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Practical Engineering Guidelines for Processing Plant Solutions

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Kolmetz Handbook of Process Equipment Design

Hydraulic Fluid Flow Two Phase Calculations

(ENGINEERING DESIGN GUIDELINES)

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INTRODUCTION

Scope

This design guideline covers the basic elements in the field of two phase fluid flow in sufficient detail to allow an engineer to design two phase fluid flow with the suitable size of diameter, velocity, and pressure drop. This design guideline includes flow regime in horizontal and vertical pipelines, pressure drop and liquid holdup in horizontal and vertical pipelines.

The flow regime is a very important design consideration for two-phase flow since it has significant effects on mechanical design, heat transfer, flow splitting, etc. The flow regime is influenced by the physical properties of two phases. The physical properties of a flowing fluid must be known to predict pressure drop in piping.

The design of two phase fluid flow may be influenced by factors, including process requirements, economics and safety. All the important parameters use in the guideline are explained in the definition section which help the reader more understand the meaning of the parameters or the term used.

In the application section of this guideline, four case studies are shown and discussed in detail, highlighting the way to apply the theory for the calculation.

Example Calculation Spreadsheets are part of this guideline. This Example Calculation Spreadsheets are based on case studies in the application section to make them easier to understand.

General Design Consideration

For two phase flow, the respective distributions of the liquid and vapor phases in the flow channel is the important aspect of their description. Their respective distribution takes on some commonly observed flow structures, which are defined as two phase flow patterns that have particular identifying characteristics. Heat transfer coefficients and pressure drops are closely related to the local two phase flow structure of the fluid, and thus two phase pattern prediction is an important aspect of modeling evaporation and condensation.

In two-phase flow, interactions between liquid and vapor phases, as influenced by their physical properties and flow rates and by the size, roughness and orientation of the pipe, cause the fluids to flow in various types of patterns. These patterns are called flow regimes. Only one type of flow exists at a given point in a line at any given time. However, as flow conditions change, the flow regime may change from one type to another.

In flow of mixtures of the two phases in pipelines, the liquid tends to wet the wall and the gas to concentrate in the center of the channel, but various degrees of dispersion of each phase in the other may exist, depending on operating conditions, particularly the individual flow rates

Seven principal flow regimes have been defined to describe flow found in horizontal or slightly inclined pipes. These flow regimes are described below, in order of increasing vapor velocity. In the accompanying sketches, the direction of flow is from left to right.

1. **Bubble Flow**

   Liquid occupies the bulk of the cross-section and vapor flows in the form of bubbles along the top of the pipe. Vapor and liquid velocities are approximately equal. If the bubbles become dispersed throughout the liquid, this is sometimes called froth flow. In uphill flow bubbles retain their identity over a wider range of conditions. In downhill flow the behavior is displaced in the direction of plug flow.

   Bubble flow is of importance to the chemical process industry, where the rise of bubbles through a liquid, both individually and in swarms (clusters), has received considerable attention. Properly speaking, bubbly flow is not a fully developed flow regime because given enough time or distance, the bubbles may collide with each other; and their agglomeration could lead to the formation of large bubbles or slug flow. In some instances, where proper care is taken in their generation, the bubbles present in the stream are small enough that they will touch rarely, and bubble flow will persist for a significant distance.

2. **Plug Flow**

   As the vapor rate increases, the bubbles coalesce, and alternating plugs of vapor and liquid flow along the top of the pipe with liquid remaining the continuous phase along the bottom. In an uphill orientation, the behavior is displaced in the direction of bubble flow; downhill, stratified flow is favored.

3. **Stratified Flow**

   As the vapor rate continues to increase, the plugs become a continuous phase. Vapor flows along the top of the pipe and liquid flows along the bottom. The interface between phases is relatively smooth and the fraction occupied by each phase remains constant. In uphill flow, stratified flow rarely occurs with wavy flow being favored. Downhill, stratified flow is somewhat enhanced, as long as the inclination is not too steep.

4. Wavy Flow

As the vapor rate increases still further, the vapor moves appreciably faster than the liquid and the resulting friction at the interface forms liquid waves. The wave amplitude increases with increasing vapor rate. Wavy flow can occur uphill, but over a narrower range of conditions than in a horizontal pipe. Downhill, the waves are milder for a given vapor rate and the transition to slug flow, if it occurs at all, takes place at higher vapor rates than in horizontal pipes.

5. Slug Flow

When the vapor rate reaches a certain critical value, the crests of the liquid waves touch the top of the pipe and form frothy slugs. The velocity of these slugs, and that of the alternating vapor slugs, is greater than the average liquid velocity. In the body of a vapor slug the liquid level is depressed so that vapor occupies a large part of the flow area at that point. Uphill, slug flow is initiated at lower vapor rates than in horizontal pipe. Downhill, it takes higher vapor rates to establish slug flow than in horizontal pipe, and the behavior is displaced in the direction of annular flow. Slug flow should be avoided where possible because it may lead to pulsation and vibration in bends, valves and other flow restrictions.

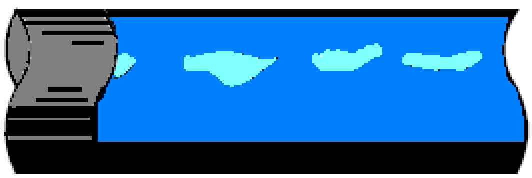
6. Annular Flow

The liquid flows as an annular film of varying thickness along the wall, while the vapor flows as a high-speed core down the middle. There is a great deal of slip between phases. Part of the liquid is sheared off from the film by the vapor and is carried along in the core as entrained droplets. At the same time, turbulent eddies in the vapor deposit droplets on the liquid film. The annular film on the wall is thicker at the bottom of the pipe than at the top, the difference decreasing with distance from slug flow conditions.

Downstream of bends, most of the liquid will be at the outer wall. In annular flow, the effects of friction pressure drop and momentum outweigh the effect of gravity, so that pipe orientation and direction of flow have less influence than in the previous flow regimes. Annular flow is a very stable flow regime. For this reason and because vapor-liquid mass transfer is favored, this flow regime is advantageous for some chemical reactions.

7. Spray Flow (Mist Flow or Dispersed Flow)

When the vapor velocity in annular flow becomes high enough, all of the liquid film is torn away from the wall and is carried by the vapor as entrained droplets. This flow regime is almost completely independent of pipe orientation or direction of flow.



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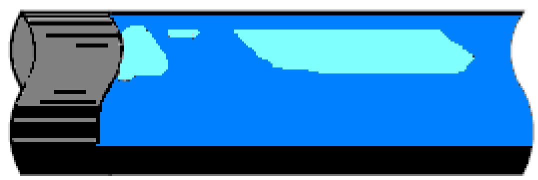

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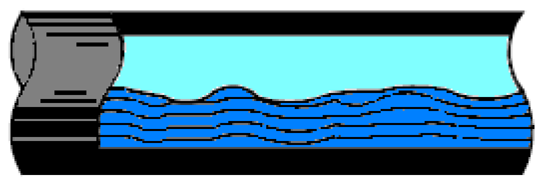

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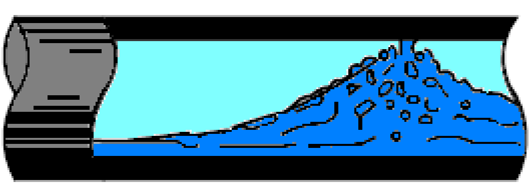

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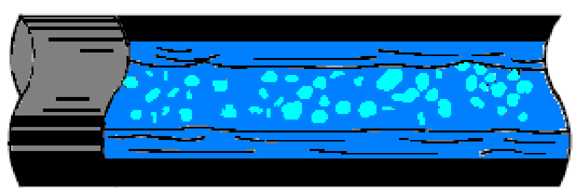

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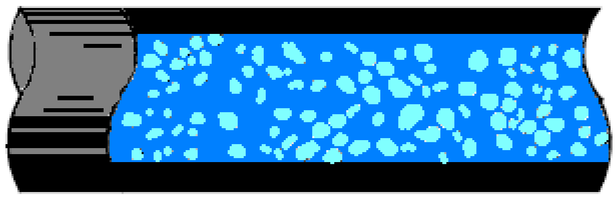


(g)

Figure 1: Flow regime in horizontal pipeline; (a). Bubble flow, (b) Plug flow, (c) Stratified flow, (d) Wavy flow, (e) Slug flow, (f) Annular flow, and (g) Spray flow

Flow behavior in vertical pipes, where gravity plays an important role, has been less extensively investigated than has flow in horizontal pipes. Most of the available information on vertical flow pertains to up-flow. Conditions under which certain flow regimes exist depend largely on the orientation of the pipe and the direction of flow. In a situation where stratified or wavy flow would exist in a horizontal pipe, tilting the pipe downward increases the relative velocity of the liquid, making a larger part of the flow area available for the vapor.

On the other hand, tilting the pipe upward causes the liquid to drain back downhill until enough has accumulated to block off the entire cross-section. The vapor can then no longer get past the liquid, and therefore pushes a slug of liquid through the inclined section of the line. Five principal flow regimes have been defined to describe vertical flow. These flow regimes are described below, in order of increasing vapor velocity.

1. Slug Flow

As the vapor rate increases, bubbles coalesce into slugs which occupy the bulk of the cross-sectional area. Alternating slugs of vapor and liquid move up the pipe with some bubbles of vapor entrained in the liquid slugs. Surrounding each vapor slug is a laminar film of liquid which flows toward the bottom of the slug. As the vapor rate is increased, the lengths and velocity of the vapor slugs increase. Slug flow can occur in the downward direction, but is usually not initiated in that orientation. However, if slug flow is well established in an upward leg of a coil, it will persist in a following downward leg, provided that other conditions remain the same.

2. **Froth Flow**

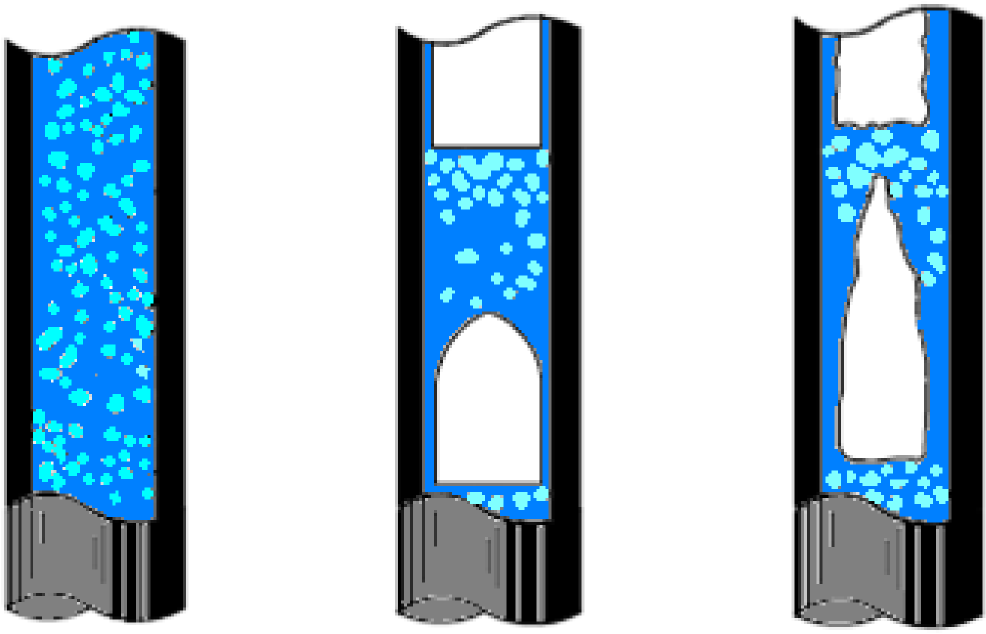
As the vapor rate increases further, the laminar liquid film is destroyed by vapor turbulence and the vapor slugs become more irregular. Mixing of vapor bubbles with the liquid increases and a turbulent, disordered pattern is formed with ever shortening liquid slugs separating successive vapor slugs. The transition to annular flow is the point at which liquid separation between vapor slugs disappears and the vapor slugs coalesce into a continuous, central core of vapor. Since froth flow has much in common with slug flow, the two regimes are often lumped together and called slug flow. In the downward direction, froth flow behaves much the same as slug flow does, except that the former is more easily initiated in this orientation, particularly if conditions are bordering on those for annular flow.

3. **Annular Flow**

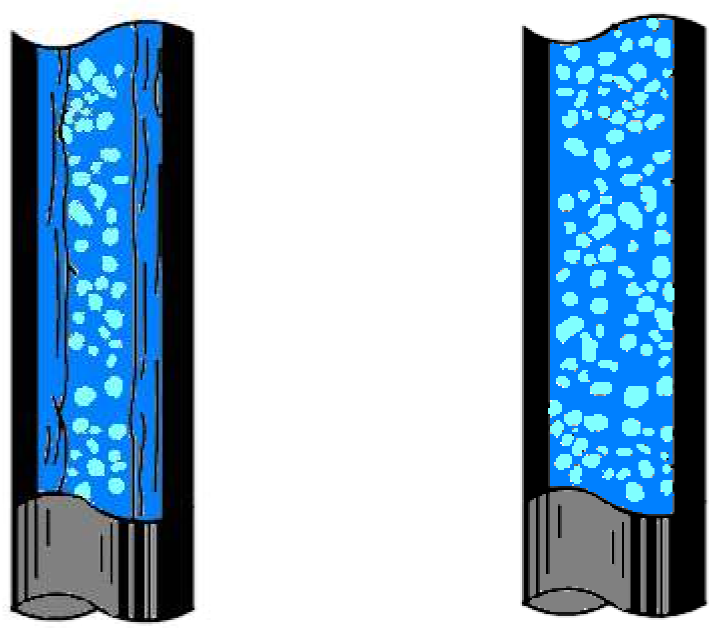
This flow regime is similar to annular flow in horizontal pipe, except that the slip between phases is affected by gravity. In up-flow, the annular liquid film is slowed down by gravity, which increases the difference in velocities between vapor and liquid. In down-flow, the reverse is true, with gravity speeding up the liquid and reducing the difference in velocities between vapor and liquid. On the other hand, the liquid film thickness is more uniform around the circumference of the pipe than in horizontal flow. Annular flow tends to be the dominant regime In vertical down-flow.

4. **Mist Flow**

This flow regime is essentially the same as spray flow in horizontal pipe. The very high vapor rates required to completely disperse the liquid essentially eliminate the effects of orientation and direction of flow. In identification of vertical two-phase flow regimes, annular and mist flow are often considered together (and called annular-mist).



(a) (b) (c)

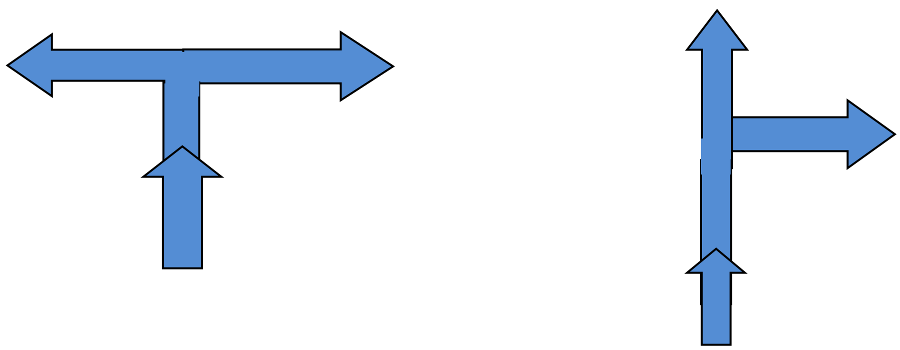


(d) (e)

Figure 2: Flow regime in vertical pipeline; (a). Bubble flow, (b) Slug flow, (c) Froth flow, (d) Annular flow, (e) Mist flow,

The behavior of a two-phase mixture in a tee is highly unpredictable. Liquid or vapor may prefer one branch over the other resulting in uneven splitting, so that the volume fraction of vapor (or liquid) differs in the two split streams. It is generally true that if the flow entering the tee is a dispersed flow the split will be more even than when the entering stream is in a separated flow regime. The splitting of a two-phase stream in a pipe tee is also dependent on the configuration of the flow. In general the splitting is more even if it is done in a more symmetrical fashion.

Splitting is more even in an impacting tee (a) than in a straight-through tee (b) as shown below. In order to maintain symmetry, elbows immediately upstream of an impacting tee should be mounted perpendicular to the plane of the tee. If this is not possible a blanked-off tee should be used instead of the elbow.



(a) (b)

Figure 3: (a) an impacting tee and (b) a straight-through tee

Characteristic of two phase fluid flow

1. Surface tension makes all dynamical problems nonlinear.
2. In the case of air and water at standard temperature and pressure, the density of the two phases differs by a factor of about 1000. Similar differences are typical of water liquid/water vapor densities.
3. The sound speed changes dramatically for materials undergoing phase change, and can be orders of magnitude different. This introduces compressible effects into the problem.
4. The phase changes are not instantaneous, and the liquid vapor system will not necessarily be in phase equilibrium.

DEFINITIONS

Coalesce - to grow together or into one body: The two lakes coalesced into one.

Critical point - The location along the flow path that experiences the steepest pressure gradient in critical flow. For a valve or a nozzle, the critical point is located at the narrowest point of the device and for a crack or a short pipe, it is usually at the exit.

Critical pressure ratio - the ratio of the pressure at the critical point to the stagnation pressure.

Critical flow - If the pressure drop is severe enough, a situation can arise in which the release rate becomes independent of the surrounding pressure. In other words, the release rate cannot be increased by further reduction in the surrounding pressure

Fitting - An accessory such as a locknut, bushing, or other part of a wiring system that is intended primarily to perform a mechanical rather than an electrical function.

Flashing - When a liquid or a vapor-liquid mixture under pressure is released to the surroundings through a pressure relief valve or a crack in a pipe or vessel

Flow maldistribution - In branching flows, such as tee junctions or perforated pipe distributors, the flow maldistribution measures the preferential distribution of flow among alternative paths.

Flow regime - A range of stream flows having similar bed forms, flow resistance, and means of transporting sediment. When two phases flow co-currently in a channel, they can arrange themselves in a number of different configurations.

Stagnation - Location upstream of the critical point where flow is stagnant or moving very slowly.

Velocity slip - In actual two-phase flow there is slip between vapor and liquid, with vapor flowing at a higher average velocity.

Fanning Friction Factor - Empirical factor in the Fanning equation for pressure drop in straight pipe. This factor is a function of Reynolds Number and relative pipe wall roughness, ε/d. For a given class of pipe material, the roughness is relatively independent of the pipe diameter, so that in a plot of f vs. Re, d often replaces ε/d as a parameter. The Fanning friction factor should not be confused with the Darcy friction factor, which is four times as large.

Laminar or Viscous Flow - Laminar flow occurs when adjacent layers of fluid move relative to each other in smooth streamlines, without macroscopic mixing. In laminar flow, viscous shear, which is caused by molecular momentum exchange between fluid layers, is the predominant influence in establishing the fluid flow. This flow type occurs in pipes when Re < 2,100.

Liquid slugging - a condition which occurs when liquid is allowed to enter one or more cylinders. Where extreme cases of flooded start or liquid flood back occur.

Maldistribution - bad or faulty distribution, undesirable inequality or unevenness of placement or apportionment (as of population, resources, or wealth) over an area or among members of a group

Phase equilibrium – phase where The energy of a system does not change when a particle undergoes a transition from one phase to another at equilibrium. In other words, the chemical potentials of each component in the different phases are equal at equilibrium

Physical properties – any property use to characterize matter and energy and their interactions. The measurement of physical properties may change the arrangement of matter but not the structure of its molecules.

Pipeline - a line of pipe or A conduit of pipe with pumps, valves, and control devices for conveying liquids, gases, or finely divided solids.

Pressure drop - decrease in pressure from one point in a pipe or tube to another point downstream. Pressure drop occurs with frictional forces on a fluid as it flows through the tube.

Reynolds Number, Re - A dimensionless number which expresses the ratio of inertial to viscous forces in fluid flow.

Specific gravity - The ratio of the mass of a given volume of a substance to that of another equal volume of another substance used as standard. Unless otherwise stated, air is used as the standard for gases and water for liquids, with the volumes measured at 60°F and standard atmospheric pressure.

Slug catchers - devices at the downstream end or other intermediate points of a pipeline to absorb the fluctuating liquid inlet flow rates through liquid level fluctuation.

Surface tension - A property of liquids arising from unbalanced molecular cohesive forces at or near the surface, as a result of which the surface tends to contract and has properties resembling those of a stretched elastic membrane.

Transition Flow - Flow regime lying between laminar and turbulent flow. In this regime velocity fluctuations may or may not be present and flow may be intermittently laminar and turbulent. This flow type occurs in pipes when $2{,}100 < Re < 4{,}000$.

Turbulent Flow - Turbulent flow occurs when macroscopic mixing results both perpendicular to, and in the direction of, the main flow. Turbulent flow is characterized by fluid particles having fluctuating motions and erratic paths. It is the flow that occurs when inertial forces are the predominant influence in establishing the fluid flow. This flow type occurs in pipes in industrial situations when $Re > 4{,}000$. Under very controlled laboratory situations, laminar flow may persist at $Re > 4{,}000$.

Water Hammer - Water hammer is the dynamic pressure surge that results from the sudden transformation of the kinetic energy in a flowing fluid into pressure when the flow is suddenly stopped. The sudden closing of a valve can cause a water hammer. Water hammer pressure can be large enough to shatter pump casings or burst line pipe and should, therefore, be considered in the design of pipes.

NOMENCLATURE

A	Radius-sectional area, ft^2
A_P	Cross sectional area of pipe, ft^2
A_V	Cross sectional area based on valve nominal size, ft^2
C	Pipe constraint coefficient
C_{LO}	Heat capacity of liquid at stagnation conditions, Btu/lbmF
d	Inside diameter of pipe, in
E	Pipe material Young's modulus, lbf/ft^2
Ek	The kinetic energy per unit volume of the inlet stream, psi
fn	The single phase friction factor,
f_{tpr}	The two-phase friction factor ratio,
g	Gravity constant, ft/s^2
G_C	Critical mass flux, lbm/ft^2-s
G_C*	Normalized critical mass flux
Gt	Total mass velocity, lbm/ft^2 s
ΔH	Surge pressure, ft-liq
ΣH	The vertical elevation rise of a hill, ft
h_{GO}	Enthalpy of vapor at stagnation conditions, Btu/lbm
H_{Lf}	Elevation head factor
h_{LO}	Enthalpy of liquid at stagnation conditions, Btu/lbm
IL	The liquid inventory in the pipe, ft^3
J	Factor for calculating head loss along a perforated pipe distributor.
K	Liquid bulk modulus, lbf/ft^2
L	Length of pipe, ft
L_m	Length of line, miles
ΔP_e	The elevation pressure drop
ΔP_f	The frictional pressure drop

ΔP_O	The required pressure drop, psi
ΔP_p	The pressure change along the pipe due to friction and momentum recovery
P_C	Critical pressure, psi
P_O	Stagnation pressure, psi
Q	Quantity (volume) flow rate at conditions, gpm
Q_G	Gas volumetric flow rate at flowing conditions, ft^3/s
Q_L	Liquid volumetric flow rate at flowing conditions, ft^3/s
Re_{mix}	Reynolds Number of inlet mixture
R_L	The liquid holdup fraction
t	Ppipe wall thickness, in
Te	Effective valve stroking time, s
T_O	Stagnation temperature, R
Tv	Valve stroking time, s
ΔV	Change of linear flow velocity, ft/s
$V_{2\Phi O}$	Two-phase specific volume
V_{GO}	Specific volume of vapor at stagnation conditions, ft^3/lbm
V_{LO}	Specific volume of liquid at stagnation conditions, ft^3/lbm
v_{mix}	Velocity of inlet mixture
v_{sG}	The superficial vapor velocity, ft/s
v_{sl}	Superficial velocity of liquid , ft/s
v_w	Wave speed, ft/s
W	Total mass flow rate, lbm/h
x	Mass fraction vapor (quality),
X	Parameter to determine flow regime in horizontal pipe
x_O	Stagnation quality
Y	Parameter to determine flow regime in horizontal pipe

Greek letters

α	Velocity correction factor.
γ	Parameter in R_L for vertical pipe
η	Critical pressure ratio
λ	Volume fraction liquid
μ_G	Gas viscosity, cp
μ_L	Liquid viscosity, cp
μ_{mix}	Viscosity of inlet mixture
ρ_G	Vapor density, lbm/ft^3
ρ_L	Liquid density, lb/ft^3
ρ_{mix}	Density of inlet mixture
σ	Liquid surface tension, dynes/cm
Φ	Parameter
ψ	Parameter