KLM Technology Group

Practical Engineering Guidelines for Processing Plant Solutions

KLM Technology Group

Consulting, Guidelines and Training

www.klmtechgroup.com

Rev 1

KLM Technology Group
P. O. Box 281
Bandar Johor Bahru,
80000 Johor Bahru, Johor,
West Malaysia

Kolmetz Handbook of Process Equipment Design

Two Phase Flow Measurement Selection, Sizing and Troubleshooting

(ENGINEERING DESIGN GUIDELINES)

Co Author: Reni Mutiara Sari

Author / Editor

Karl Kolmetz

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Scope

Two-phase flow is one of the most common flows in nature as well as in industrial applications; it covers gas-solid, liquid-liquid, solid-liquid and gas-liquid flows. Gas-liquid flow, which also includes the whole subject of boiling and condensation, is probably the most relevant topic, and can be encountered in a wide range of industrial applications including evaporators, boilers, distillation towers, chemical reactors, condensers, oil pipelines, nuclear reactors, etc. Thus, the early research on two-phase flow was carried out on gas-liquid flow.

All flow meter technologies have limitations, and most have a tough time with two-phase flow, such as air mixed in a liquid stream. The fluid dynamic characteristics of a liquid and air mixture are extremely complex, and to a large degree are still not characterized by modern-day fluid dynamic models. It is not surprising that measurement of such an unpredictable flow stream is a challenge with all types of flow meters[10].

Measurement techniques in two-phase flows are quite different from those of single-phase flows: in fact, there exist peculiar quantities of this kind of flows, such as the void fraction and the interfacial area concentration, which require a specifically conceived instrumentation.

This document is intended to serve as a guide for users and manufacturers of two phases measurement. Its purpose is to provide a common basis for, and assistance in, the classification of applications and meters, as well as guidance and recommendations for the use of such meters.

This design guideline also covers what is needed is an introduction to newcomers in the field of two phases flow measurement, with definition of terms and description of two phases flow in closed conduits being included, credible principles. The theory about basic two phases hydraulic and the sizing are clearly explained in this guideline.

Briefly the measurements for two phases flow are also summarized in this guideline. As known, two phases flow is different with single phase. It must be experimented by researchers to obtain almost exact value. Many measurements that can be used by considering the performance of a two phase in terms of accuracy, repeatability, range, etc. which is described in this guideline.

General Design Consideration

An accurate two-phase flow rate measurement is essential in many applications and industries such as; oil/gas, chemical, pipeline transportation and nuclear industry. As the two-phase flow has a fluctuating nature, measuring the two-phase flow is extremely complex, and require a specifically conceived instrumentation. In this section, the fundamentals are described.

A. Flow Regime

When two phases flow co-currently in a channel, they can arrange themselves in a number of different configurations, called flow patterns or flow regimes. Each flow pattern is characterized by a relatively similar distribution of the two phases and of their interfaces. Transition from one flow pattern to another takes place whenever a major change occurs in geometry of the gas-liquid interface.

There are many types of flow patterns/regimes that can occur in two-phase flow, depending on the flow parameters that include pipe diameter, flow rate and velocity. For flow regime analysis, several flow pattern maps have been proposed as follow :

a. Horizontal Flow

Several two phase flow regimes take place in horizontal pipelines. Phase separation usually occurs when the gravity effect is perpendicular to the pipe axis. There are seven flow regimes that represented as shown in table 1.

Table 1: seven flow regimes in horizontal pipelines

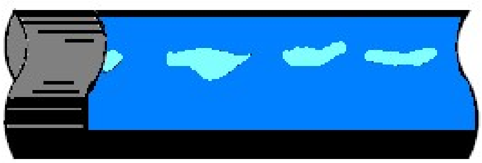
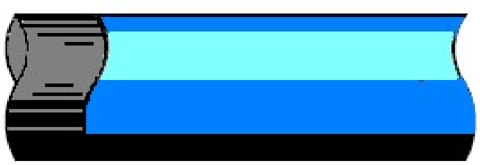
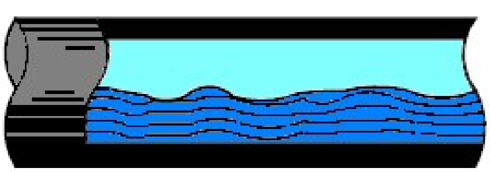
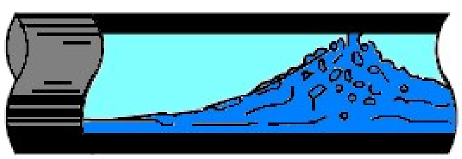
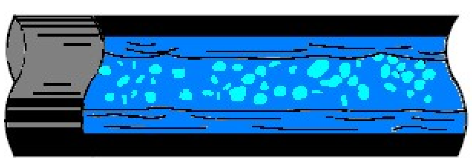
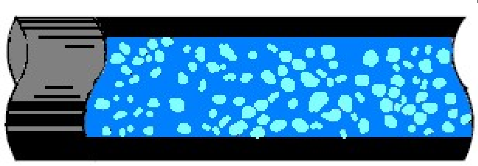
Flow regimes	Description
	**Bubble flow** Bubble flow occurs at very low gas/liquid ratios where the gas forms bubbles at that the top of the pipe. Bubbles dispersed in liquid with vapor and liquid velocities are approximately equal.
	**Plug flow** This flow regime has liquid plugs that are separated by elongated gas bubbles. Bullet shape bubbles occur, but they tend to move along in a position closer to the top of the tube.
	**Stratified flow** The gas and liquid phases flow separately one on top of the other at low gas and liquid velocity. The liquid flows along the bottom of the pipe while the gas flows in the top section of the pipe.
	**Wavy flow** Increased gas velocity in stratified flow creates wave on the interface in the flow direction. The amplitude of the wave depends on the relative velocity (slip ratio) but it normally does not touch the upper side of the pipe wall.

Table 1 Continued

Flow regimes	Description
	**Slug flow** Large amplitude wave or splashes of liquid occasionally pass through the upper side of the pipe when there is a high gas velocity than the average liquid velocity. Slug flow can cause sudden pressure pulses and vibrations in the pipelines.
	**Annular flow** The liquid phase forms a continuous film around the inside wall of the pipe and the gas flows in the central core with higher velocity. Due to effect of gravity, usually the liquid film is thicker at the bottom of the pipe in horizontal flows[8].
	**Spray flow** Gas and liquid dispersed. 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.

At certain points, the flow regime transition can create unfavorable flow conditions when a slug of water travels at the high velocity of the gas stream. Slug flow should be avoided in the fluid transmission lines since it negatively impacts both the equipment and pipeline integrity. Slug flow may cause fatigue that can reduce pipe strength and cause severe damage in pipe support structures. Two-phase pipelines should be designed for annular flow regime conditions to minimize the possibility of encountering slug flow[8].

b. Vertical Flow

Flow behavior in vertical pipes, where gravity plays an important role, has been less extensively investigated than has flow in horizontal pipes. The vapor/gas phase tends to be distributed as small bubbles at low vapor flow rates for a constant liquid flow rate. Increasing void fraction causes the agglomeration of bubbles into larger plugs and slugs. Further agglomeration of slugs, caused by further increasing void fraction, causes separation of the phases into annular patterns wherein liquid concentrates at the channel wall, and vapor flows in the central core of the vertical pipes.

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.

Table 2: Description of flow regime in vertical pipeline

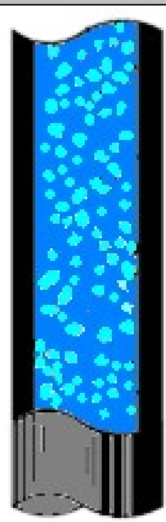
Flow regime in vertical pipeline	Description
	**Bubble Flow** Bubbles (gas) are dispersed throughout the liquid & moves along the upper part of the pipe due to their buoyancy. o Velocity of the bubble of gas ≈ velocity of the liquid o Occurs when the gas content is 0.3 wt. frac. of the o total volumetric flow & at high mass flow rates

Table 2 Continued

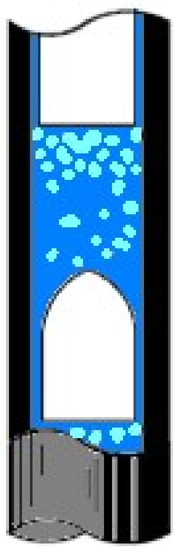
Flow regime in vertical pipeline	Description
	**Slug Flow** As the vapor rate increases, bubbles coalesce into slugs which occupy the bulk of the cross-sectional area. Alternating slugs of vapor and liquid move up the pipe with some bubbles of vapor entrained in the liquid slugs. Surrounding each vapor 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.

Table 2 Continued

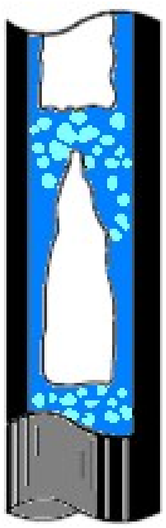
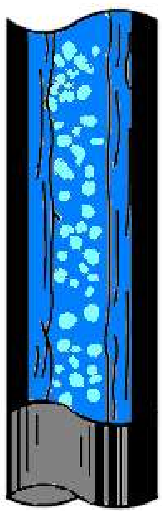
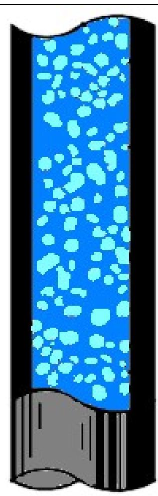
Flow regime in vertical pipeline	Description
	**Froth Flow** As the vapor rate increases further, the laminar liquid film is destroyed by vapor turbulence and the vapor slugs become more irregular. Mixing of vapor bubbles with the liquid increases and a turbulent, disordered pattern is formed with ever 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.

Table 2 continued

Flow regime in vertical pipeline	Description
	**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.
	**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).

In this pipeline, the flow quality values and flow rate depend on the fluid and pressure. The main flow regimes in vertical pipeline based the flow quality are shown in the table 3.

Table 3: basic flow patterns in vertical pipelines[11]

Flow quality	Flow rate	Flow pattern
Low	Low and intermediate	Bubble
	High	Dispersed bubble
Intermediate	Low and intermediate	Slug
	High	Churn / froth
High	High	Annular
	High (post-dryout)	Mist

B. Principal Of Two-Phase Flow Measurement

The principal of two-phase flow measurement is based on the mixture mass flow rate and the pressure drop as well as the flow quality. The online measurement of mass quality is still a challenge. Thus, instead of relying on the mass flow quality, it is more practical to rely upon the measurement of the void fraction parameter. The void fraction represents the key parameter to find the mass flow rate of each phase[1].

a. Void Fraction Measurement

Void fraction is a dimensionless quantity indicating the fraction of a geometric or temporal domain occupied by the gas phase, and it is probably the most significant quantity one can measure in two-phase flow. Void fraction measurement techniques are based on various principles: usually, instruments are sensitive to some physical property which is different for the two phases, such as the fluid density or the electrical conductivity.

The importance is even greater in applications, where the void fraction is often a key parameter in design as well as in financial issues (just think of the petroleum industry, where one of the main problems is the oil-water-gas flow metering). On the other hand, void fraction measurements are essential to validate the predictions of mathematical models[2].

As a method which identifies the two-phase flow condition, many techniques have been proposed for a sectional void fraction measurement. Despite of measurement techniques for the void fraction measurement, the quality measurement of two-phase flow is quite difficult since the quality of the two-phase flow is not obtained from the sectional void fraction when there is velocity difference between the liquid phase and the gas phase.

C. Classification of Two-phase and Multiphase Flows

Another way to classify two-phase and multiphase flows, apart from the classification according to the flow pattern, is by the GVF (Gas Volume Fraction) of the flow. This method of classification is relevant to multiphase metering; one would expect that a meter measuring predominately liquid with just a few percent gas would be significantly different from one designed to operate in what is generally understood as a wet gas application. The classes are defined in table 4[3].

Table 4: Classification of two-phase and multiphase flows

Class	Indicative GVF range	Comment
Low GVF	0 – 25%	This Low GVF range of multiphase flow could also be termed ‘gassy liquid’. In the lower end of this range traditional single-phase meters could in many cases provide the sufficient measurement performance. Increasing measurement uncertainty, and also risk of malfunctioning must be expected as the GVF increases.
Moderate GVF	25% - 85%	The Moderate GVF can be considered as the ‘sweet spot’ of multiphase meters, i.e. the range where they have their optimum performance, and where at the same time traditional single-phase meters are not a viable option.

Table 4 Continued

Class	Indicative GVF range	Comment
High GVF	85% - 95%	Entering this High GVF range the uncertainty of multiphase meters will start to increase, with a rapid increase towards the upper end of the range. This increase in uncertainty is not only linked to more complex flow patterns at high gas fraction, but also because the measurement uncertainty will increase as the relative proportion of the fraction of the component of highest value (in this case the oil) decreases.
Very high GVF	95% - 100%	This upper end of the multiphase range could also be termed the ‘wet gas’ range. In the lower end of the very high GVF range the measurement performance of in-line multiphase meters may still be sufficient for well testing, production optimization and flow assurance. For allocation metering, in particular at the high end of this range, often gas is the main ‘value’ component, and a wet gas meter would be the preferred option. This corresponds to a Lockhart-Martinelli (LM) value in the range from 0 to approximately 0.3.

DEFINITIONS

Dispersed flow - Is characterized by a uniform phase distribution in both the radial and axial directions. Examples of such flows are bubble flow and mist flow.

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

Gamma rays - Electromagnetic waves of the highest frequencies known, originally discovered as an emission of radioactive substances and created by transition of a nucleus to lower energy states.

Gas Volume Fraction (GVF) - The gas volume flow rate, relative to the multiphase volume flow rate, at the pressure and temperature prevailing in that section. The GVF is normally expressed as a fraction or percentage.

Liquid-Gas-Ratio (LGR) - The ratio of liquid volume flow rate and the total gas volume flow rate. Both rates should be converted to the same pressure and temperature (generally at the standard conditions). Expressed in volume per volume, e.g. m^3/m^3.

Microwave - Electromagnetic radiation having a wavelength from 300 mm to 10 mm (1 GHz to 30 GHz).

Multiphase flow meter - A device for measuring the individual oil, water and gas flow rates in a multiphase flow.

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.

Slip - Term used to describe the flow conditions that exist when the phases have different velocities at a cross-section of a conduit. The slip may be quantitatively expressed by the phase velocity difference between the phases.

Superficial phase velocity - The flow velocity of one phase of a multiphase flow, assuming that the phase occupies the whole conduit by itself. It may also be defined by the relationship (Phase volume flow rate) / (Pipe cross-section).

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

Void fraction - The ratio of the cross-sectional area in a conduit occupied by the gas phase and the cross-sectional area of the conduit, expressed as a percentage.

NOMENCLATURE

A	Radius-sectional area, ft^2
A_P	Cross sectional area of pipe, ft^2
Av	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
ΔPo	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
S	Slip ratio
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
α	Void fraction
β	Venturi diameter ratio
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

REFERENCES

1. Ammar Zeghloul et al. 2021. *Theoretical study and experimental measurement of the gas liquid two-phase flow through a vertical Venturi meter*. Proceeding of the Institution of Mechanical Engineers, Part C : Journal of Mechanical Engineering Science, ImechE 2020 Sage Journal. Algeria.

2. Bertola, V. 2003. *Modelling and Experimentation in Two-Phase Flow : Two-Phase Flow Measurement Techniques*. Springer-Verlag Wien. Paris, France.

3. Christian Michelsen Research. 2005. *Handbook of Multiphase Flow Metering Revision 2*. Norwegian Society for Oil and Gas Measurement. Norwegia, Solli.

4. Fusheng Zhang, Feng Dong, Chao Tan. 2010. Flow Measurement and Instrumentation : High GVF and low pressure gas- liquid two-phase flow measurement based on dual-cone flowmeter. Science Direct : Elsevier Ltd.. China.

5. F Dong, C Tan, W Li, F S Zhang. 2009. *Flow rate measurement of oil-water two-phase flow based on V-cone flow meter*. Journal of Physics: Conference Series 147 (2009) 012059 : IOP Publishing. China.

6. Kolmetz, Karl. 2013. *Kolmetz handbook of Process Equipment Design : Hydraulic Fluid Flow Two Phase Calculations*. KLM Technology Group, Malaysia.

7. Mitsuhiro Fukuta et al. 2018. *Quality Measurement of Two Phase Flow with Plug Flow. International Refrigeration and Air Conditioning Conference. Paper 1889*. Purdue e-Pubs, Purdue University. Japan.

8. Rizaldy et al. 2016. *Proceedings 38th New Zealand Geothermal Workshop : Pressure Drop in Large Diameter Geothermal Two-Phase Pipelines*. ResearchGate. Auckland, New Zealand.

9. Ron DiGiacomo. 2014. *ABB Whitepaper : Two Phase Flow Considerations for Coriolis Meters. ABB Limited Process Automation*. Oldends Lane, Stonehouse, Gloucestershire

10. Tim Patten, Micro Motion, Inc.. 2004. *Micro Motion White Paper : Understanding the Challenges of Two-Phase Flow*. Emerson Process Management, Colorado, USA

11. https://www.thermal-engineering.org/what-is-two-phase-fluid-flow-definition/

12. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/239411

13. https://eng.ox.ac.uk/airg/research/coriolis-research/measuring-two-phase-flow/

14. K Kolmetz et al, Kolmetz Handbook of Process Equipment Design, Instrumentation Selection, Sizing and Troubleshooting, Engineering Design Guidelines, 2011.

15. K Kolmetz et al, Kolmetz Handbook of Process Equipment Design, Fluid Flow, Engineering Design Guidelines, 2011.