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Research note

Two-Phase Flow Pressure Drop Calculation Using Homogeneous Equilibrium Model

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ABSTRACT

Although two-phase flow is frequently encountered in various locations of the process plants, there is no a generally accepted and verified two-phase flow model that may be used to size lines for such conditions. An obvious example is condensate water return lines. The API method used in this study is based on the homogeneous equilibrium flow assumption, that is, equal velocity and equal temperature in both liquid and vapor phases. Moreover, DIERS method was used to verify and clarify the HEM approach to calculating the pressure drop in two-phase regimes. The objective of this study is to introduce a solution for process lines design during different flashing scenarios. Applying API method, this study can find the two-phase line pressure drop and upstream pressure, while, by using DIERS method, one could realize that for a specified length of pipe how much two-phase flow could pass through when the pressure drop is just the same as that in the API model.

1. Introduction

For two-phase flow conditions, typically, a two-phase pressure drop method, such as Brill and Beggs or the homogeneous equilibrium method (HEM), may be used. Critical flow conditions are typically handled by considering homogeneous flow and applying basic thermodynamic relationships. Moreover, the two-phase flow methods that are currently considered to be the most appropriate for relief valve sizing are based on the homogeneous equilibrium (HEM) models. Here, the current study used the same concept for two-phase line sizing [1, 2]. In this model, the flashing two-phase flow mixture is treated much like the classical compressible gas, while undergoing an adiabatic expansion with equal velocities and temperature (thermodynamic equilibrium) in both phases. Among the many other flow models tested in the DIERS program (Design Institute for Emergency Relief Systems), the HEM model yields conservative (low) estimates of the flow capacity. In flow passages greater than 0.1 m in length (frequently encountered in relief systems), the HEM model in fact provides a best-estimate calculation [3]. The Omega method is a

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special case of the HEM model in which the two-phase density is represented as a linear function of pressure and the thermal/physical properties of the fluid in the stagnation state. A version of this model is recommended by the American Petroleum Institute (API RP 521, "Pressure-relieving and Depressuring Systems").

DIERS equations for two-phase flow are used to calculate a mass flux based on physical properties of the fluid. It can be used to approximate the two-phase flow rate through the various sizes of lines and, at the same time, the pressure drop would be calculated. There are various specific DIERS methodologies for calculating two-phase flashing flow. The specific equations presented here were developed by Leung. These equations enjoy ease of use and require inlet conditions [4].

2. API model

Regardless of which equation is used, actual mass flux (*G*) is a function of critical mass flux, frictional resistance (*N*), and the ratio of downstream to upstream pressure. For the case of a single diameter, horizontal line, the compressible flow relationship given in Equation (1) can be used to determine pressure drop in multiphase flow systems:

$$C_1 f \frac{L}{D} = \frac{C_2 p_R \rho_R}{G^2}\left[\frac{\eta_1 - \eta_2}{1-\omega\prime} - \frac{\omega}{(1-\omega\prime)^2}\ln\frac{(1-\omega\prime)\eta_2 + \omega\prime}{(1-\omega\prime)\eta_1 + \omega\prime}\right] + \ln\left[\frac{(1-\omega\prime)\eta_2 + \omega\prime}{(1-\omega\prime)\eta_1 + \omega\prime}\left(\frac{\eta_1}{\eta_2}\right)\right] \quad (1)$$

According to Figure 1, the pipe outlet pressure, p_2, of a constant-diameter pipe is the higher of the pressure at the exit of the pipe and the critical choking pressure given in Equation (2):

$$p_C = C_3 . G\sqrt{\frac{\omega . p_R}{\rho_R}} \quad (2)$$

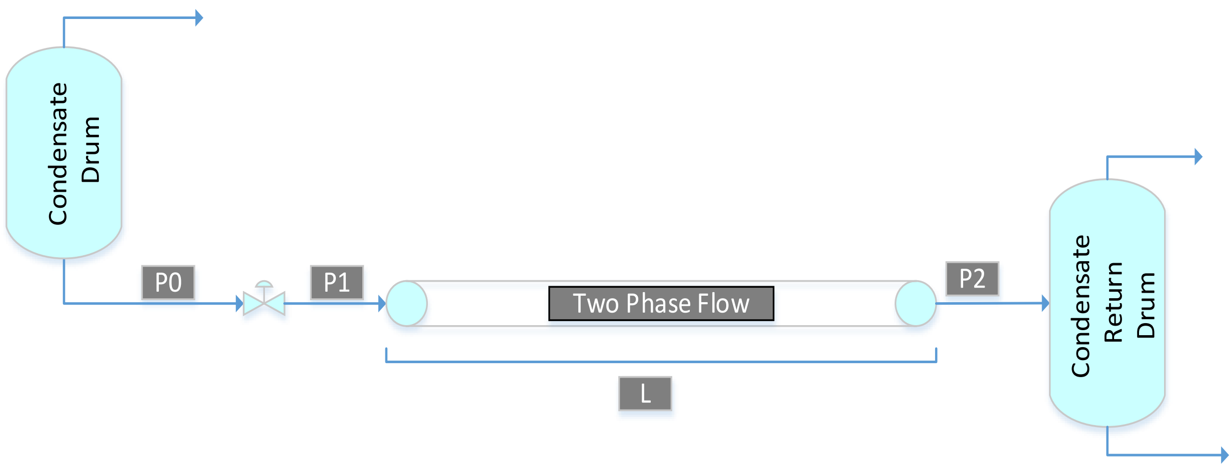

Figure 1. Two-phase process flow diagram.

If the pressure at the pipe exit (e.g., atmospheric pressure or other known pressure) is lower than p_C, then the flow is choked. In this case, p_2 is replaced with p_C in the η_2 term used in Equation (1). Otherwise, the flow is not choked; thus, the pipe exit pressure should be used as p_2 in Equation (1).

Based on the API method below, five steps should be followed to find p_1 pressure; then, consequently, the pressure drop across the pipe would be specified.

Step 1: Perform an isenthalpic flash starting from source (p_0) condition to a referenced pressure (p_R). In many cases involving multiphase, density change has a linear form treated with pressure drop; therefore, for the first try, assume that p_R ~ 25 % to 75 % of the source pressure and determine the density of the multiphase mixture. This density is the new reference density, ρ_R.

Step 2: Perform an isenthalpic flash from relieving conditions to 50 % of the reference pressure, from Step 1 or atmospheric pressure, whichever is greater. Consider this pressure as p and the multiphase mixture density at this pressure as ρ.

Step 3: calculate parameter ω using the following equation:

$$\omega' = \frac{(\rho_R/\rho)-1}{(p_R/p)-1} \quad (3)$$

Note that the value of ω here is *not* the same as the one used in DIERS method. This calculated parameter must only be used in Equations (1) and (2).

Step 4: Equations (1), (2), and (3) are used to calculate the upstream pressure (i.e., p_1).

Step 5: Calculate the pressure drop across the line length. If it is not accepted according to the sizing criteria, increase the line diameter and repeat Steps 1 to 5 [5].

2.1. Example using API method

The following example uses API calculation approach, the fluid is condensed water steam from a tower reboiler, which is collected in a low-pressure flash drum. The condensate flow rate from this flash drum will be controlled under a level control valve as 23000 lb/hr and sent to an atmospheric condensate return drum on the other side of the plant. The upstream flash drum pressure is 80 psia and the area atmospheric pressure is 14.7 psia. The distance between these two drums is about 2000 ft (fittings included). The general arrangement is shown in Figure 1. As per accepted design criteria, the pressure drop across the line should not exceed 1 psi/100 ft.

In this example, the HYSYS steady-state simulator with ASME Steam fluid package was used to generate the physical and thermodynamic properties in different conditions. Moreover, we have tried three different line sizes and the results are reported in Table1.

a) $p_R = 0.5 \times p_0 = 0.5 \times 80 = 40$ psia.

b) $p = 0.5 \times p_R = 0.5 \times 40 = 20$ psia.

c) By applying an isenthalpic flashing from p_0 to p_R and p, the relevant densities would be equal to $\rho_R = 1.917$ lb/ft^3, and $\rho = 0.56$ lb/ft^3.

d) ***ω*** can be determined through Equation (3); $\omega = \frac{(1.917/0.56)-1}{(40/20)-1} = 2.4232$.

e) p_C can be calculated through Equation (3);
$p_C =$
$0.00058742 \times 1830.282\sqrt{\frac{2.4232\times 40}{1.917}} =$
7.645 psia
since p_C does not exceed the outlet pressure (i.e., p_2), p_2 is used directly. Then,
$\eta_2 = p_2/p_R$=14.7/40 = 0.3675.

f) Crane handbook fanning factor is equal to 0.00425 for 4 in line.

g) Now, Equation (1) is solved by trial and error for η_1; thus, $p_1 = \eta_1 . p_R$

$$\eta_1 = 1.312 \text{ and } p_1 = 1.312 \times 40 = 52.48 \text{ psia}$$

$$\Delta P = p_1 - p_2 = 52.48 - 14.7 = 37.78 \text{ psia}$$

$$\frac{\Delta P}{100\text{ft}} = 1.89\ \text{psi}/100\text{ft}.$$

h) Determine if the selected line size is appropriate for the calculated pressure drop.

By following the above procedure, results have been developed for two other sizes in Table 1.

Table 1
Pressure drop analysis for the two-phase flow.

Line Size (in)	4	6	8
P0 (psia)	80	80	80
PR (psia)	40	40	40
ρR (lb/ft^3)	1.917	1.917	1.917
P (psia)	20	20	20
ρ(lb/ft^3)	0.56	0.56	0.56
ω’	2.4232	2.4232	2.4232
Line Length (ft)	2000	2000	2000
F	0.00425	0.00375	0.0035
Mass Flux (lb/hr/in^2)	1830.282	813.46	457.57
Pc (psia)	7.65	3.4	1.9
P1 (psia)	52.48	26.54	18.26
P2 (psia)	14.7	147	14.7
ΔP/100 ft	1.89	0.59	0.18

As illustrated in Table 1, the proper line sizes that follow the proper sizing criteria are 6 and 8, where their pressure drop rates are 0.59 and 0.18 psi/100ft, respectively. However, the questions is, “which is preferable?”

DIERS approach has been used to verify and demonstrate the reliability of the above method. In DIERS method, the passing flow rate capacity for each alternative, considering its size and length, will be calculated. Actually, through this approach, this study aims find how much the two-phase flow could be transferred across each line while the pressure drop is occurring.

3. DIERS model

The method presented in this section can be used for sizing the lines, handling either flashing or nonflashing flow. In condensing the two-phase flow, fluids both above and below the thermodynamic critical point can be handled, as well. It is generally assumed that the HEM model is adequate in most cases for two-phase flow in relatively long pipes, for both constant quality and flashing flows, when the fluid properties are properly evaluated.

As said earlier, The DIERS methods treat the two-phase fluid as a single homogeneous "compressible" fluid. Leung's method does this by calculating a compressible flow parameter, $\boldsymbol{\omega}$. This parameter is a measure of the fluids "compressibility". The larger the value of $\boldsymbol{\omega}$, the more the fluid behaves like a compressible fluid. Based on the API, standard values for $\boldsymbol{\omega}$ fall in these categories:

Flashing flow: $\boldsymbol{\omega} > 1$

Gas/vapor flow: $\boldsymbol{\omega} < 1$

Liquid flow: $\boldsymbol{\omega} = 0$

The $\boldsymbol{\omega}$ is made up of two terms: the first term $({}^{x_0\rho}/_{\rho_V})[1 - {}^{P_0}/_{(2.7\,\lambda\,\rho_V)}]$ describes the compressibility due to the presence of vapor in the mixture; the second term $\{0.18505\ C_p\ T_0\ P_0\ \rho_0 \left[\left(\frac{1}{\rho_V}-\frac{1}{\rho_L}\right)\big/\lambda\right]^2\}$ accounts for compressibility due to the phase change upon depressurization. All of the properties are based on the high-pressure side (inlet) conditions.

$$\omega = \left(\frac{x_0\rho}{\rho_V}\right)\left[1-\frac{P_0}{(2.7\ L\ \rho_V)}\right] +\{0.18505\ C_p\ T_0\ P_0\ \rho \left[\left(\frac{1}{\rho_V}-\frac{1}{\rho_L}\right)\big/\lambda\right]^2\} \quad (4)$$

The method consists of three equations: one for line inlet, one for the flow through the line, and one for pipe discharge.

Inlet pipe equation:

$$G^* = \{\frac{\{-2[\omega \ln(\eta'_1)+(\omega-1)(1-\eta'_1)]\}^{\frac{1}{2}}}{\left[\omega\left(\frac{1}{\eta'_1}-1\right)+1\right]}\} \quad (5)$$

Pipe:

$$f\frac{L}{D} = \frac{2}{G^{*2}}\left[\frac{\eta'_1-\eta'_2}{1-\omega}+\frac{\omega}{(1-\omega)^2}\ln\frac{(1-\omega)\eta'_2+\omega}{(1-\omega)\eta'_1+\omega}\right] - 2\ln\left[\frac{(1-\omega)\eta'_2+\omega}{(1-\omega)\eta'_1+\omega}\left(\frac{\eta'_1}{\eta'_2}\right)\right] \quad (6)$$

Outlet pipe equation:

$$G^* = \frac{\eta'_2}{\sqrt{\omega}} \quad (7)$$

These equations are combined and, then, solved numerically to obtain G*. Mass flux can be calculated through Equation (8).

$$G = 1700\ G^*\ (P_1\rho)^{\frac{1}{2}} \quad (8)$$

By calculating the pipe cross-section area using Equation (9), the mass flow rate across the pipe could be calculated according to Equation (10):

$$A = \frac{\pi}{4}\ (D)^2 \quad (9)$$

$$W = A\ (\ G) \quad (10)$$

At this point, total flow rate through the rupture has been calculated [6].

In this approach, the following steps should be followed to determine the best line size for two-phase flow.

Step 1: Predetermine a size for line.

Step 2: Estimate the inlet pressure, i.e., P_0.

Step 3: Isenthalpic process should be done from the source pressure to P_0. By applying a proper equation of state, the physical properties would be extracted (i.e., $x_0, T_0, \rho, \rho_v, \rho_l, C_p, \lambda, \ldots$).

Step 4: $\boldsymbol{\omega}$ is calculated through Equation (4).

Step 5: Equations 5, 6, and 7 will be solved at the same time and η_1, η_2, and G^* will be specified and, then, $p_1 = \eta'_1 \times p_0$.

Step 6: Equation (8) is used to measure G and Equations (9) and (10) are used to calculate W.

Step 7: P_0 changes until W = actual available flowrate.

Step 8: if **Δ**P/100 ft is within the accepted criteria – generally below 1psi/100ft – the predetermined size is proper; otherwise, the line size and Steps 2 to 8 should be repeated.

3.1. Example using DIERS method

Now, an attempt should be made to tackle the previous example using the recent DIERS concept.

Step 1: Primary estimated size is set to 4.

Step 2: The source pressure is 80 psia; however, 40 psia is selected as the first estimate for line upstream pressure.

Step 3: By doing an isenthalpic flash from 80 psia to 40 psia and using ASME steam as the equation of state, the following information is extracted:

$x_0 = 0.05$

$T_0 = 727$ R

$\rho = 1.874\ \mathrm{lb/ft}$

$\rho_v = 0.095\ \mathrm{lb/ft}$

$\rho_l = 58.29\ \mathrm{lb/ft}$

$C_p = 1\ \mathrm{But/lb.ft}$

$\lambda = 934\ \mathrm{But/lb}$

Step 4: ω is calculated using the following equation:

$$\omega = \left(\frac{0.05 \times 1.874}{0.095}\right)\left[1 - \frac{40}{(2.7 \times 934 \times 0.095)}\right] + \left\{0.18505 \times 1 \times 727 \times 40 \times 1.874 \left[\frac{\left(\frac{1}{0.095} - \frac{1}{58.29}\right)}{934}\right]^2\right\} = 2.1$$

Step 5: By solving Equations 5, 6, and 7 at the same time, the following results could be achieved:

$\eta'_1 = 0.997$

$\eta'_2 = 0.12$

$G^* = 0.083$

$p_1 = 0.997 \times 40 = 39.86\ \mathrm{psia}$

Step 6: Then,

G = 1220.83 lb/hr/in^2

A = 12.566 in^2

W = 15341.46 lb/hr and **Δ**P/100 ft = 1.26 psia/100ft

However,, as illustrated in the above example, the line shall be capable to pass 23000 lb/hr as a minimum requirement. Therefore, the above line size is not acceptable and, by increasing the size, the calculation shall be repeated. The summary of results in different cases is reported in Table 2.

Table 2
DIERS method analysis.

Case number	p1 (psia)	W (lb/hr)	ΔP/100 ft (psia/100ft)
Case 1 (4”)	40	15341.5	1.25
Case 2 (4”)	53	23387	1.91
Case 3 (6”)	40	44207	1.25
Case 4 (6”)	25	23990	0.51

According to Table 2, 4-in line is not suitable for handling the above example requirement because although the required flow can pass through the line in Case 2 (4”), its pressure drop exceeds the sizing criterion, which necessities that the pressure drop across the line should not be more than 1 psi/100 ft. It appears that increasing the line size could be really helpful. In Case 3 (6”), by setting the upstream pressure equal to 40 psia, the pressure drop again exceeds the sizing criterion; however, it should be noted that passing flow across the line in this case is practically so much more than the required amount. As a process solution, the upstream pressure shall be reduced to a number that the actual flow rate would be equal to or a little bit more than the required flow rate. In this example, by changing the upstream pressure to 25 psia, the actual flow rate across the line would be about 24000 lb/hr, which satisfies the proposed problem quite well. By using the pressure drop calculation, we can find that it also follows the criterion rule. Finally, Case 4 (6”) is the proper size for this problem.

Final results for 6-in line size in Tables 1 and 2 show that the DIERS method pressure drop prediction is quite close to the model that was based on the API approach, and they are in good agreement. Actually, we found that these two methods can cover each other; in other words, by applying API method, we can determine the two-phase line pressure drop and upstream pressure; then, by using DIERS method, it becomes clear that how much flow could pass through the line when pressure drop is just the same as the API model at a specified length.

4. Software verification

Almost all process engineers usually use a kind of steady state simulator or other in-house software in order to perform the fast estimation of line sizing. HYSYS thermodynamic simulator from ASPEN Tech Co. is one of the most popular companies in this domain. This software is well equipped with “Pipe Segment” option for line sizing. There are some different approaches to calculating the pressure drop across the pipes. Some of these models are based on the equations that were developed by Beggs and Brill, Gregory Aziz Mandhane and HTFS, Homogeneous Flow. Using Hysys software, we can select each of them and calculate the pressure drop for every length of line. As a verification step, now, we can solve the former example in this article by using the above Hysys models. The generated results are presented in Table 3 and shown in Figure 2.

Simulation cases were studied for a 4-in line with 2000 ft length, and the results were compared with those from two previous models. Our analysis illustrated that the quantity of pressure drop calculation was influenced by selecting each equation. As shown in Figures 2, it was found that the application of Beggs and Brill’s equation causes an overestimated pressure drop, while, at the same time, Gregory Aziz Mandhane model gives an underestimated calculation for pressure drop. Among the above methods, HTFS, Homogeneous model is in really good agreement with API and DIERS approaches.

As a solution, on the basis of the simulation and engineering judgment, an alternative which could be used for a rough estimation will be HTFS, Homogeneous model in HYSYS simulator.

Table 3

Different models for two-phase pressure drop calculation.

Models	ΔP/100 ft (psia/100ft)
API Method 4”	1.89
DIERS Method 4”	1.91
Beggs and Brill 4”	2.24
Gregory Aziz Mandhane 4”	1.66
HTFS, Homogeneous Flow 4”	1.84

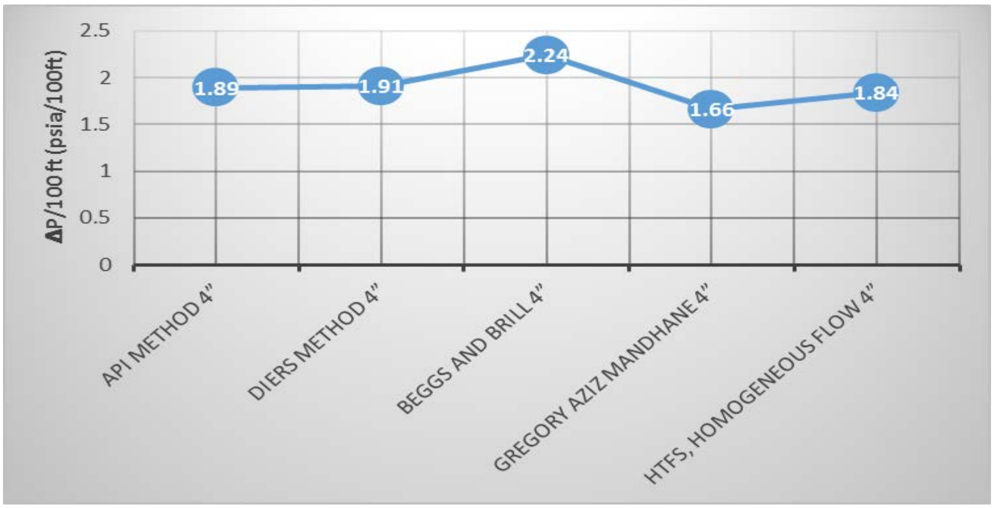

Figure 2. Comparison between different 2-phase flow models.

5. Conclusions

An attempt was made here to compare the available two-phase flashing flow methods as practiced in various engineering communities. Our comparison shows that the API method is in close agreement with the DIERS method. This article demonstrated the application of homogeneous equilibrium model to the two-phase systems pressure drop calculation. Here, it was assumed that the destination pressure was known and it was required to find the upstream pressure. First, to seek the upstream pressure, the API method was used. Then, after the DIERS model, a sensitivity analysis was performed to choose the best upstream pressure based on the required allowable flow rate through the line. The difference between the API and DIERS models is that the DIERS case, pressure drop, and allowable flow rate could be calculated at the same time, while, in API approach, only the pressure drop would be predictable. Based on the results, good agreement between the API and DIERS models was observed. Next, in order to perform the simulator verification, the results were compared with those developed from HYSYS software; there are several useful points that have been discussed. In addition, results showed that the application of HTFS, Homogeneous model in sizing was typically conservative. Nevertheless, while the API method provided the practicing engineers with a simple to use approximation when no other easy-to-use calculational method was available, the simplicity and ease of computation afforded by the generalized HEM flow correlations provide a superior, more realistic and thermodynamically consistent approach to the two-phase system design.

Nomenclature

L	total equivalent length of pipe having diameter d (including fittings), expressed in [m, ft].
d	inside pipe diameter, expressed in [mm, in].
f	Fanning friction factor, assumed constant over the length of pipe.
p_R	reference condition absolute pressure, expressed in [kPa, psi].
ρ_R	reference condition density, expressed in [kg/m^3, lb/ft^3].
G	mass flux in the pipe, expressed in [kg/h mm^2, lb/h in^2], use G as the required flow rate divided by the pipe cross-sectional area.
η_1	p_1/p_R.
η_2	p_2/p_R.
p_1	pipe inlet absolute pressure, expressed in [kPa, psi].
p_2	pipe exit absolute pressure, expressed in [kPa, psi].

ω'	correlating parameter referenced to pR, ρR [see equation (3)].
C_1	a constant, equal to 2000 in SI units (C1 = 24 in USC units).
C_2	a constant, equal to 0.01296 in SI units (2.898 × 106 in USC units).
p_C	critical choking absolute pressure, expressed in [kPa, psi].
C_3	a constant, equal to 8.784 in SI units (5.8742 × 10–4 in USC units).
x_0	vapor mass fraction at the line inlet.
ρ	overall fluid density at the line inlet [lb/ft^3].
ρ_v	vapor density at the line inlet [lb/ft^3].
ρ_l	liquid density at the line inlet [lb/ft^3].
C_p	liquid specific heat [btu/lb/°F].
T_0	temperature of fluid at line inlet [R].
P_0	pressure of fluid at line inlet - estimated [psia].
P_1	pressure of fluid at line inlet - actual [psia].
P_2	pressure of fluid at line outlet - actual [psia].
λ	liquid portion latent heat of vaporization [btu/lb].
η'_1	p_1/p_0.
η'_2	p_2/p_0.
ω	flashing factor - is the correlating parameter referenced to Equation (4).
W	two-phase mass flow rate across the line [lb/hr].
A	line cross section area [in^2].

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