Predicting Wet-Steam Flow Regime in Horizontal Pipes

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Summary. Knowing or predicting the flow regime for a wet steam flowing in a steam-distributing network is important to the engineering, management, and economics of steamflood EOR projects. The flow-regime data of steam in horizontal pipes were compiled and analyzed with Taitel and Dukler's model of predicting flow regimes for two-phase flow. These data were used to construct steam flow charts, to determine the effect of operating variables on the transitions of flow regimes, and to establish transition criteria for steam flow in horizontal pipes.

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Introduction

All steam EOR projects involve a steam-distribution system. Most steam used in oilfield steam stimulation and steamflood operations is a wet steam, with various levels of quality. It is classified as a two-phase fluid. Many aspects of two-phase flow behavior—such as frictional pressure loss, liquid holdup, and phase splitting at piping tees—are affected by the flow regime existing in the distribution system. Predicting the flow regime is important to the efficient and effective operation of oil recovery projects. However, the flow regimes are much more complicated for two-phase fluids. To date, no method or chart has been published specifically for the prediction of wet-steam flow regimes. This problem can be addressed either through experiments or by adapting a general flow-regime prediction technique developed for two-phase flow. The latter approach is used in this study.

After several techniques[1-3] for predicting flow regimes of two-phase flow were reviewed and compared, Taitel and Dukler's[3] model was selected for steam flow. The flow regimes of wet steam flowing in horizontal pipes are presented here.

To facilitate the computation of the flow regimes, a two-phase-flow computer program based on Taitel and Dukler's model[3-5] was used. These flow-regime data are then used to construct steam flow charts, to determine the effect of steam quality and operating variables on flow-regime transitions, and to establish criteria for these transitions.

This study covers steam pressure ranging from 200 to 2,000 psia [1.38 to 13.8 MPa]; steam quality, from 2 to 90%; pipe size, from 2 to 24 in. [5 to 61 cm] (Schedule 80); and steam flow rate, from 50 to 620,000 B/D [8 to 98 600 m^3/d] cold water equivalent (CWE). A pipe roughness of 0.001 in. [0.025 mm] was used for all pipes except where specified. Steam properties are based on those listed in the steam tables.[6]

Taitel and Dukler's Theoretical Model

Taitel and Dukler classified horizontal two-phase flow into five flow regimes: stratified smooth, stratified wavy, intermittent, annular, and dispersed bubble (**Fig. 1**). In stratified smooth flow, the liquid phase flows along the bottom of the pipe, the gas phase flows along the top, and the interface is smooth. In stratified wavy flow, the two phases are separated in the same manner, except the interface is wavy. In intermittent flow, the liquid phase in the pipe is distributed nonuniformly along the flow direction. Plugs or slugs of liquid are separated by gas bubbles or vice versa. In annular flow, sometimes also called annular dispersed or annular/mist flow, the liquid phase flows as a film on the pipe wall surrounding a core of high-velocity gas phase containing various degrees of entrained liquid. Finally, in dispersed bubble flow, the gas phase is distributed as discrete bubbles within a continuous liquid phase.

Using physical mechanisms associated with the instability of a solitary wave, Taitel and Dukler developed a theoretical and empirical model to predict the transitions between flow regimes and presented those regimes in the form of a flow-regime map (**Fig. 2**). The dimensionless parameters used in the model are the Martinelli parameter,

$$\chi=\left[\frac{\left(\dfrac{dP}{dL}\right)_L}{\left(\dfrac{dP}{dL}\right)_G}\right]^{0.5}$$

$$=\left[\frac{\dfrac{4}{D}f_L\rho_L\dfrac{(V_{sL})^2}{2g_c}}{\dfrac{4}{D}f_G\rho_G\dfrac{(V_{sG})^2}{2g_c}}\right]^{0.5}, \quad \ldots\ldots(1)$$

the dimensionless equilibrium liquid level,

$$h_D=h/D, \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

the modified Froude number,

$$N_{Fr}=\left[\frac{\rho_G}{(\rho_L-\rho_G)}\frac{(V_{sG})^2}{Dg\cos\alpha}\right]^{0.5}, \quad \ldots(3)$$

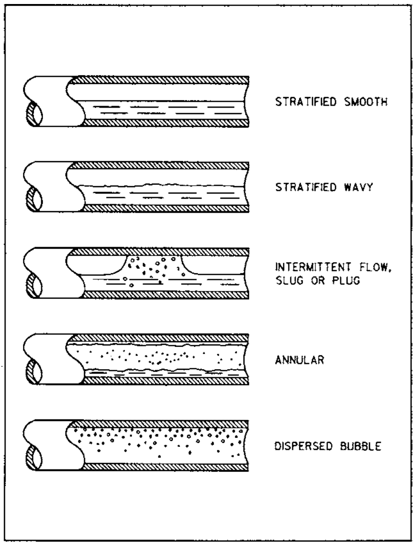

Fig. 1—Flow regime for horizontal flow.

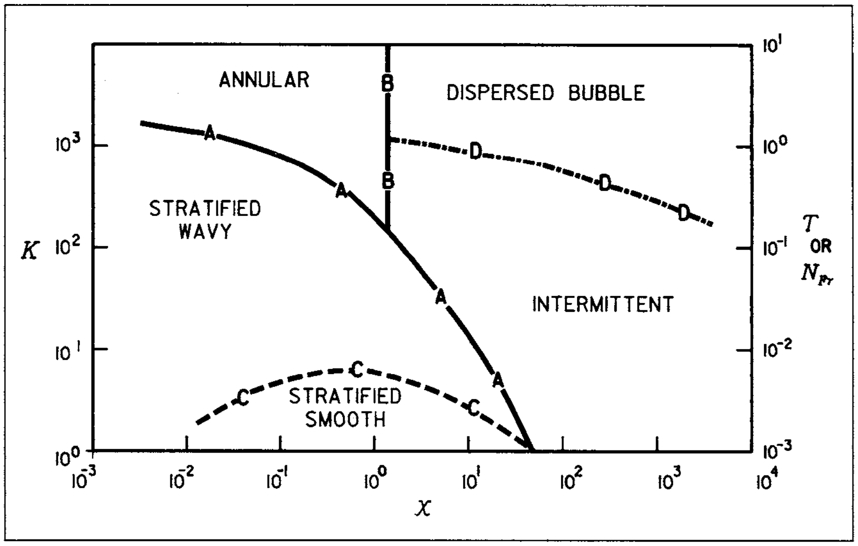

Fig. 2—Taitel and Dukler's flow-regime map.

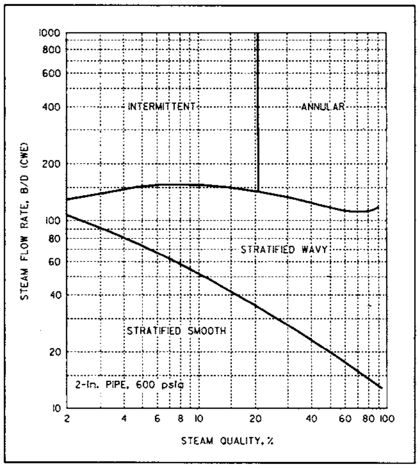

Fig. 3—Steam flow chart for 2-in. horizontal pipe, 600-psia steam.

the turbulent-forces parameter,

$$T=\left[\frac{\left(\dfrac{dP}{dL}\right)_L}{(\rho_L-\rho_G)}\,\frac{g_c}{g\cos\alpha}\right]^{0.5}$$

$$=\left[\frac{\dfrac{4}{D}f_L\rho_L\dfrac{(V_{sL})^2}{2}}{(\rho_L-\rho_G)g\cos\alpha}\right]^{0.5}, \quad\ldots\ldots(4)$$

and the wave-generation parameter,

$$K=\left[\frac{\rho_G(V_{sG})^2}{(\rho_L-\rho_G)Dg\cos\alpha}\right]^{0.5}$$

$$\times\left(\frac{DV_{sL}}{\nu_L}\right)^{0.5} \quad\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

The superficial velocities used in these parameters are calculated with the assumption that either the liquid or the gas phase is flowing alone in the pipe. For horizontal flow, $\alpha=0$ and the dimensionless equilibrium liquid level is a unique function of the Martinelli parameter. Thus, χ or h_D joined with one of the other three parameters is used to determine the flow-regime transition and hence the flow regime.

The values of h_D (or χ) and N_{Fr} determine the transition between the annular and stratified wavy and between the intermittent and stratified wavy flow regimes, as well as the location of the flow within the annular-flow-regime area of the map. The values of h_D (or χ) and T determine the transition between the intermittent and dispersed bubble flow regimes and the location of the flow within either of these areas on the map. The values of h_D (or χ) and K determine the transition between the stratified wavy and stratified smooth flow regimes and the location of flow within either of these on the map.

The computer program used here to determine flow regimes follows Taitel and Dukler's model with only a minor change in the calculation of the friction factor. Taitel and Dukler used a friction factor of

$$f=16/N_{\mathrm{Re}} \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

for laminar flow, and

$$f=0.046/(N_{\mathrm{Re}})^{0.2} \quad\ldots\ldots\ldots\ldots\ldots(7)$$

for turbulent flow.

In this study, these friction factors are replaced by Churchill's[7] friction-factor correlation, which is applicable to both laminar and turbulent flow and includes the effect of pipe roughness in turbulent flow:

$$f=\left[\left(\frac{16}{N_{\mathrm{Re}}}\right)^{12}+\frac{4{,}096}{(C_1+C_2)^{1.5}}\right]^{0.0833}, \quad\ldots\ldots\ldots\ldots(8a)$$

where $C_1=$

$$\left\{2.457\ln\left[\frac{1}{\left(\dfrac{7}{N_{\mathrm{Re}}}\right)^{0.9}+\left(\dfrac{0.27\epsilon}{D}\right)}\right]\right\}^{16}, \quad\ldots\ldots\ldots\ldots(8b)$$

and $$C_2=\left(\frac{37{,}530}{N_{\mathrm{Re}}}\right)^{16}. \quad\ldots\ldots\ldots\ldots(8c)$$

The superficial liquid Reynolds number,

$$N_{\mathrm{Re}L}=DV_{sL}/\nu_L, \quad\ldots\ldots\ldots\ldots\ldots(9)$$

and superficial gas Reynolds number,

$$N_{\mathrm{Re}G}=DV_{sG}/\nu_G, \quad\ldots\ldots\ldots\ldots(10)$$

are used in friction-factor calculations.

Steam Flow Charts for Horizontal Pipe Flow

Description. In the steam flow charts, the flow regimes of wet steam flow in horizontal pipes are presented as functions of steam flow rate and steam quality for a constant steam pressure and pipe size. The typical steam flow chart in **Fig. 3** is for steam at 600 psia [4.14 MPa] in 2-in. [5-cm] pipe. Note that the dimensionless parameters used

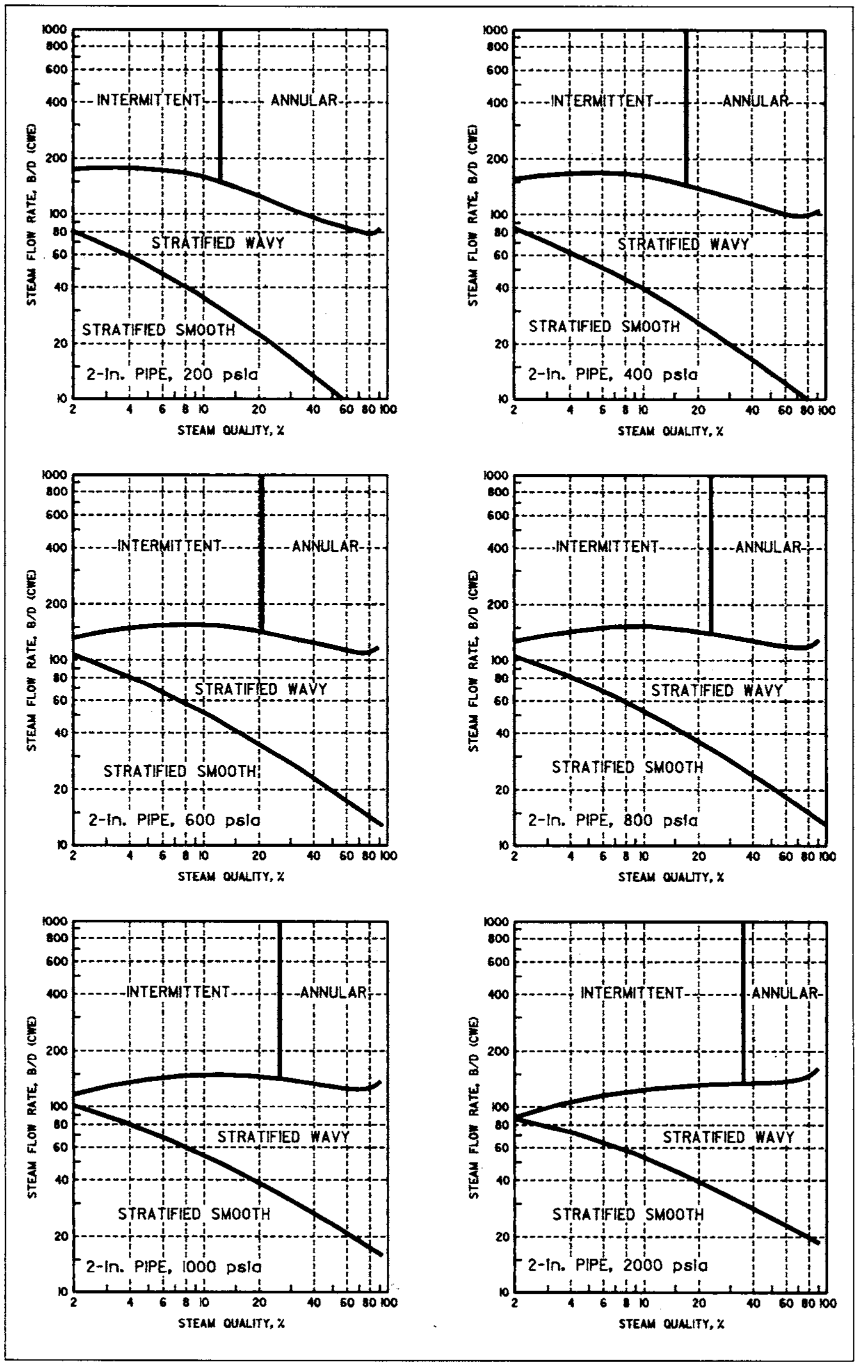

Fig. 4—Effect of steam pressure on flow-regime transition, 2-in. pipe.

in Taitel and Dukler's map have been replaced by familiar engineering steam and flow parameters. The flow regime can readily be predicted once the steam quality and the flow rate are known. It is easy to see how a change in steam quality, flow rate, or pressure will affect the flow regime.

Note that the steam flow rate referred to is the sum of the flow rate of the liquid and vapor phases, and the steam quality referred to is a "homogeneous steam quality." The liquid and vapor phases are assumed to be a homogeneous equilibrium mixture with both phases moving at the same velocity. This steam quality is actually the flow rate fraction of the vapor phase in the flow.

The basic reasons that the dimensionless parameters used in Taitel and Dukler's flow-regime map can be converted to the steam flow rate and quality used in the steam flow charts are discussed in Appendix A. Several unique features of the charts deserve mention.

1. The transition between annular and intermittent flow occurs at a specific steam quality, called the transitional steam quality, X_c. As discussed later, the transitional steam quality depends on steam pressure.

2. For flow in horizontal pipes, dispersed bubble flow occurs at a very high steam flow rate beyond the practical flow rate range. Therefore, no dispersed bubble flow is present in the steam flow charts and no further discussion is needed.

3. The steam flow rates at the stratified-wavy/annular and stratified-wavy/intermittent transitions are referred to as the transitional steam flow rate, q_c. Fig. 3 shows that q_c for a constant steam pressure and pipe size varies with steam quality. However, the range of q_c for the entire steam quality range is relatively small. For the example shown in Fig. 3, q_c varies from 110 to 156 B/D [17.5 to 24.8 m^3/d] CWE, while the steam quality varies from 2 to 90%.

4. For a constant steam pressure and pipe size, the steam flow rate corresponding to the stratified-wavy/stratified-smooth transition depends heavily on the steam quality. The steam flow rate for this transition decreases as the steam quality is increased. However, stratified smooth flow occurs at either a rather low steam quality or a rather low steam flow rate. Such low quality and flow rate probably will seldom be practiced. Therefore, no further attention is given to the stratified-wavy/stratified-smooth transition, although all steam flow charts show it.

5. From this study, it becomes apparent that the flow regimes important to horizontal steam flow are annular, intermittent, and stratified wavy. The remainder of this paper focuses on the annular/intermittent, stratified-wavy/intermittent, and stratified-wavy/annular transitions.

Effect of Steam Pressure on Flow Regime. The effect of steam pressure on flow-regime transition is illustrated by the steam flow charts in **Fig. 4.** All the charts in this figure are for flow in 2-in. [5-cm] pipes, but the steam pressure varies from 200 to 2,000 psia [1.38 to 13.8 MPa]. The transitional steam quality increases as the steam pressure is increased. At 200 psia [1.38 MPa], it is 12.7%, and at 2,000 psia [13.8 MPa], it increases to 35.7%, but it does not change with pipe size. Steam flow charts for steam flowing in 24-in. [61-cm] pipe at 200 and 2,000 psia [1.38 and 13.8 MPa] are shown in **Fig. 5.** The X_c for steam flowing in 2-in. [5-cm] pipe at 200 psia [1.38 MPa] (as shown in Fig. 4) is the same as that in a 24-in. [61-cm] pipe at the same pressure (as shown in Fig. 5). The same statement applies to the X_c for 2,000-psia [13.8-MPa] steam in these two figures.

Fig. 6 shows X_c for all steam pressures studied as a function of steam pressure. The relationship between the X_c and steam pressure can be correlated as

$$X_c=0.01176p^{0.449}, \quad \ldots\ldots\ldots\ldots (11)$$

where $200 \leq p \leq 2{,}000$ psia. In SI units, 0.01176 becomes 0.004942, where $1380 \leq p \leq 13\,800$ kPa.

Besides X_c, the shape of the q_c curve also changes with steam pressure. For the given pipe size, however, the range of q_c remains relatively narrow for all the pressures studied. For 2-in. [5-cm] pipe, q_c is between 78 and 175 B/D [12.4 and 28 m^3/d] CWE for the entire pressure and quality range of this study; for 24-in. [61-cm] pipe, q_c varies between 33,000 and 72,000 B/D [5250 and 11 450 m^3/d] CWE for the same pressure and quality range.

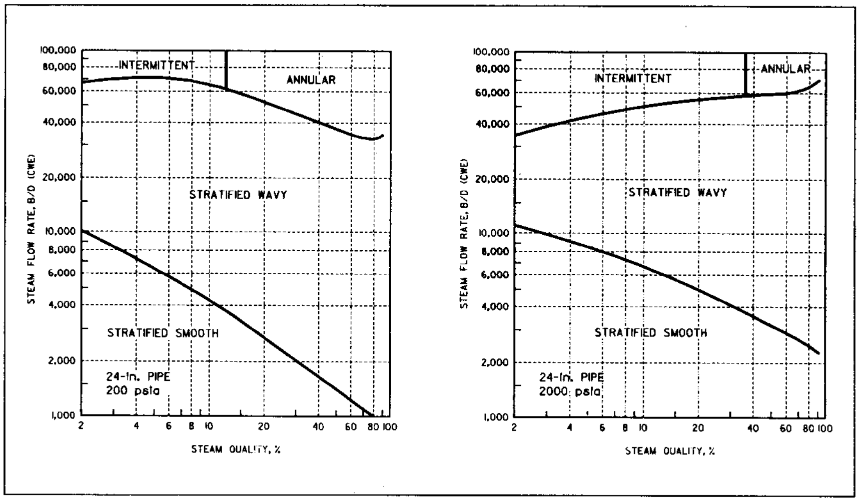

Fig. 5—Effect of steam pressure on flow-regime transition, 24-in. pipe.

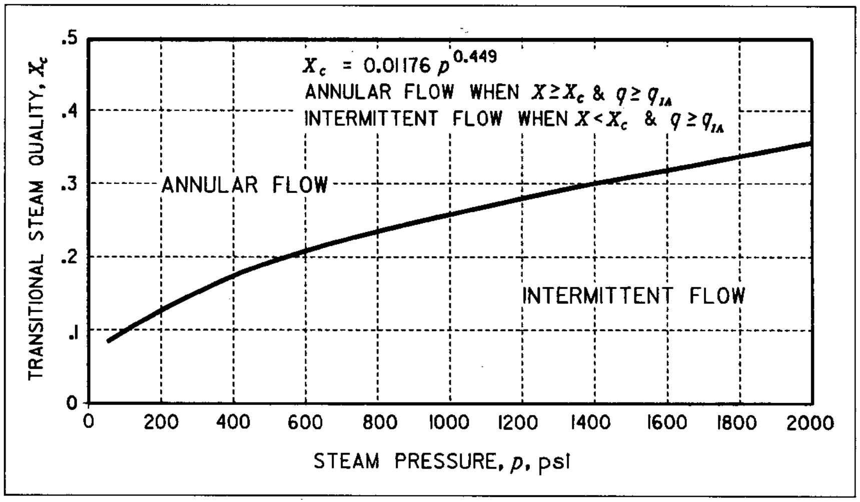

Fig. 6—Transitional steam quality as a function of steam pressure.

Effect of Pipe Diameter on Flow Regime. The steam flow charts shown in **Fig. 7** are all for steam at 600 psia [4.14 MPa] but for pipe sizes between 2 and 24 in. [5 and 61 cm]. Because the steam pressure for these charts is constant, X_c is the same; however, the range of q_c increases noticeably as the pipe size is increased. For 2-in. [5-cm] pipe, q_c ranges from 110 to 156 B/D [18 to 25 m^3/d] CWE; for 14-in. [36-cm] pipe, 11,500 to 16,500 B/D [1830 to 2625 m^3/d] CWE; and for 24-in. [61-cm] pipe, 46,000 to 63,000 B/D [7315 to 10 015 m^3/d] CWE. Note that the shape or trend of the q_c curve does not change for various pipe sizes. Thus, the q_c data for one pipe size can readily be extended to other sizes at the same steam pressure and quality according to

$$\frac{q_c \text{ for pipe with } D_1}{q_c \text{ for pipe with } D_2} = \left(\frac{D_1}{D_2}\right)^m \quad \ldots(12)$$

For the range of variables investigated, the value of m varies from 2.46 to 2.50, depending on steam quality and pressure. Generally, for steam quality higher than 10%, m can be assumed to be 2.50 for all the steam pressures investigated.

The q_c data can be extended from one pipe size to another because the transition from stratified wavy flow to either intermittent or annular flow for a constant Martinelli parameter (or constant steam quality) occurs at a constant modified Froude number. As shown in Appendix A, the modified Froude number is directly proportional to the steam flow rate and inversely proportional to the pipe ID to the 2.50th power. Thus, a constant modified Froude number means that the q_c at a constant steam pressure and quality is directly proportional to the pipe ID to the 2.50th power.

Effect of Pipe Roughness on Flow Regime. Taitel and Dukler used friction factors of smooth pipe in their calculation of frictional pressure gradient. Therefore, pipe roughness does not enter into their consideration of flow regimes or transitions. Churchill's friction-factor correlation does include pipe roughness in the turbulent-flow portion of the correlation. Unfortunately, the effect of roughness is hidden in the Martinelli and turbulent-forces parameters and cannot be explicitly revealed. **Fig. 8** shows an example of the effect of pipe roughness on q_c for steam flow at 600 psia [4.14 MPa] in a 2-in. [5-cm] pipe. The pipe roughness varied from smooth to 0.006 in. [0.152 mm]. Most commercial steel pipes have a roughness of about 0.001 to 0.002 in. [0.025 to 0.051 mm]. It is apparent from Fig. 8 that pipe roughness does not seriously affect the flow-regime transitional steam flow rate; therefore, its effect can be disregarded. A pipe roughness of 0.001 in. [0.025 mm] is used for all other cases in this study.

q_c That Predicts Annular, Intermittent, and Stratified Wavy Flow

For a constant pipe diameter under various steam pressures, the 200-psia [1.38-kPa] case has the highest q_c for flow to become intermittent and the lowest q_c for flow to become stratified wavy. Furthermore, the q_c for flow to become annular is less than the q_c for flow to become intermittent. Therefore, the highest q_c of the entire steam-quality range at 200-psia [1.38-MPa] steam pressure can be used as a rate that predicts either intermittent or annular flow. The lowest q_c of the entire steam-quality range at 200-psia [1.38-MPa] steam pressure can be used to predict a stratified wavy flow. The q_c that predicts intermittent or annular flow (which is equal to the highest q_c at 200 psia [1.38 MPa]) is designated q_{IA}, and the q_c that predicts stratified wavy flow (which is equal to the lowest q_c at 200 psia [1.38 MPa]) is designated q_S. Values of q_{IA} and q_S for various pipe sizes are presented in **Fig. 9** and are correlated as functions of the pipe ID for the range of variables covered in this study:

$$q_{IA} = 34.808d^{2.475}, \quad \ldots\ldots\ldots\ldots(13)$$

where $1.94 \leq d \leq 21.56$ in.,

$$\text{and } q_S = 15.085d^{2.496}, \quad \ldots\ldots\ldots\ldots(14)$$

where $1.94 \leq d \leq 21.56$ in. In SI units, Eqs. 13 and 14 become $q_{IA} = 0.5509d^{2.475}$, where $4.9 \leq d \leq 55$ cm, and $q_s = 0.2341d^{2.496}$, where $4.9 \leq d \leq 55$ cm.

If $q \geq q_{IA}$ and $X \geq X_c$, annular flow is predicted, and if $q \geq q_{IA}$ and $X < X_c$, intermittent flow is predicted. Similarly, if $q \leq q_S$ and $0.02 \leq X \leq 0.90$, stratified wavy flow is predicted.

Eqs. 13 and 14 and the inequalities given above are valid only within the range of variables used in this study. When $q_S < q < q_{IA}$ or the steam and flow variables are outside the ranges of this study, the usual computation procedure of Taitel and Dukler's model can be used to determine the flow regime.

Note that Eqs. 13 and 14 again show that q_c increases proportionally to the approximately 2.50th power of the pipe ID.

Examples of Flow-Regime Prediction

The following examples illustrate the applications of the steam flow charts and the correlations established in this study.

The steam flow rates for 600-psia [4.14-MPa] steam flowing in a 2-in. [5-cm] pipe ($d = 1.939$ in. [4.93 cm]) are calculated according to an average steam velocity

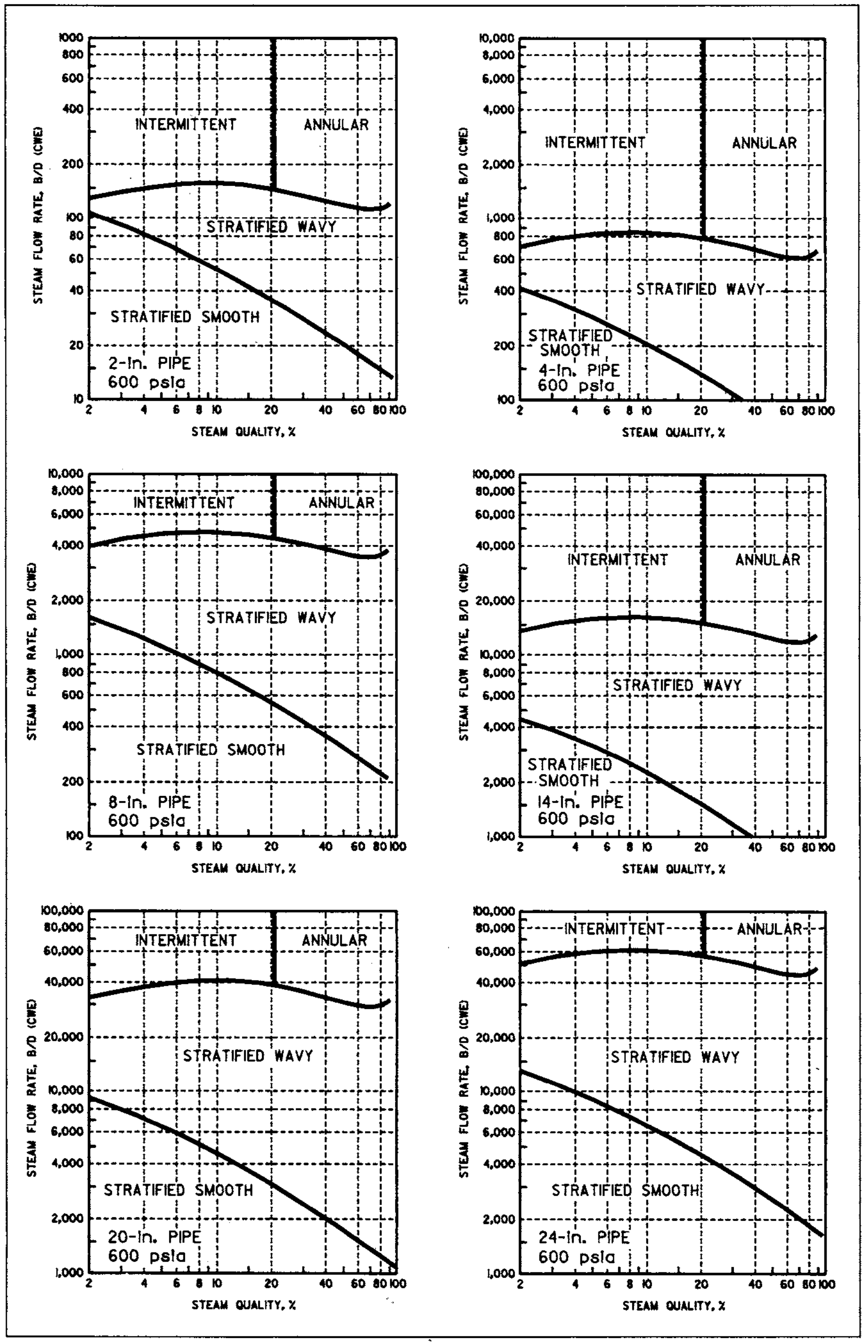

Fig. 7—Effect of pipe size on flow-regime transition, steam at 600 psia.

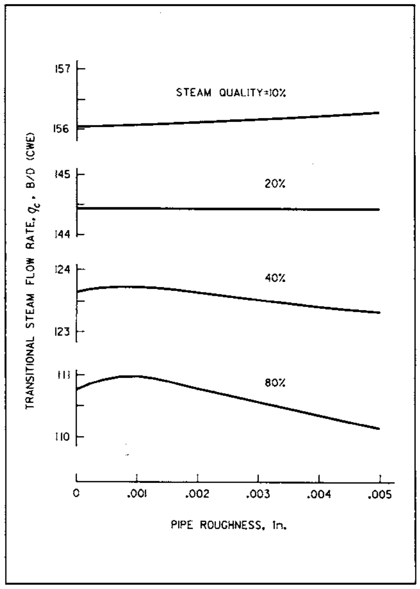

Fig. 8—Effect of pipe roughness on transitional steam flow rate, 600-psia steam flowing in 2-in. pipe.

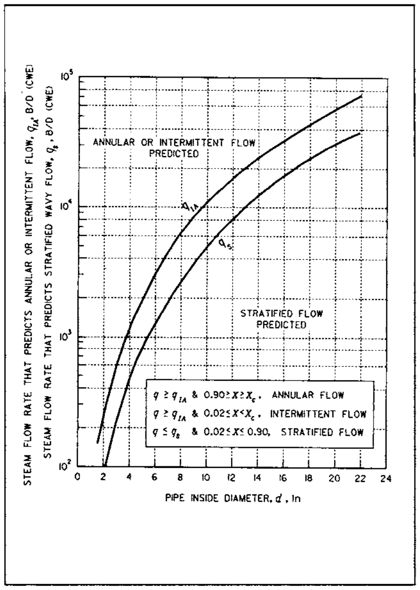

Fig. 9—Steam flow rate that predicts annular, intermittent, or stratified-wavy flow.

TABLE 1—STEAM FLOW RATE DETERMINED ACCORDING TO $75/(\rho_H)^{0.5}$ ft/sec (2-in. pipe, 600-psia steam)

Steam Quality (%)	Steam Flow Rate (B/D CWE)
5	1,580
10	1,230
20	919
30	766
40	670
60	553
80	481
90	455

of $75/(\rho_H)^{0.5}$ ft/sec [$91.48/(\rho_H)^{0.5}$ m/s] for various steam qualities (Appendix B). These flow rates are shown in **Table 1.** Either the steam flow charts or the correlations can be used to determine the flow regime for each of these flow rates.

Using the steam flow charts, Fig. 3 shows that the flow at steam qualities higher than 21% is annular and that at lower than 20%, the flow is intermittent.

To use the correlations, at a steam pressure of 600 psia [4.14 MPa], the transitional steam quality is 20.8%:

$$X_c = 0.01176(600)^{0.449} = 0.208.$$

The value of q_{IA} for the steam flowing in a 2-in. [5-cm] pipe is 179.24 B/D [28.5 m^3/d] CWE:

$$q_{IA} = 34.808(1.939)^{2.475} = 179.24.$$

All the steam flow rates in Table 1 are considerably higher than 179.24 B/D [28.5 m^3/d]. Therefore, the flow is either intermittent or annular, depending on whether the steam quality is lower or higher than 20.8%.

Conclusions

1. The two-phase-flow-regime prediction model developed by Taitel and Dukler was adapted to predict the flow regimes of wet steam flowing in horizontal pipes and to determine the effect of steam quality and operating variables on the flow-regime transitions.

2. Steam flow charts, constructed for a given pipe size and steam pressure, show the flow regime as a function of steam flow rate and quality. These charts indicate that for the flow variables used in practice, three flow regimes—annular, intermittent, and stratified wavy—are most likely to occur in horizontal pipe flow of wet steam.

3. The transitional steam quality, which determines the transition between annular and intermittent flow, is a function of steam pressure.

4. The shape or trend of the transitional-steam-flow-rate curve on the steam flow charts remains the same for different pipe sizes as long as the steam pressure is constant. This makes it possible to extend the transitional-steam-flow-rate data from one pipe size to another at the same steam pressure and quality.

5. Over the range of the variables investigated, the steam flow rate that predicts annular or intermittent flow and the steam flow rate that predicts stratified wavy flow were determined and correlated as functions of pipe diameter.

Nomenclature

C_1, C_2 = constants in Churchill's friction factor correlation, dimensionless
d = pipe ID, in. [cm]
$(dP/dL)_G$ = frictional pressure gradient of gas flow based on superficial gas velocity, lbf/ft^3 [N/m^3]
$(dP/dL)_L$ = frictional pressure gradient of liquid flow based on superficial liquid velocity, lbf/ft^3 [N/m^3]
D = pipe ID, ft [m]
f = friction factor, dimensionless
f_L = friction factor of liquid flow, dimensionless
f_G = friction factor of gas or vapor flow, dimensionless
g = gravitational acceleration, 32.174 ft/sec^2 [9.8 m/s^2]
g_c = gravitational conversion factor, 32.174 (lbm-ft)/(lbf-sec^2) [1.0]
h = equilibrium liquid level or thickness of liquid layer inside pipe, ft [m]
h_D = equilibrium liquid level, dimensionless
K = wave-generation parameter, dimensionless
L = length, ft [m]
m = exponent in Eq. 12, dimensionless
N_{Fr} = modified Froude number, dimensionless
N_{Re} = superficial Reynolds number, dimensionless
$N_{\mathrm{Re}G}$ = superficial gas- or vapor-flow Reynolds number, dimensionless
$N_{\mathrm{Re}L}$ = superficial liquid-flow Reynolds number, dimensionless
p = steam pressure, psia [kPa]
P = steam pressure, lbf/ft^2 [kPa]
q = steam flow rate, B/D [m^3/d] (CWE)
q_c = transitional steam flow rate, B/D [m^3/d] (CWE)
q_{IA} = steam flow rate that predicts intermittent or annular flow, B/D [m^3/d] (CWE)
q_S = steam flow rate that predicts stratified flow, B/D [m^3/d] (CWE)
T = turbulent-forces parameter, dimensionless
v_f = specific volume of saturated liquid, ft^3/lbm [m^3/kg]
v_g = specific volume of saturated vapor, ft^3/lbm [m^3/kg]
ν_f = kinematic viscosity of saturated liquid, ft^2/sec [m^2/s]
ν_g = kinematic viscosity of saturated vapor, ft^2/sec [m^2/s]
ν_G = kinematic viscosity of gas phase, ft^2/sec [m^2/s]
ν_L = kinematic viscosity of liquid phase, ft^2/sec [m^2/s]
$\bar{V}$ = average velocity, ft/sec [m/s]
V_{sf} = superficial liquid velocity of wet steam, ft/sec [m/s]
V_{sg} = superficial vapor velocity of wet steam, ft/sec [m/s]
V_{sG} = superficial gas velocity, ft/sec [m/s]
V_{sL} = superficial liquid velocity, ft/sec [m/s]
X = homogeneous steam quality, fraction
X_c = transitional steam quality, fraction
α = pipe inclination angle, degrees
ϵ = pipe roughness, ft [m]
ρ_f = density of saturated liquid of steam, lbm/ft^3 [kg/m^3]
ρ_g = density of saturated vapor of steam, lbm/ft^3 [kg/m^3]
ρ_G = density of gas phase of two-phase fluid, lbm/ft^3 [kg/m^3]
ρ_H = density of homogeneous steam, lbm/ft^3 [kg/m^3]
ρ_L = density of liquid phase of two-phase fluid, lbm/ft^3 [kg/m^3]
χ = Martinelli parameter, dimensionless

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Appendix A—Conversion of Parameters

For simplicity, in the following discussion the turbulent-flow friction factor of Taitel and Dukler's model is used to calculate frictional pressure gradients for liquid and vapor (or gas) phases, and customary units are used in the derivation.

Conversion Between Martinelli Parameter and Steam Quality. The Martinelli parameter of two-phase flow is defined as

$$\chi=\left[\frac{\dfrac{4}{D}f_L\rho_L\dfrac{(V_{sL})^2}{2g_c}}{\dfrac{4}{D}f_G\rho_G\dfrac{(V_{sG})^2}{2g_c}}\right]^{0.5} \quad \ldots\ldots \text{(A-1)}$$

For steam flow, it can be written as

$$\chi=\left(\frac{\nu_f}{\nu_g}\right)^{0.1}\left(\frac{\rho_f}{\rho_g}\right)^{0.5}\left(\frac{V_{sf}}{V_{sg}}\right)^{0.9}. \quad \ldots\ldots\ldots\ldots\ldots \text{(A-2)}$$

With the conversion between superficial velocity and steam flow rate shown in Appendix C, the Martinelli parameter becomes

$$\chi=\left(\frac{\nu_f}{\nu_g}\right)^{0.1}\left(\frac{\rho_g}{\rho_f}\right)^{0.4}\left(\frac{1}{X}-1\right)^{0.9}. \quad \ldots\ldots\ldots\ldots\ldots \text{(A-3)}$$

For a constant steam pressure, ν_f, ν_g, ρ_f, and ρ_g are constants, and Eq. A-3 becomes

$$\chi\propto\left(\frac{1}{X}-1\right)^{0.9}, \quad \ldots\ldots\ldots\ldots\ldots \text{(A-4)}$$

which shows that the Martinelli parameter can be converted to steam quality. Furthermore, Taitel and Dukler's model suggests

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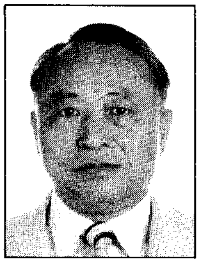

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that the annular/intermittent flow transition occurs at a constant value of h_D. Because h_D is a unique function of the Martinelli parameter, the annular/intermittent flow transition occurs at a constant value of Martinelli parameter. Eq. A-3 clearly indicates that a constant Martinelli parameter means that the transitional steam quality, X_c, depends only on the steam properties ν_f, ν_g, ρ_f, and ρ_g. Because these steam properties are functions of steam pressure,[8] X is a function of steam pressure only.

Conversion Between Modified Froude Number and Steam Flow Rate. For steam flow, the modified Froude number can be written as

$$N_{\mathrm{Fr}}=\left[\frac{\rho_g}{(\rho_f-\rho_g)}\frac{(V_{sg})^2}{gD}\right]^{0.5}.$$

Using the conversion of superficial velocity and steam flow rate (Appendix C) yields

$$N_{\mathrm{Fr}}=\left[\frac{1}{(\rho_f-\rho_g)gD\rho_g}\right]^{0.5}\frac{Xq}{193.704D^2}. \quad \text{(A-5)}$$

For a constant steam pressure and pipe size, ρ_f, ρ_g, and D are constants and

$$N_{\mathrm{Fr}}\propto Xq. \quad \text{(A-6)}$$

And for a constant steam quality,

$$N_{\mathrm{Fr}}\propto q. \quad \text{(A-7)}$$

Thus, the modified Froude number can be converted to steam flow rate. Furthermore, Eq. A-5 shows that a constant modified Froude number means that for a constant steam pressure and steam quality,

$$q\propto D^{2.5}. \quad \text{(A-8)}$$

Eq. A-8 made it possible to extend the q_c data of one pipe size to others at the same steam pressure and quality, as shown in Eq. 12.

Conversion Between Turbulent-Forces Parameter and Steam Flow Rate. For steam flow, the turbulent-forces parameter can be written as

$$T=\left[\frac{4}{D}\frac{0.046\rho_f}{(\rho_f-\rho_g)g}\left(\frac{\nu_f}{DV_{sf}}\right)^{0.2}\frac{(V_{sf})^2}{2}\right]^{0.5}.$$

Using the conversion between superficial velocity and steam flow rate yields

$$T=\left[\frac{0.092\rho_f}{(\rho_f-\rho_g)gD}\left(\frac{\nu_f}{D}\right)^{0.2}\right]^{0.5}\times\left[\frac{q(1-X)}{193.904D^2\rho_f}\right]^{0.9}. \quad \text{(A-9)}$$

For a constant steam pressure, steam quality, and pipe size,

$$T\propto q^{0.9}, \quad \text{(A-10)}$$

which shows that the turbulent-forces parameter can be converted to steam flow rate.

Conversion of the Wave-Generation Parameter to the Steam Flow Rate. For steam flow, the wave-generation parameter can be written as

$$K=\left[\frac{\rho_g}{(\rho_f-\rho_g)gD}\frac{DV_{sf}}{\nu_f}\right]^{0.5}V_{sg}.$$

Using the conversion between superficial velocity and steam flow rate yields

$$K=\left[\frac{(1-X)}{(\rho_f-\rho_g)\rho_f\rho_g g\nu_f}\right]^{0.5}\times\left(\frac{q}{193.704D^2}\right)^{1.5}X. \quad \text{(A-11)}$$

For a constant pipe size, steam pressure, and steam quality,

$$K\propto q^{1.5}. \quad \text{(A-12)}$$

Eq. A-12 shows that the wave-generation parameter can be converted to steam flow rate.

Appendix B—Steam Flow Rate Designed According to an Average Velocity of $75/(\rho_H)^{0.5}$ ft/sec

Although the engineering design criterion for steam-flow piping is still developing, a popular practice is to design flow rates or pipe sizes according to an average velocity of $C_3/(\rho_H)^{0.5}$. For customary units, ρ_H is the homogeneous steam density and C_3 can vary from 50 to 100, depending on the user's experience in a particular application. In this study, a constant of 75 is used:

$$\bar{V}=75/(\rho_H)^{0.5}. \quad \text{(B-1)}$$

In SI units, $\bar{V}=91.48/(\rho_H)^{0.5}$ m/s.

The homogeneous steam density can be calculated according to

$$\rho_H=[v_f+X(v_g-v_f)]^{-1}.$$

Thus, the steam flow rate in a pipe of ID d can be written as

$$q=100.887d^2[v_f+X(v_g-v_f)]^{-0.5}, \quad \text{(B-2)}$$

where q is in barrels of steam per day CWE (1 B/D CWE=350.32 lbm/D [1 m^3/d CWE=1000 kg/d] water). In SI units, Eq. B-2 becomes $q=0.621d^2$ $[v_f+X(v_g-v_f)]^{-0.5}$.

As examples of Eq. B-2, a 600-psia [4.14-MPa] steam flowing in a 2-in. [5-cm] pipe (d=1.939 in. [4.925 cm]) will have a steam rate of 1,230 B/D [196 m^3/d] CWE at 10% quality and 553 B/D [88 m^3/d] CWE at 60% quality. Table 1 shows the steam rates of this example at other steam qualities.

Appendix C—Conversion Between Superficial Velocities and Steam Flow Rate

As the name implies, the superficial velocity of two-phase flow may not exist in reality. However, it has been used for convenience in many two-phase fluid-flow problems. The superficial velocity of the liquid phase is calculated assuming that the liquid phase alone is flowing in the pipe. Similarly, the superficial velocity of vapor (or gas) phase is calculated assuming that the vapor (or gas) phase alone is flowing in the pipe. In steam flow, the superficial liquid velocity, V_{sf}, and the superficial vapor velocity, V_{sg}, can be related to the steam flow rate, q, and steam quality, X:

$$V_{sf}=\frac{q(1-X)}{193.704D^2\rho_f} \quad \text{(C-1)}$$

$$\text{and } V_{sg}=\frac{qX}{193.704D^2\rho_g}. \quad \text{(C-2)}$$

In SI units, Eqs. C-1 and C-2 become

$$V_{sf}=\frac{q(1-X)}{67.858D^2\rho_f}$$

$$\text{and } V_{sg}=\frac{qX}{67.858D^2\rho_g}.$$

SI Metric Conversion Factors

bbl	× 1.589 873	E−01	=	m³
ft	× 3.048*	E−01	=	m
in.	× 2.54*	E+00	=	cm
psi	× 6.894 757	E+00	=	kPa

*Conversion factor is exact.

Provenance

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