Lecture Five

4.4 Flow patterns

Predicting the flow pattern that occurs at a given location in a well is extremely important .the empirical correlation or mechanistic model used to predict flow behavior varies with flow pattern. Brill and Beggs summarized numerous investigation that have described flow patterns in well and that made attempts to predict when they occur.

Essentially all flow-pattern prediction is based on data from low-pressure systems, with negligible mass transfer between the phases and with a single phase. Consequently, these predictions may be inadequate for high-pressure, high temperature well, or for wells producing oil and water or crude oils with foaming tendencies. A consensus exists on how to classify flow pattern.

Flow pattern Classification in vertical wells:

For multiphase flow of gas and liquid most investigators now recognize the existence of four flow patterns: bubble flow, slug flow, churn flow, and annular flow. These flow pattern shown in figure 4.1 are describe next:

Bubbly flow: Numerous bubbles are observable as the gas is dispersed in the form of discrete bubbles in the continuous liquid phase. The bubbles may vary widely in size and shape but they are typically nearly spherical and are much smaller than the diameter of the tube itself.

Slug flow: With increasing gas void fraction, the proximity of the bubbles is very close such that bubbles collide and coalesce to form larger bubbles, which are similar in size to the tube diameter and have a characteristic shape similar to a bullet with a hemispherical nose and a blunt tail. They are commonly referred to as Taylor bubbles. These bubbles are separated by slugs of liquid, which may include small entrained bubbles. Taylor bubbles have a thin liquid film between them and the tube wall, which may flow downward due to gravity, even though the net flow of fluid is upward.

Churn flow: Increasing the velocity of the flow, the structure of the flow becomes unstable with the fluid travelling up and down in an oscillatory fashion but with a net upward flow. The instability is the result of the relative parity of the gravity and shear forces acting in opposing direction on the thin liquid film surrounding Taylor bubbles. This flow pattern is in fact an intermediate regime between the slug flow and annular flow regimes. Churn flow is typically a flow regime to be avoided in two-phase transfer lines, such as those from a reboiler back to a distillation column or in refrigerant piping networks, because the slugs may have a destructive consequence on the piping system.

Annular flow: Once the interfacial shear of the high velocity gas on the liquid film becomes dominant over gravity force, the liquid is expelled from the center of the tube and flows as a thin film on the wall (forming an annular ring of liquid) while the gas flows as a continuous phase up the center of the tube. The interface is disturbed by high frequency waves and ripples. In addition, liquid may be entrained in the gas core as small droplets, so much so that the fraction of liquid entrained may become similar to that in the film. This flow regime is particularly stable and is the desired flow pattern for two-phase pipe flows.

Mist flow: At very high gas flow rates, the annular film is thinned by the shear of the gas core on the interface until it becomes unstable and is destroyed, such that all the liquid in entrained as droplets in the continuous gas phase, analogous to the inverse of the bubbly flow regime. Impinging liquid droplets intermittently wet the tube wall locally. The droplets in the mist are often too small to be seen without special lighting and/or magnification.

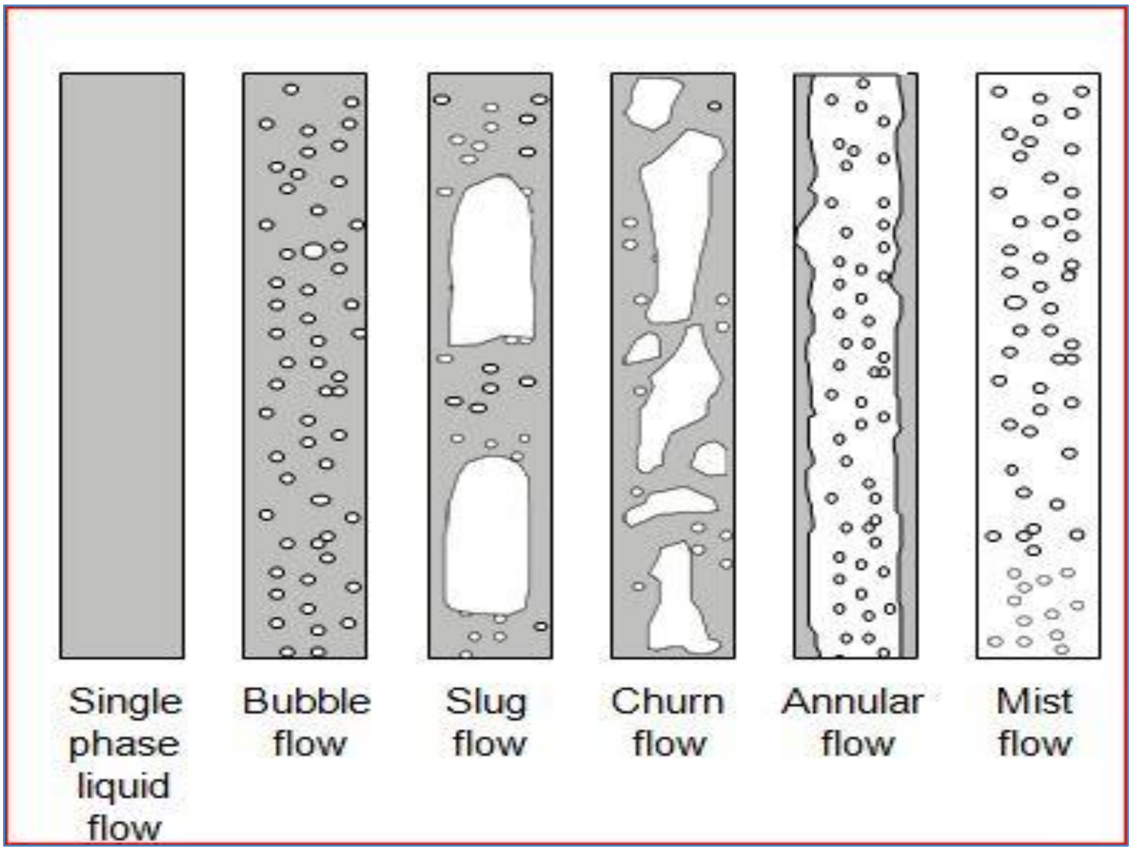

Figure 4-1: Flow regimes in two phase vertical pipes.

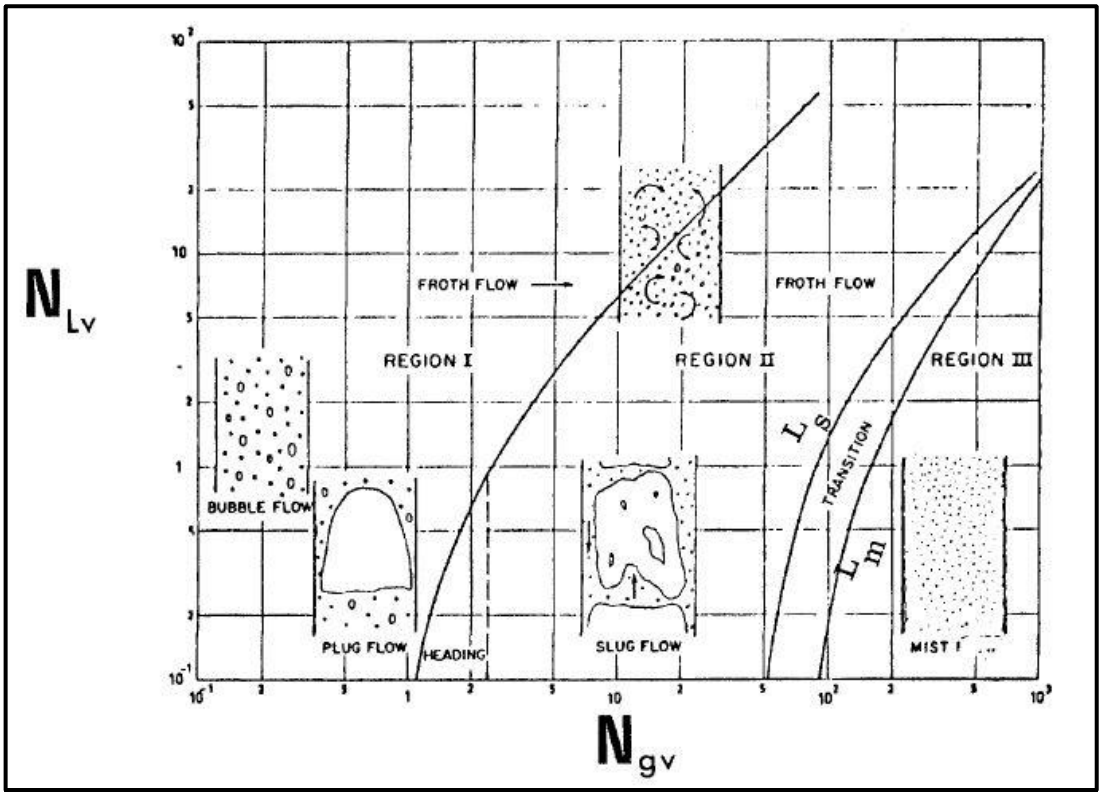

Figure 4-2: Flow regime map

4.5 Pressure gradient prediction for vertical well

The method use to predict pressure gradient can be classified as empirical correlation and mechanistic models.

Empirical correlation the empirical correlation to be discussed in this chapter can be placed in one of three categories:

Category "a": no slip no flow pattern consideration .the mixture density is calculated based on the input gas /liquid ratio .that is the gas and liquid are assumed to travel at the same velocity .the only correlation required is for the two-phase friction factor .no distinction is made for different flow patterns.

Category "b": slip considered, no flow pattern considered correlation is required for both liquid holdup and friction factor .because the liquid and gas can travel at different velocities, a method must be provided to predict the portion of the pipe occupied by liquid at any location .the same correlation used for liquid holdup and friction factor are used for all flow patterns.

Category "c": slip considered, flow pattern considered. Not only are correlation required to predict liquid holdup and friction factor, but methods to predict which flow pattern exist are necessary. Once the slow pattern is established, the appropriate holdup and friction factor correlation are determined. The methods used to calculate the factor acceleration pressure gradient also depend on flow pattern.

The following list gives the published empirical correlation for vertical upward flow and the categories in which belong.

Method	**category**
Pottmann and carpenter	a
Baxendell and Thomas	a
Hagedorn and brown	a
Gray	b
Asheim	b
Duns and Rose	b
Orkiszewski	c

Aziz et al c
Chierici et al c
Begs and brills c
Mukherjee and brills c

Category a Correlations

The three correlations considered in this category are based on the same approach and differ only in the correlation presented for friction factor. The basic equation for calculating a pressure gradient at given conditions of pressure and temperature is

$$\frac{dp}{dZ} = \frac{g}{g_c}\rho_n + \frac{f \rho_n v_m^2}{2 g_c d} \quad \text{.................. (4.25)}$$

For any consistent set of units.

Poettmann and Carpenter preferred to base the equation on a total mass flow rate. The equation and units given below are identical to their original equation except for the constant in the denominator, which has been modified to a Darcy - Weisbach or Moody equation rather than a Fanning equation for friction loss.

$$\frac{dp}{dZ} = \frac{1}{144}\left[\frac{g}{g_c}\rho_n + \frac{f w^2}{2.9652 \times 10^{11} \rho_n d^5}\right] \quad \text{......... (4.26)}$$

where

$\frac{dp}{dZ}$ = pressure gradient, psi/ft.

ρ_n = no-slip density, lbm/ft^3

w = total mass flow rate, lbm/day

d = I.D. of tubing, ft.

f = two-phase friction factor, dimensionless

In each method the friction factor was correlated empirically with the numerator of the Reynolds number. The friction factor correlations for the methods of Poettmann and Carpenter, Baxendell and Thomas and Fancher and Brown are shown in Figures 4.3, 4.4 and 4.5. Since the numerator of the Reynolds number is not dimensionless, units must be specified for the abscissa in the graphs. For the graphs presented in Figures 4.3, 4.4 and 4.5, the units for the abscissa are lbm/ft - sec. In the Fancher and Brown correlation the three curves for gas - liquid ratio can be considered to represent gas - liquid ratios for 1500, 2250 and 3000 for interpolation purposes.

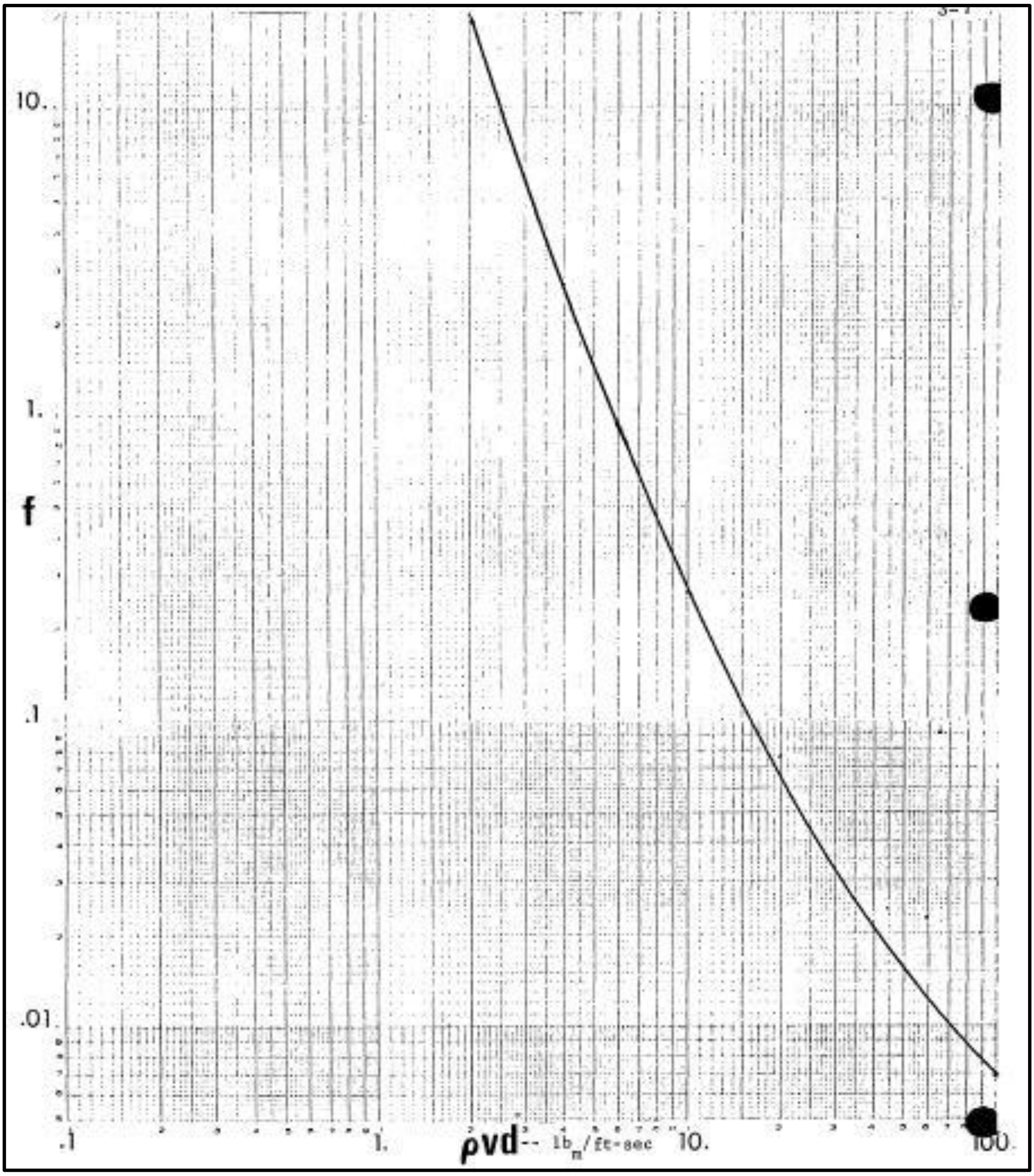

Figure 4-3: Poettmann and Carpenter friction factor correlation

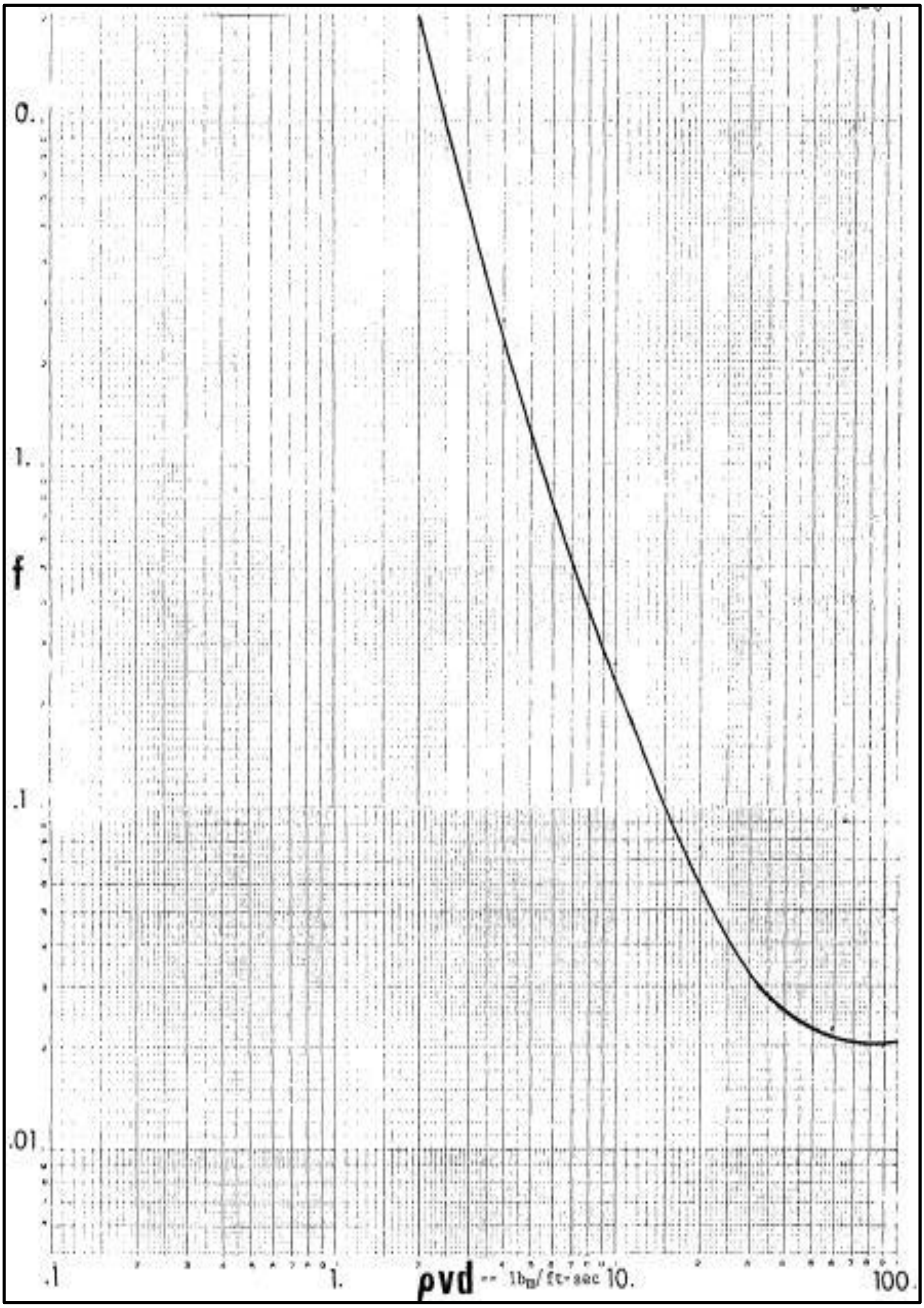

Figure 4-4: Baxendell and Thomas friction factor correlation

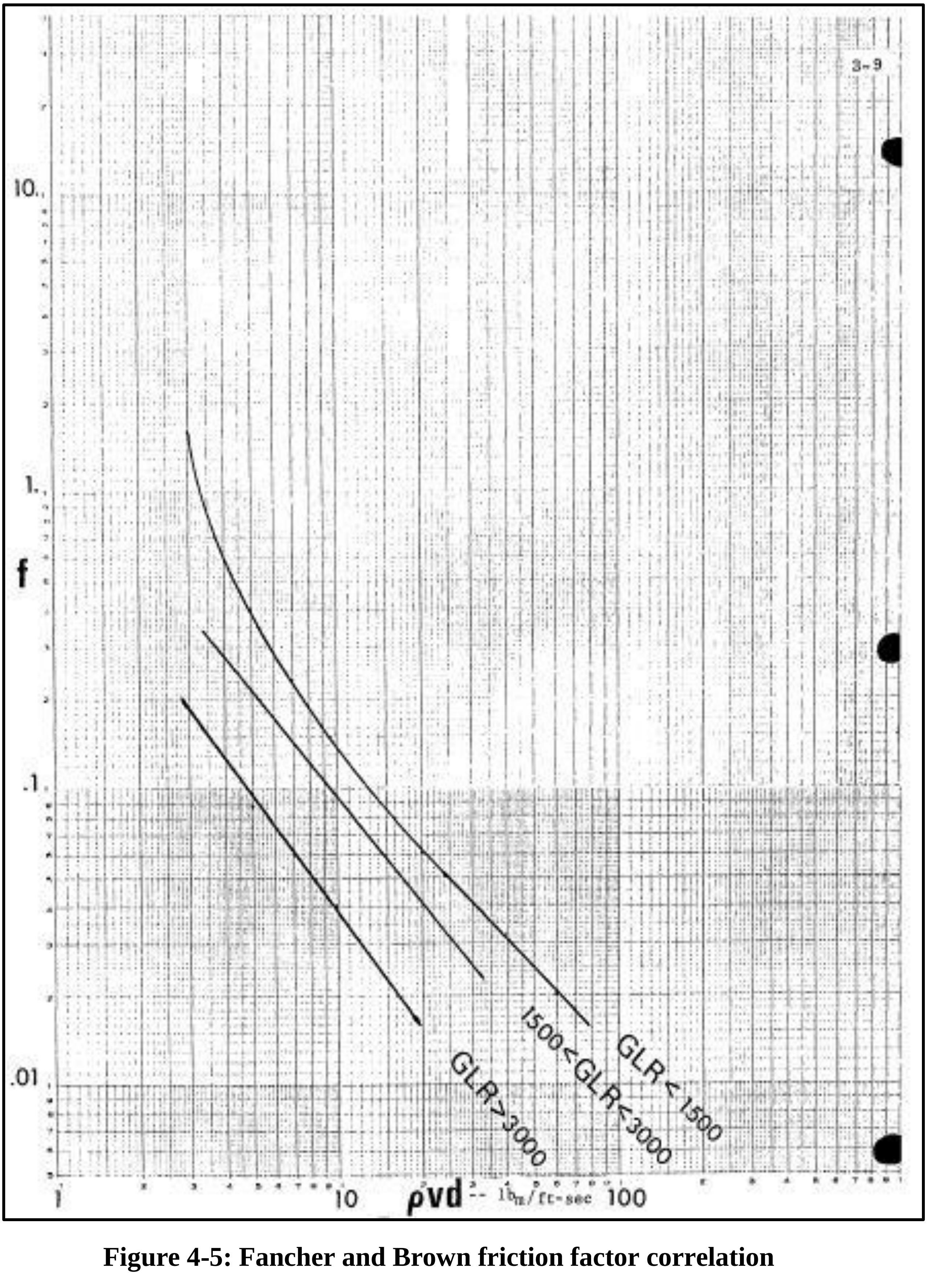

Figure 4-5: Fancher and Brown friction factor correlation

Example 4.3:

By Poettmann - Carpenter Method calculate the flowing pressure gradient at these conditions given:

$v_{sg} = 4.09$ ft/sec
$v_{sL} = 2.65$ ft/sec
$d = .249$ ft
$P = 720$ psia

$\rho_L = 56.6$ lbm/cu ft
$\rho_g = 2.84$ lbm/cu ft
$w_m = 7.87$ lbm/sec

Solution:

1. Determine no-slip density

$$\lambda_L = \frac{v_{sL}}{v_{sL} + v_{sg}} = \frac{2.65}{2.65 + 4.09} = \frac{2.65}{6.74} = 0.393$$

$$\lambda_g = 1 - \lambda_L = 0.607$$

$$\rho_n = \rho_L \lambda_L + \rho_g \lambda_g = (56.6)(.393) + (2.84)(.607) = 23.97 \text{ lbm/cu ft}$$

2. Determine friction factor

$$\rho v d = (23.97)(6.74)(.249) = 40.23$$

From Fig. **4.3** $f = .021$

3. Determine total pressure gradient

$$\frac{dp}{dZ} = \rho_n + \frac{f w^2}{2.9652\text{x } 10^{11} \quad \rho\, d^5} = 23.97 + \frac{(.021)\left[(7.87)(86400)\right]^2}{2.9652\text{x } 10^{11}(23.97)(.249)^5}$$

$$\frac{dp}{dZ} = 23.97 + 1.43 = 25.40 \frac{\text{lbf}}{\text{ft}^3} = 0.176 \text{ psi/ft}$$

4.6 Pressure gradient prediction for horizontal well

Different correlations for liquid holdup are presented for each of three horizontal flow regimes. The liquid holdup that would exist if the pipe were horizontal is first calculated and then corrected for the actual pipe inclination angle. The horizontal-flow patterns are illustrated in Figure 4-A.

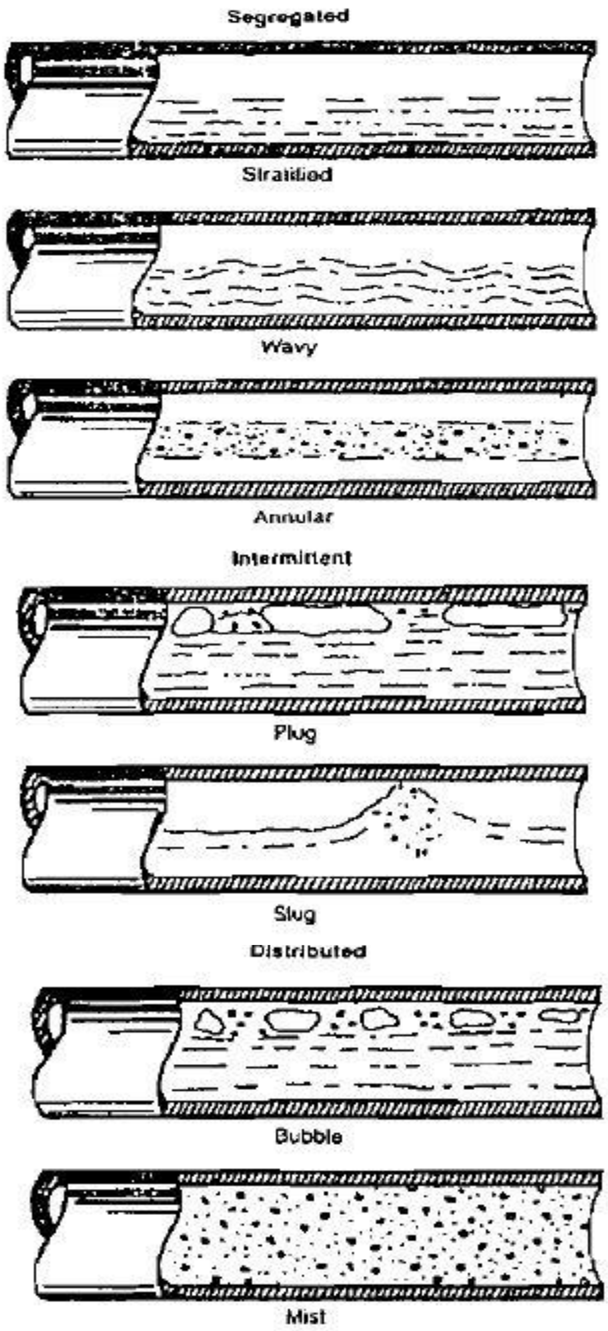

Figure 4-A: The horizontal-flow patterns

According to the definition of flow geometry, when the pipe is in the horizontal position the angle, and therefore the sin of the angle, are zero. This means that there is no elevation pressure drop and the pressure gradient equation becomes

$$\frac{dp}{dX} = \frac{f\ \rho_f\ v_m^2}{2\ g_c\ d} + \frac{\rho\ v_m\ d\ v_m}{g_c\ dX} \quad \text{............ (4.27)}$$

or

$$\frac{dp}{dX} = \left(\frac{dp}{dX}\right)_f + \left(\frac{dp}{dX}\right)_{acc}$$

Prediction of liquid holdup is less critical for pressure loss calculations in horizontal flow than for inclined or vertical flow, but several of the correlations discussed in this chapter require a holdup value for calculating the density terms used in the friction and acceleration pressure drop components. The acceleration pressure drop is usually minor and is often ignored in design calculations. The procedures for calculating friction loss, acceleration loss and liquid holdup are outlined for several of the most widely accepted horizontal correlations.

4.6.1 Dukler et al Correlation

The Dukler et al correlation was based on similarity analysis and the friction factor and liquid holdup correlations were developed from field data. This correlation is recommended in a design manual published jointly by the AGA and API.

Dukler Friction Factor

$$\left(\frac{dp}{dX}\right)_f = \frac{f\ \rho_k\ v_m^2}{2\ g_c\ d} \quad \text{..................... (4.28)}$$

where

$$\rho_k = \frac{\rho_L\ \lambda_L^2}{H_L} + \frac{\rho_g\ \lambda_g^2}{H_g} \quad \text{................ (4.29)}$$

A correlation was developed for a normalized friction factor f / f_n and is given in Fig. 4.6. The friction factor f_n is obtained from

$$f_n = 0.0056 + 0.5\, N_{Rek}^{-0.32} \quad \text{……………… (4.30)}$$

where
$$N_{Rek} = \frac{\rho_k\, v_m\, d}{\mu_n} \quad \text{……………… (4.31)}$$

$$v_m = v_{sL} + v_{sg}\ ,$$

$$\mu_n = \mu_L\, \lambda_L + \mu_g\, \lambda_g$$

The normalized friction factor can be calculated from

$$\frac{f}{f_n} = 1 + \frac{y}{1.281 - 0.478y + 0.444\, y^2 - 0.094\, y^3 + 0.00843\, y^4} \quad \text{…… (4.32)}$$

where $y = -\ln(\lambda_L)$

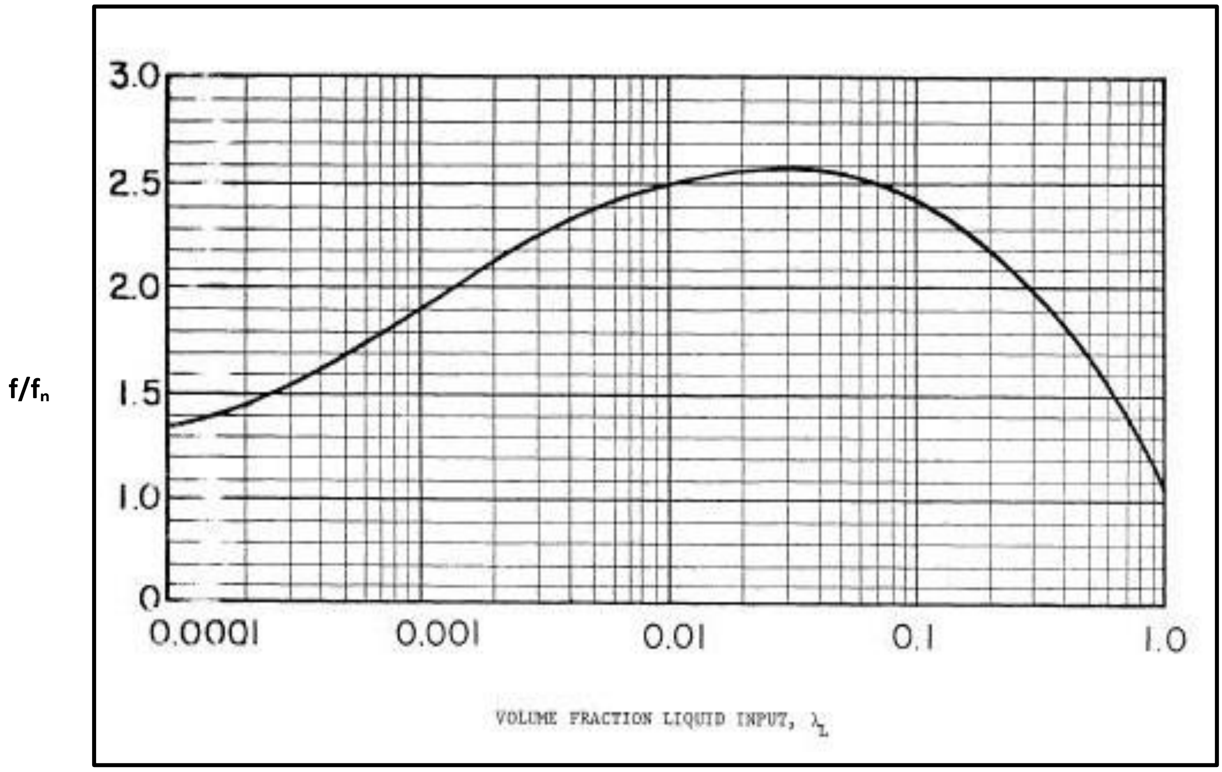

Figure 4.6: Normalized Friction Factor Curve

Dukler Liquid Holdup

An iterative or trial and error procedure is required to obtain a value of liquid holdup using Dukler's method. That is

$$H_L = f(\lambda_L, N_{Rek}) \text{ and } N_{Rek} = f(H_L)$$

The correlation is given in Fig. 4.7 with liquid holdup plotted versus no - slip holdup with Reynolds number as a parameter. The procedure for obtaining a holdup value consists of

1. Calculate λ_L
2. Estimate H_L
3. Calculate N_{Rek} (Eq. 4.31
4. Obtain H_L from Fig. 4.7

5. Compare values of H_L from steps 2 and 4. If they are not sufficiently close, set the value obtained in step 4 as the new value and return to step 3. Agreement within 5 % is considered close enough.

Dukler Acceleration Term

The pressure gradient due to acceleration is given by

$$\left(\frac{dp}{dX}\right)_{acc} = \frac{1}{g_c \, dX} \Delta \left[\frac{\rho_g \, v_{sg}^2}{H_g} + \frac{\rho_L \, v_{sL}^2}{H_L} \right] \quad \text{........ (4.33)}$$

or

$$\frac{dp}{dX} = \left(\frac{dp}{dX}\right)_f + \left(\frac{dp}{dX}\right)_{acc}$$

The total pressure gradient is

$$\frac{dp}{dX} = \frac{\left(\frac{dp}{dX}\right)_f}{1-E_k} \quad \text{.................. (4.34)}$$

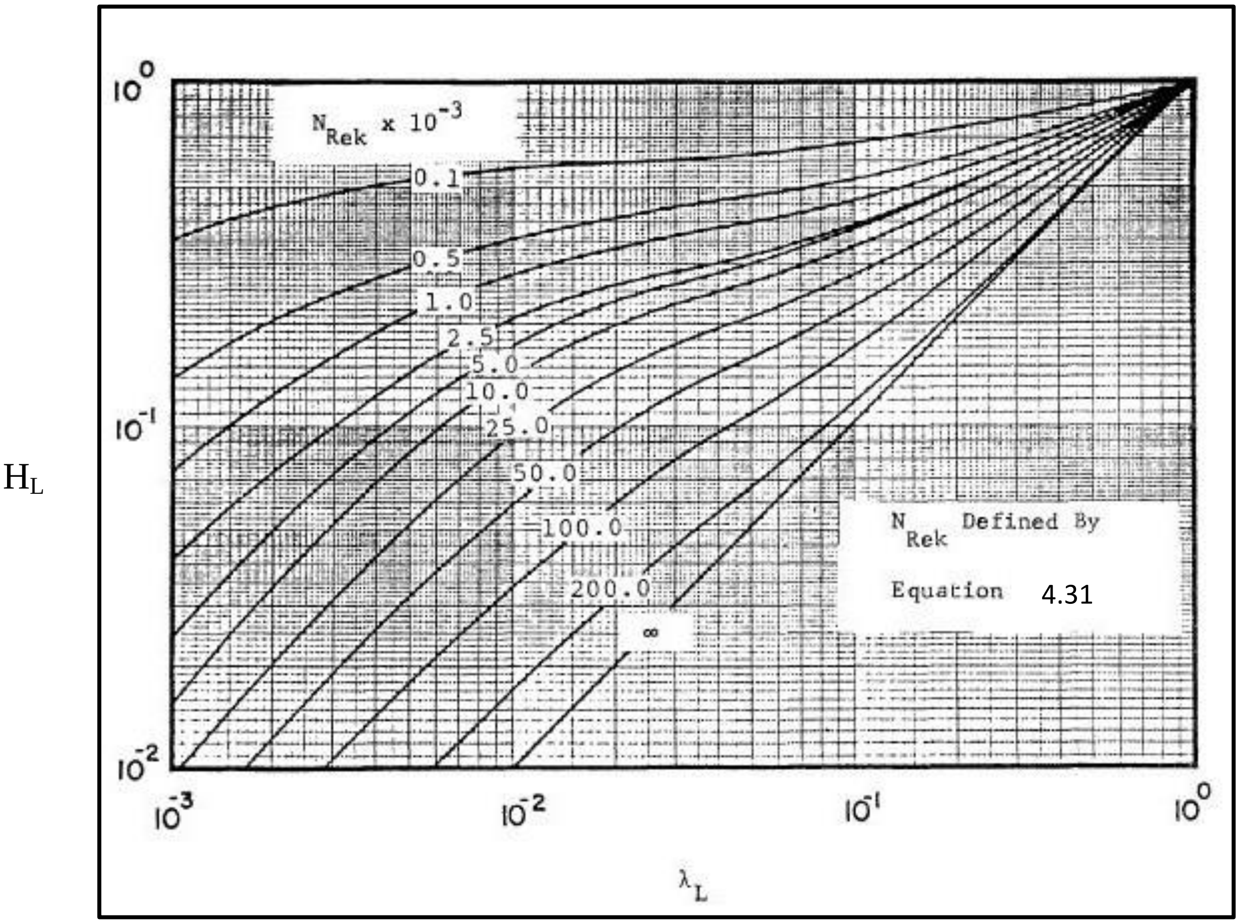

Figure 4.7: Dukler Liquid Holdup Correlation.

Example 4.4:

Given the following information for a wet gas pipeline, calculate the pressure gradient using the Dukler et al. Correlation but neglecting kinetic energy effects.

q_g = 400 MMscf/D q_o= 4000 STBO/D   d = 16.0 in = 1.333 ft

Sp.gr = 0.70 = constant   API = 40 °   p = 2500 psia   T = 60 ° F

€ = 0.0006 ft (€/ d= 0.00045)

Solution:

1. Determine Liquid Holdup

Assume $H_L = 0.02$

$$\rho_k = \frac{\rho_L \lambda_L^2}{H_L} + \frac{\rho_g \lambda_g^2}{H_g}$$

$$= \frac{(42.45)(.02)^2}{(.02)} + \frac{(13.66)(.98)^2}{(.98)} = 14.236\ lb_m/ft^3$$

$$N_{Rek} = \frac{1488\ \rho_k\ v_m\ d}{\mu_n} = 7.416 \times 10^6$$

From Fig **4.7** for $N_{Rek} \approx \infty$,

$$H_L = 0.02$$

∵ Convergence is obtained on first iteration.

2. Determine friction factor

$$f_n = 0.0056 + 0.5\ N_{Rek}^{-0.32} = 0.00877$$

From Fig 4.6 $\frac{f}{f_n} = 2.57$

Using Eqn. 4.32 $\frac{f}{f_n} = 2.533$

$$f = f_n \cdot \frac{f}{f_n} = (0.00877)(2.57) = 0.0225$$

3. Determine Pressure Gradient

$$\frac{dp}{dX} = \left(\frac{dp}{dX}\right)_f = \frac{f\ \rho_k\ v_m^2}{2\ g_c\ d}$$

$$= \frac{(0.0225)(14.236)(13.131)^2}{(2)\ (32.174)(1.333)}$$ **=0.6349 psf/ft**

=0.00447 psi/ft