Flow correlations for brine flashing through round and square submerged orifices
by Ralph Coolidge Huntsinger

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Chemical Engineering
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Abstract:
The flow properties of salt water flashing through submerged round and square orifices are investigated in this thesis. New correlations that will satisfactorily represent the flow of brine flashing through submerged orifices are presented. The correlations are developed for a stage pressure range of 7.0 psia to 22.2 psia and for brine concentrations ranging from fresh water to 3.4 times the concentration of normal sea water. Four sizes of round sharp edged orifices and three sizes of square sharp edged orifices were used.

The investigation was carried out in a two-stage single-effect flash evaporation saline water conversion pilot plant. The correlations are based on the fluid properties evaluated at the high and low pressure stage conditions. .The best correlations for the high pressure stage conditions and the low pressure stage conditions respectively are as follows: $(Q(\Delta P)^2 gc^{1/2})/(\mu^2 \lambda^{3/2}) = 37.83((D\Delta P gc^{1/2})/(\mu\lambda^{1/2}))^{1.826} ((\rho\lambda/\Delta P))^{-0.7434}$ $(Q(\Delta P)^2 gc^{1/2})/(\mu^2 \lambda^{3/2}) = 33.05((D\Delta P gc^{1/2})/(\mu\lambda^{1/2}))^{1.830} ((\rho\lambda/\Delta P))^{-0.7349}$ The exponents were determined by performing a multiple linear regression analysis on the logarithms of the dimensionless groups for 93 experimental points. The multiple correlation coefficient for the regression analysis is 0.9952 for the upstream stage conditions and 0.9949 for the downstream stage conditions.

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ABSTRACT

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INTRODUCTION

Several investigations have been made on the flow characteristics of two phase flow of various liquids and gases through orifices, short tubes and abrupt expansions in general.

The purpose of this thesis is to specifically investigate the flow of flashing salt water of various concentrations through submerged round and square sharp edged orifices and to obtain a new set of correlations that will satisfactorily represent the two phase flow of salt water in terms of the physical conditions of the flashing.

The reason for the interest in the flow of flashing salt water through orifices is to obtain design correlations that can be used in the design of large multi-stage flash evaporation saline water conversion plants. It is desired to obtain a correlation that does not require a knowledge of the quality of the fluid to satisfactorily predict the two-phase flow of flashing brine through orifices.

Pasqua (22) investigated the metastable flow of freon-12 through short tubes. Experimental data as well as photographs show that saturated and subcooled liquid freon-12 flowing through short tubes is not in a stable equilibrium state. The following correction factor for the standard orifice equation was developed:

$$G = C_e C \sqrt{2g_c \quad (P_s - P_x)}$$

$$C_e = \left[\frac{1}{\dfrac{0.37(L/D)^{.2} - P_x/P_s}{C_v^2 \quad 1 - .37(L/D)^{.2}} + 1} \right]^{0.5}$$

G = mass flow rate of fluid (mass per unit area per unit time)

C_e = coefficient of contraction

C_v = coefficient of velocity of an orifice

L = length of tube

D = diameter of tube

P_s = saturation pressure of the liquid

ρ = density of fluid (mass per unit volume)

P_x = discharge pressure (force per unit area)

C = standard coefficient of discharge

Isbin, Moy and DaCruz (13) developed a method of measuring the critical flow behavior of steam-water mixtures for flow in pipes and annular spaces.

The homogeneous flow model for evaluating critical discharges for low qualities was demonstrated to be inadequate. The flow is correlated on the basis of quality.

An approximation of the Martinelli (17) correlation of R_g was obtained by Isbin, Moy and DaCruz for the steam-water system as follows:

$$R_g = a X + b$$

$$X^2 = \left(\frac{1 - x}{x}\right)^{1.8} \left(\frac{\nu_f}{\nu_g}\right) \left(\frac{\mu_f}{\mu_g}\right)^{0.2}$$

a and b = constants to be determined for each range

X = quality

ν = specific volume (volume per unit mass)

μ = viscosity

subscripts:

f = fluid

g = gas

Min, fauske and Petrick (19) have studies the effect of shape of flow passages on two-phase critical flow. Saturated and subcooled freon-11 was discharged into a vacuum through short tubes and orifices. The different geometric shapes of sharp edged orifices used were: circle, triangle, square, eye-shape, W shape and rectangular.

A modified cavitation number was defined which was plotted on a log log plot against the Reynolds number. The cavitation number was defined as follows:

$$C_a' = \frac{\Delta P \; L}{\left(\frac{\rho_i U^2}{2g_c}\right) D}$$

U = velocity

ρ_i = initial density

ΔP = pressure difference

L = length of tube or orifice

D = diameter of tube or orifice

Bailey (3) investigated the metastable flow of saturated water. Short tubes, nozzles and orifices were studied in this investigation. A correction coefficient was developed for the general orifice equation as follows:

$$G = C_e C \sqrt{2g_c(P_o - P_x)/V}$$

$$C_e = 1.0 - 17200\ K(L/D)\ V^{-0.5}\ P_o^{-0.435}\ Z$$

$$K = 3.52(10^6)(D/L)P_c^{0.935}\left[(P_o - P_c)\ V\right]^{1/2}/(P_s - P_c)$$

G = mass flow rate

C_e = correction coefficient

C = standard coefficient of discharge

K = coefficient of evaporation ($time^{-1}$)

L = length of orifice

D = diameter of orifice

V = specific volume of liquid

P_o = initial pressure

Z = graphical factor (function of P_o, P_s and P_x)

P_s = saturation pressure

P_x = exit pressure

P_c = critical pressure of the liquid

Sudden contraction pressure losses in two-phase flow were investigated by Geiger and Rohrer (10). The separated flow model was compared with the fog flow model.

The fog flow model was the best predictor for their experimental data. The following correlation was developed for the 200 to 500 psia pressure range:

$$P_c = \frac{G_3^2}{2g_c}\left[1 - \sigma^2 + \bar{K}_{TP_c}\right]$$

$$\bar{K}_{TP_c} = (\sigma^2 - 1) + \frac{2x^2\bar{\rho}}{g}\left[\frac{\alpha_{3g}}{R_3} - \frac{\alpha_{2g}}{R_2 C_c}\right]$$

$$+ \frac{2(1-x)^2\bar{\rho}}{\rho_f}\left[\frac{\alpha_{3f}}{(1-R_3)} - \frac{\alpha_{2f}}{(1-R_2)C_c}\right]$$

$$+ \frac{x^3\bar{\rho}^2}{\rho_g^2}\left[\frac{\beta_{2g}}{R_2^2 C_c^2} - \frac{\beta_{1g}\sigma^2}{R_1^2}\right]$$

$$+ \frac{(1-x)\bar{\rho}^2}{\rho_f^2}\left[\frac{\beta_{2f}}{(1-R_2)^2 C_c^2} - \frac{\beta_{1f}\sigma^2}{(1-R_1)^2}\right]$$

X = mixture quality, mass of vapor to mass of mixture flowing

σ = area contraction ratio A_3/A_1

R = vapor volume fraction

α = momentum correction factor

β = kinetic energy correction factor

f = liquid phase subscript

g = vapor phase subscript

C_c = contraction coefficient of vena contracta

ρ = density, mass per unit volume

$\bar{\rho}$ = density of homogeneous two-phase fluid

subscript 1 = upstream of area change

subscript 2 = at vena contracta

subscript 3 = downstream of area change

The test range for the correlation is given in the following table:

σ	$G(LB/HR\text{-}FT^2) \times 10^6$ Min	Max	X Max
0.398	0.520	1.824	0.265
0.253	0.902	2.850	0.245
0.144	1.560	4.820	0.160

Murdock (21) investigated the measurement of two-phase flow with orifices. Some of the two-phase systems studied were: natural gas - water, natural gas - salt water, air - water, and steam-water.

The range of the ratio of orifice diameter to internal pipe diameter for this work was from 0.26 to 0.50. The following correlation was developed:

$$\sqrt{\frac{\Delta P_{TP}}{\Delta P_G}} = 1.26 \sqrt{\frac{\Delta P_L}{\Delta P_G}} + 1.0$$

ΔP_{TP} = pressure drop for two-phase flow

ΔP_G = pressure drop for gas flow only

ΔP_L = pressure drop for liquid flow only

This correlation fits Murdock's results very well, but the quality of the flow must be known to compute ΔP_L and ΔP_G. Murdock combined his correlation with the American Society of Mechanical Engineers' standard flow equation to give the following correlation for two-phase flow:

$$W = \frac{359 K_G Y_G F_a d^2 \sqrt{h_{WTP} \rho_v}}{(1 - y) + 1.26 y \frac{K_G Y_G}{K_L} \sqrt{\frac{\rho_v}{\rho_L}}}$$

W = weight rate of flow (lb/hr)

$K_G Y_G$ = product of flow coefficient and net expansion factor for gas flow through an orifice

K_L = flow coefficient for liquid flow through an orifice ($Y_L = 1$)

F_a = factor to account for the thermal expansion of the orifice

h_{WTP} = effective differential head produced by two-phase flow through the orifice, in inches of water

y = liquid weight fraction

d = orifice diameter, in inches

ρ_v = density of the vapor

ρ_L = density of the liquid

The flow of steam - water mixtures in a heated annulus and through orifices was studied by Hoopes (12). A homogeneous two-phase mixture is assumed in developing the flow model. The following correlation is based on vena contracta conditions:

$$\frac{\Delta P_{oTP}}{\Delta P_{of}} = \frac{(1-x)^2}{R_f} + \frac{\nu_g x^2}{\nu_f R_g}$$

R = fraction of cross-section occupied by a phase

X = quality (Wg/W)

W = weight rate of flow, mass per unit time

g = gas phase subscript

f = liquid phase subscript

ν = specific volume, volume per unit weight

ΔP_{oTP} = two-phase orifice pressure drop based on W

ΔP_{of} = orifice pressure drop if W lb/sec of liquid were flowing

$R_g = (1 - R_f)$

The flow of saturated water through throttling orifices was investigated by Benjamin and Miller (4). The results were presented in graphical form and required that the quality be known to predict the mass flow rate for a given pressure difference. The downstream pressure was