P_F = 4f\left(\frac{L}{D}\right)\left(\frac{G^2}{2\rho_l}\right)(R_1 + 2) \tag{9}$$

In reference 4, the constants 2 and 4 were lumped with f so that

$$\Delta P_F = f_{TP}\left(\frac{L}{D}\right)\left(\frac{G^2}{\rho_l}\right)(R_1 + 2) \tag{10}$$

Plain-Tube Friction-Factor Correlation

The two-phase friction factor f_{TP} for water boiling in heat exchangers with no inserts was correlated empirically in reference 4. The effective mean values of f_{TP} for the data of references 4 and 8 were correlated as follows:

$$f_{TP} = 0.020\ Re_g^{-0.2}\left(1 + 0.027\ Re_l^{0.5}\right) \tag{11}$$

Application to Boilers with Inserts

To determine the frictional pressure drop from the experimental data, it is assumed that the insert affects only the frictional pressure drop. Any rotational effects, as well as any changes in ΔP_I and ΔP_G, are lumped with the actual frictional pressure drop. Two types of inserts are considered: a wire helix touching the tube wall (refs. 5 and 6), and a helical vane attached to a center rod (ref. 2). The effect of entrance region plugs is considered negligible for the data correlated herein. The data of reference 3 are not used, since the boiler pressure drop listed therein includes the pressure drop across the inlet orifices and unheated buffer zones.

RESULTS AND DISCUSSION

The semi-empirical, slip-flow model presented herein is used to evaluate effective two-phase friction factors from the experimental data of references 1, 2, 5, and 6. It is found that the two-phase friction factor can be correlated as a function of superficial mean liquid and gas Reynolds numbers and the insert-pitch-to-tube-diameter ratio, p/D. The Reynolds numbers are calculated as follows:

$$Re_l = \frac{DG}{\mu_l}(1 - x_e/2) \tag{12a}$$

$$Re_g = \frac{DG}{\mu_g}\left(\frac{x_e}{2}\right) \tag{12b}$$

It is assumed that the variation of f_{TP} with Re_g is similar to the relation with no inserts, i.e., $f_{TP} \sim Re_g^{-0.2}$. Therefore, $f_{TP}Re_g^{0.2}$ is plotted versus Re_l in figure 1 and compared in the following sections with the plain-tube correlation of reference 4,

$$f_{TP}Re_g^{0.2} = 0.020\left(1 + 0.027\ Re_l^{0.5}\right) \tag{13}$$

No Inserts

To demonstrate that the correlation of reference 4 is applicable to alkali-metal boilers, the plain-tube data for sodium (ref. 1) and potassium (ref. 2) are shown in figure 1. The parameter, $f_{TP}Re_g^{0.2}$, is plotted versus Re_l for exit qualities above 0.1, but less than 1.0 and $\Delta P_B > 25\ kN/m^2$. From reference 1, only data categorized as stable, with no critical heat-transfer phenomena, are shown; the phase condition at the boiler inlet is indicated as either liquid or flashing. The data agree reasonably well with the correlation of reference 4 (the solid line in fig. 1), but on the average do fall somewhat lower. A better idea of the actual data scatter is given in figure 2, where experimental and calculated pressure drops are compared. For $\Delta P_{B\text{-}exp} > 50\ kN/m^2$, 96 percent of the experimental data fall within the band +6 to -20 percent of calculated values. The scatter increases for lower $\Delta P_{B\text{-}exp}$, as might be expected, since in both references 1 and 2, ΔP_B is obtained from the difference between two numbers generally much larger than ΔP_B. Thus, it is concluded that the correlation of reference 4 provides a valid limiting condition for $p/D \to \infty$.

With Helical-Flow Inserts

The data of reference 2, for potassium boiling in a tube with helical-vane inserts, and references 5 and 6, for water boiling in a tube with a helical-wire insert are shown in figure 1 for $0.1 \leq x_e < 1.0$ and $\Delta P_B > 25$ kN/m^2. From references 5 and 6 only data categorized as stable, with no exit vapor superheat, are shown. The data with inserts fall well above the plain-tube correlation, as expected; $f_{TP}Re^{0.2}$ increases with decreasing p/D for a given Re_l. It also appears that the dependence of $f_{TP}Re_g^{0.2}$ on Re_l is weaker than in the plain-tube case. The following equation, shown by the dashed curves in figure 1, is found to fit the data reasonably well for $Re_l \leq 10^5$:

$$f_{TP}Re_g^{0.2} = 0.020 + 0.42\left(\frac{D}{p}\right)^2 + 0.00054\left(1 + \frac{D}{p}\right)^3 Re_l^{0.5} \tag{14}$$

This equation reduces to the plain-tube correlation, equation (13), in the limit as $D/p \to 0$. There are insufficient data to extend the correlation beyond $Re_l = 10^5$. A better idea of the actual data scatter is given in figure 3, where experimental and calculated pressure drops are compared. For $\Delta P_{B\text{-}exp} > 50$ kN/m^2, 95 percent of the experimental data fall within ±20 percent of calculated values, with the scatter increasing for lower $\Delta P_{B\text{-}exp}$, as expected.

CONCLUDING REMARKS

An empirical correlation is presented of boiling pressure drop, accounting for the effect of helical-flow-promoting inserts. A constant-slip model previously reported by the author, based on modification of Thom's model, is used, with the assumption that the inserts affect pressure drop through an increase in the friction factor and reduction of the flow area. The correlation is based on data for water, sodium, and potassium, covering a range of liquid-to-gas density ratio of about 330 to 6000, at superficial liquid Reynolds numbers from 1.6×10^3 to 10^5. The range of boiler geometries include insert-pitch-to-tube-diameter ratios down to 1.9 in tubes of 1.1 to 2.3 cm diameter and length to diameter ratios from 73 to 140. The use of this correlation does not require a detailed knowledge of the heat flux and void fraction distributions within the boiler, nor does it require trial and error or iterations, thus allowing simple, straightforward calculations.

NOMENCLATURE

D	inside diameter of boiler tube
f	friction factor, eq. (8)
f_{TP}	two-phase friction factor, eq. (10)
G	mass velocity of boiling fluid
g	acceleration due to gravity
L	boiler length
ℓ	axial distance along boiler

ΔP_B boiler pressure drop

ΔP_F frictional pressure drop

ΔP_G gravitational pressure drop

ΔP_I inertial pressure drop

p insert pitch

R_1 inertial pressure drop multiplier, eq. (5a)

R_2 gravitational pressure drop multiplier, eq. (7a)

Re mean superficial Reynolds number, eq. (12)

u mean velocity

v specific volume

x vapor quality

α void fraction

μ viscosity

ρ density

Subscripts:

calc calculated

e value at boiler exit

exp experimental

g gas

l liquid

mean mean value

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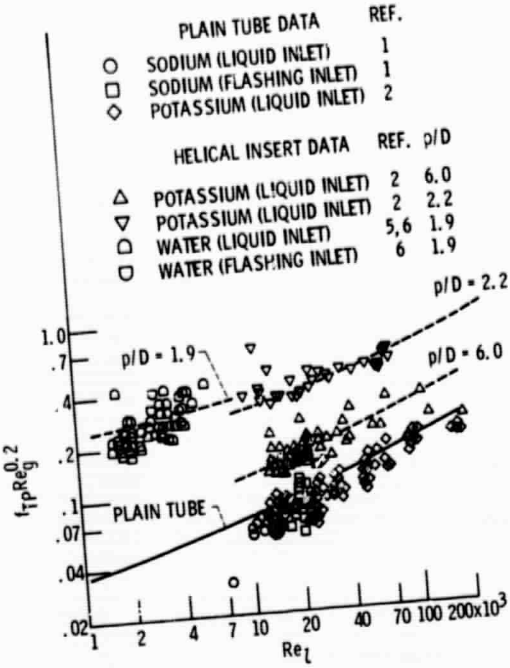

Figure 1. - $f_{TP}Re_g^{0.2}$ against Re_l for various geometries.

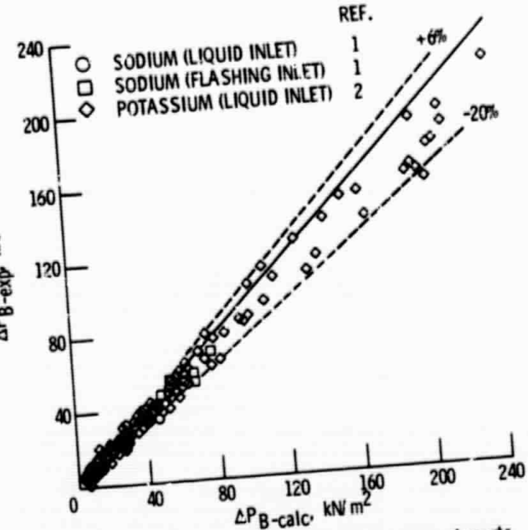

Figure 2. - ΔP_{B-exp} against ΔP_{B-calc}; no inserts.

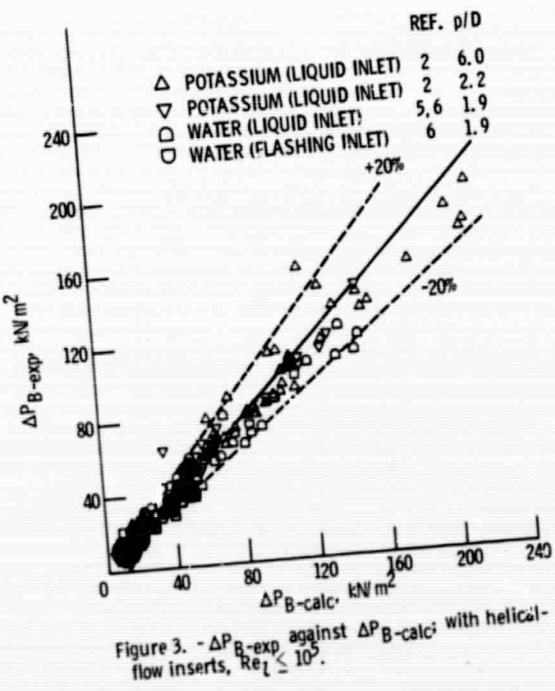

Figure 3. - ΔP_{B-exp} against ΔP_{B-calc}; with helical-flow inserts, $Re_l \leq 10^5$.