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Multiphase Flow Patterns in Pipelines: A Review of Research Results

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Abstract

This paper is a literature review covering various aspects of multiphase flow patterns in horizontal, inclined and vertical pipes. A description of commonly observed flow patterns in horizontal, slightly inclined and vertical pipes are presented and discussed. Experimental techniques for direct and indirect determination of flow patterns are reviewed. Flow pattern transition criteria based on correlations and theoretical derivations are equally presented. The paper made attempts to identify the current state of knowledge and highlighted areas where new development work is required.

1.0 Introduction

Simultaneous passage of gas and liquid (water and or oil) in a transport or export pipeline / tiebacks often results in a variety of flow patterns, see Figure 1. Two-phase flow or three-phase flow is simultaneous flow of any two or three of the discrete phases (solid, liquid or gas). These phases are commonly encountered in the petroleum or allied industry. The formation of particular pattern is dependent on flow rates, fluid properties, pipe size and pressure profiles. The critical issue is how to define flow patterns which are somewhat subjective depending on the researchers own interpretation. This is because flow pattern definition in multiphase flow is still largely obtained by visual observation.

The concept of flow patterns in pipes introduces new challenges in the understanding of multiphase fluids principally because of the form in which fluids exist in pipes. The pipe may be horizontal, near horizontal or vertical. For a two-phase gas-liquid system, the flow patterns can be grouped into four main classes where each class can be subdivided into sub-classes for detailed description. The following classes of flow patterns have been well documented in literatures [1 - 5]

(i) Stratified flow (Subclasses: stratified smooth, stratified wavy)
(ii) Intermittent flow (Subclasses: elongated bubble, slug, churn)
(iii) Annular flow (Subclass: wispy annular)
(iv) Bubble flow (Subclasses: bubbly, dispersed bubble)

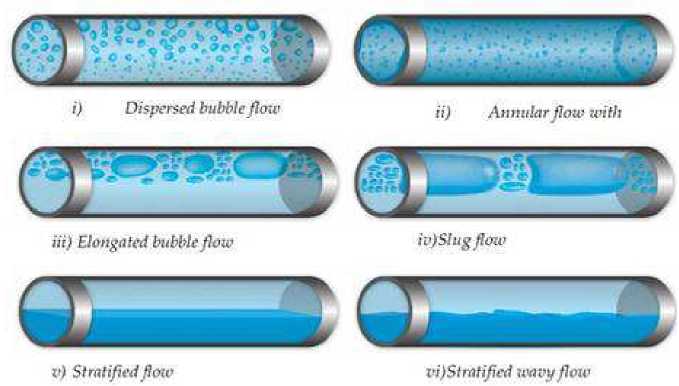

Figure 1: Flow patterns in horizontal pipe [6]

2.0 Multiphase Flow Patterns in Horizontal Pipes

Pipeline transportation in deep and ultra-deep wells however presents a unique challenge such as extremely uneven seabed and topographies. When oil and gas mixture flows through a long subsea tieback, a number of different patterns can be observed. In a horizontal pipes or slightly inclined pipes different flow patterns are recognisable. For relatively low gas and liquid rates a stratified configuration occurs with the liquid flowing on the bottom and the gas flowing above it. As the liquid

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rate is increased (at a constant gas rate) waves appear on the interface. At still higher liquid rates the waves can grow to the top of the pipe and, intermittently, form liquid blockages. At low gas velocities this intermittent regime is characterized as a plug pattern, whereby the gas flows as steady elongated bubbles along the top of the pipe. At high gas flows a slug pattern exists whereby slugs of highly aerated liquid move downstream approximately at the gas velocity [7]. At low liquid throughputs transitions from stratified-wavy to annular flow occur with increasing gas throughputs. An increase of liquid flow causes a transition to an intermittent slug flow, which is accompanied by large, undesirable pressure pulsations [8].

For oil dominated systems, the possible flow patterns are dispersed bubble and intermittent flow [9]. Oddie [10] generated a total of 444 experimental data for water-gas and oil-water-gas flows and observed that bubble, churn, elongated bubble, slug and stratified flow dominate in inclined pipes. While dispersed/homogenous, mixed/semi-mixed and segregated/semi segregated flows were observed for oil water flows.

It is important from the designer's point of view to be able to predict accurately what flow pattern will occur for given input flow rates, pipe size, and fluid properties [11]. Only then can the proper flow model be selected. Method for the prediction of flow pattern can be classified into two categories, experimental correlations and mechanistic modelling.

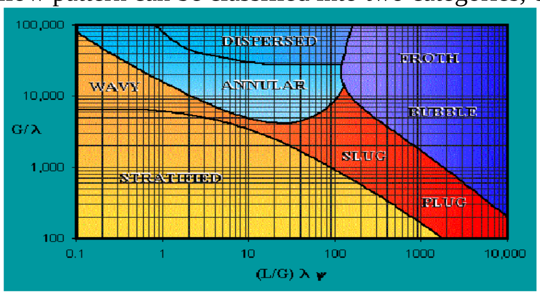

Figure 2: Flow pattern maps for horizontal pipes two-phase, air-water

The most common correlation used to calculate the conditions for the transition from one flow pattern to another is the Mandhane plot [1]. However, a number of flow pattern maps exist based on pipe configurations (see Figure 2). Many of these maps result from data covering a rather limited range of fluid properties and pipe diameters. Consequently, large discrepancies are often observed between a predicted flow regime and that actually observed in a subsequent test (See Table 1) for descriptions of various flow patterns in horizontal pipes.

3.0 Multiphase Flow Patterns in Vertical Pipes

One of the earliest works of Govier and Aziz [12] on liquid–liquid two-phase flow through vertical pipes was to study the flow patterns, pressure drop and holdup using three different oils with high-speed photography. Other researchers' have been making efforts at representing the flow patterns observed under different conditions in the form of a flow pattern map (see Figure 3). For the particular case of upwards flow in vertical tubes four main flow patterns may be distinguished [13] these are bubble flow, churn flow, plug flow and annular flow (see Figure 2). Similar flow patterns were observed in [14] and they were classified as bubble, bubbly-slug, slug and churn flow. They observed that liquid superficial velocity has great impact on the flow pattern transitions in vertical pipe rather than gas superficial velocity. Churn flow possesses some of the characteristics of plug flow, with the main differences being that the gas plugs become narrower and more irregular; the continuity of the liquid in the slug is repeatedly destroyed by regions of high gas concentration and the thin falling film of liquid surrounding the gas plugs cannot be observed [13]. The liquid-liquid, kerosene-water flow experiment carried out in [15] showed that at low flow rates of kerosene, kerosene flows as droplets in the continuous water phase named as bubbly flow pattern. At high flow rates of kerosene, the analysis shows that there may be a separate flow pattern like core annular flow. No slug flow was observed rather there was transition consisting of irregular shaped chunks and bubbles of kerosene in water which they referred to as churn turbulent flow pattern. (See Table 2) for descriptions of various flow patterns in vertical pipes.

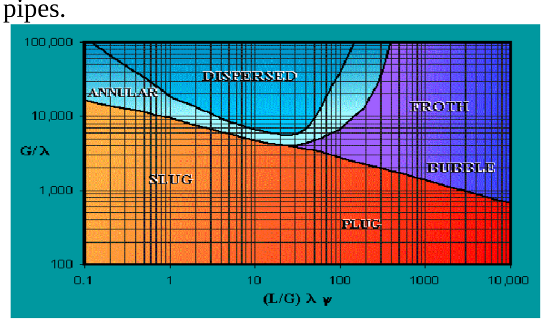

Figure 3: Flow pattern maps for vertical pipes two-phase, air-water

Table 1: Liquid-gas flow pattern classifications in horizontal pipes

Flow Patterns	**Characteristics**	**Conditions of occurrence**
Fluid flow modes		
Annular dispersed flow (ADF)	The liquid travels partly as a continuous film around the perimeter of the pipe and partly as a small droplets distributed in the gas phase.	This occurs at very high gas velocity and low liquid velocity.
Stratified (wavy) flow (SWF)	This is characterised by separation of fluids into different layers, with lighter fluids flowing above the heavier fluids.	For low flow rates of liquid and gas, a smooth or wavy stratified flow will occur. The interface may be smooth or wavy; hence the term wavy stratified flow.
Slug (intermittent)flow	Slugs of liquid are separated by coalesced gas bubbles. The intermittent pattern is evidenced when fluids are subdivided into slugs and elongated bubble patterns.	For intermediate liquid velocities, rolling waves of liquids will be formed. The rolling waves increase to the point of forming a slug flow, sometimes refer to as plug flow.
Dispersed bubble flow	The gas phase is distributed as discrete bubbles in an axially continuous liquid phase. Increased liquid flow rate prevents bubble accumulations and are dispersed more uniformly in the liquid phase.	This occurs at a very high flow rate. For very high liquid velocities and low gas/liquid ratios, the dispersed bubble flow pattern will prevail.

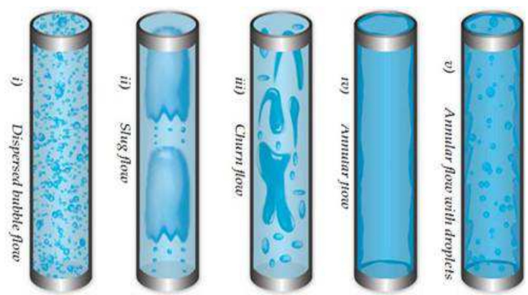

Figure 4: Flow patterns in vertical pipe [6]

McQuillan and Whalley [13] observed that it is possible to extend the description of flow patterns in vertical pipes. For example, the annular flow regime may be sub-divided into wispy and non-wispy annular flow, with wispy annular flow occurring as a result of the agglomeration of the liquid droplets in the gas core into large streaks or wisps. Furthermore, because the transitions between the various flow regimes do not occur suddenly, it is possible to observe a number of transition flow patterns which possess characteristics of more than one of the main flow patterns described above.

Table 2: Liquid-gas flow pattern classifications in vertical pipes

Flow Patterns	**Characteristics**	**Conditions of occurrence**
Fluid flow modes		
Annular dispersed flow	The gas flows along the centre of the tube or partially as droplets in the central core. The liquid travels partly in the form of an annulus at the wall.	This occurs at very high gas velocity and low liquid velocity.
Dispersed bubble flow	The gas phase is distributed as discrete bubbles in an axially continuous liquid phase. Increased liquid flow rate prevents bubble accumulations and are dispersed more uniformly in the liquid phase.	This occurs at a very high flow rate. For very high liquid velocities and low gas/liquid ratios, the dispersed bubble flow pattern will prevail.
Slug flow	Slugs of liquid are separated by coalesced gas bubbles. The intermittent pattern is evidenced when fluids are subdivided into slugs and elongated bubble patterns.	For intermediate liquid velocities, rolling waves of liquids will be formed. The rolling waves increase to the point of forming a slug flow, sometimes refer to as plug flow.
Churn flow	This is similar to slug flow pattern but highly disordered in which the vertical motion of the liquid is oscillatory. In this case, the continuity of the liquid in the slug region is destroyed by a high gas concentration.	The liquid and gas rates are intermediate between the annular flow and slug flow for churn flow to occur. Further increase in flow velocity makes the pattern unstable.

4.0 Two-Phase Flow Pattern Characterization

A number of authors have made empirical attempts to define the conditions under which the various flow patterns may be expected. This has been done by proposing flow pattern maps of various kinds [12]. It is clear for any given fluid system the major factors in determining the flow pattern are the flow velocities. The fluid densities, viscosities, and interfacial tension and pipe diameter are the other factors though their contributions are still a subject of debate.

Predicting flow patterns in multiphase flow in pipes is a rather complex exercise. Experimental data is widely used for the prediction of flow patterns [2]. It involves the collection of experimental data followed by mapping of the data in a two-dimensional plot by locating transition boundaries between the flow patterns. Such a plot is termed flow pattern map. This map often serves as the means by which prediction of the flow pattern for design purposes take place.

Another approach is mechanistic modelling. In this approach, the dominant physical phenomena that will cause a specific transition are identified. Then the physical phenomena are formulated mathematically and transition lines are calculated. This can be presented as an algebraic relation or with respect to dimensionless coordinates. Taitel and Dukler [16] adopted mechanistic modelling approach for predicting flow pattern transitions. The drawback of their work was that different models were used for horizontal, slightly inclined and for vertical flows. This was improved upon by Barnea [7], a unified model in which one uses the same models for all inclination angles. However, it is recommended that both approaches are combined [2].

Clearly there exist a number of problems with identifying and defining flow patterns and flow pattern transitions and establishing their range of applicability. Taitel [2] stated that not less than eleven parameters can be identified as affecting the flow pattern. The parameters are as highlighted below:

(i) The liquid superficial velocity, U_{LS} , m/s

(ii) The gas superficial velocity, U_{GS} , m/s

(iii) Liquid density, ρ_L , Kg/m³

(iv) Gas density, ρ_G , Kg/m³

(v) Liquid viscosity, μ_L , Kg/s m

(vi) Gas viscosity, μ_G , Kg/s m

(vii) Pipe diameter, D m

(viii) Acceleration of gravity, g m/s²

(ix) Surface tension, σ Kg/s²

(x) Pipe roughness, ϵ, m

(xi) Pipe inclination, θ

Therefore, finding a relation among these parameters based on experimental data may just be an impossible task. The complexities associated with flow pattern transitions have given rise to many predictions available in the literatures.

Govier & Aziz [12] reported separate correlations to describe different flow patterns in horizontal pipes and can be expressed as

For stratified flow:

$$\phi_G = \frac{15400X}{G_{SL}^{0.8}} \tag{1}$$

For elongated bubble flow

$$\phi_G = \frac{27.315X^{0.855}}{G_{SL}^{0.17}} \tag{2}$$

For dispersed bubble flow

$$\phi_G = \frac{14.2X^{0.75}}{G_{SL}^{0.1}} \tag{3}$$

For slug flow

$$\phi_G = \frac{1190X^{0.815}}{G_{SL}^{0.5}} \tag{4}$$

For annular mist flow

$$\phi_G = \left(4.8 - 0.3125D\right)X^{\left(0.343-\left(0.021D\right)\right)} \tag{5}$$

Where

$$X = \left[\frac{V_{SL}}{V_{SG}}\right]^{0.875}\left[\frac{\rho_L}{\rho_G}\right]^{0.375}\left[\frac{\mu_L}{\mu_G}\right]^{0.125} \quad (6)$$

G_{SL} , is the superficial mass flow rate of the liquid in Lbs/ft2 hr

Beggs and Brill [17] suggested a number of correlations for the prediction of flow patterns in gas-liquid flow in pipes applicable to both horizontal and vertical pipes. The following are the expressions,

$$N_{Fr} = \frac{u_m^2}{gD} \quad (7)$$

$$\lambda_L = \frac{q_L}{q_L + q_G} \quad (8)$$

$$L_1 = 316\lambda_L^{0.302} \quad (9)$$

$$L_2 = 0.0009252\lambda_L^{-2.4684} \quad (10)$$

$$L_3 = 0.10\lambda_L^{-1.4516} \quad (11)$$

$$L_4 = 0.50\lambda_L^{-6.738} \quad (12)$$

The following relations will determine the flow patterns as suggested by Beggs and Brill

For segregated (stratified) flow will exist if

$$\lambda_L < 0.01 \,\&\, N_{Fr} < L_1 \text{ OR } \lambda_L \geq 0.01 \,\&\, N_{Fr} < L_2 \quad (13)$$

For intermittent (slug) flow will exist if

$$0.01 \leq \lambda_L < 0.4 \,\&\, L_3 < N_{Fr} \leq L_1 \text{ OR } \lambda_L \geq 0.4 \,\&\, L_3 < N_{Fr} \leq L_4 \quad (14)$$

For bubble or dispersed bubble flow will exist if

$$\lambda_L < 0.4 \,\&\, N_{Fr} \geq L_1 \text{ OR } \lambda_L \geq 0.4 \,\&\, N_{Fr} \succ L_4 \quad (15)$$

Transition flow if

$$\lambda_L \geq 0.01 \,\&\, L_2 < N_{Fr} \leq L_3 \quad (16)$$

Taitel and Dukler [18] suggested that the criterion at transition from stratified flow occurs when

$$F^2\left[\frac{1}{\left(1-\breve{h}_l\right)^2}\frac{\breve{U}_G^2\frac{d\breve{A}_L}{\breve{A}_G}}{\breve{A}_G}\right] \geq 1 \quad (17)$$

$$F = \sqrt{\frac{\rho_G}{(\rho_L - \rho_G)}}\frac{U_{GS}}{\sqrt{Dg\cos\beta}} \quad (18)$$

The dimensionless variables are defined by

$$\breve{h}_L = \frac{h_L}{D} \quad (19)$$

$$\breve{A}_L = \frac{A_L}{D^2} \quad (20)$$

$$\breve{A}_G = \frac{A_G}{D^2} \quad (21)$$

$$\breve{U}_L = \frac{U_L}{U_{LS}} = \frac{A}{A_L} \quad (22)$$

$$\breve{U}_G = \frac{U_G}{U_{GS}} = \frac{A}{A_G} \quad (23)$$

Where F is a Froude number modified by the density ratio, h_L is the liquid level in equilibrium stratified flow, A_L is the liquid cross sectional area.
The flow conditions may generate either stratified smooth or stratified wavy flow. The waves are formed on a smooth liquid interface due to the gas flowing over the liquid or as a result of the action of gravity, even in the absence of gas flow. Taitel & Dukler [18] therefore suggested the condition for wave generation as a result of the wind effect given by

$$U_G \geq \left[\frac{4v_L(\rho_L - \rho_G)\rho\cos\beta}{s\rho_G U_L}\right]^{0.5} \quad (24)$$

Where v_L the liquid kinematic viscosity and s is the sheltering coefficient
Taitel et al [16] demonstrated that at certain gas void fraction which exceeds 0.25; there will be transition from bubble flow to slug flow and that can be expressed as

$$U_{LS} = \frac{1-\alpha}{\alpha}U_{GS} - 1.53(1-\alpha)\left[\frac{(\rho_L - \rho_G)g\sigma}{\rho_L^2}\right]^{0.25} Sin\beta \quad (25)$$

Where α = 0.25, gas void fraction, β is positive for upward flow and negative for downward flow.
Barnea [7] proposed a general method that will allow the prediction of the flow patterns once the flow rates, the pipe size, fluid properties and angle of inclinations are specified. The models presented transition criteria for different flow patterns and are summarised below.
The transition from dispersed bubbles flow can be observed when the following two conditions are satisfied

$$D > 19\left[\frac{(\rho_L - \rho_G)\sigma}{\rho_L^2 g}\right]^{0.5} \quad (26)$$

$$U_O = 1.53\left[\frac{(\rho_L - \rho_G)g\sigma}{\rho_L^2}\right]^{0.25} \quad (27)$$

Where D is the pipe diameter, ρ_L and ρ_G are the liquid and gas densities and σ is the surface tension. U_o is the bubble rise velocity.
Taitel [2] observed that so far there is no acceptable method to calculate the transition boundaries and the reason why different mechanisms are proposed by different researchers for the same transition boundaries. Even the experimental results, tends to report different transition boundaries where conditions of the experiment are identical. This has gone to show that there is sufficient evidence that current correlations for predicting flow patterns are limited in its applicability. There is the need to develop better and more accurate exact models for flow pattern prediction which are much more amenable to the practical application.

5.0 Three-Phase Flow Pattern Characterisation

Three-phase flow of two liquids and gas occurs often, especially in the production of hydrocarbons from oil and gas fields when oil, water, and natural gas flow in the transporting pipelines. In such environment, a frequently encountered flow pattern is slug flow [19]. Depending on the flow rates of the phases, if sufficient mixing takes place, one liquid may be dispersed in the other; otherwise, the liquids will flow in separate layers. Still within the stratified pattern, mixing layers at the liquid–liquid interface may develop in such a way that even the stratified configurations consist of different phase distributions [20].
It was argued [21] that in horizontal three-phase oil-water-air flow, the same flow patterns are observed as in two-phase flow of a gas and a liquid, as long as the degree of dispersion of the oil and water is not taken into account. While there have been numerous investigations of two-phase flow regimes, however limited efforts have been directed towards investigating three-phase phenomenon. Previous works can be divided into two main categories on the basis of pipe angle of inclination. The horizontal and/or slightly inclined case was studied by [20 - 23] whilst the vertical case was considered by Chen et al. [8]
Taitel [24] observed and classified seven flow patterns for three-phase in pipes which are similar to the case of two-phase flow- as stratified smooth flow, stratified wavy flow, rolling wave flow, plug flow, slug flow, pseudo slug flow and annular flow. Acikgoz et al [20] investigated an oil–water–gas system flowing in a horizontal Plexiglas tube of 5.78 m length and 19 mm internal diameter. Different flow pattern maps were constructed for different values of the oil superficial velocity. The authors classified the flow patterns according to the combination of the following flow properties:
(i) Liquid phase that is predominantly in contact with the pipe walls
(ii) Liquid–liquid flow pattern (either separated or dispersed)

(iii) Relevant flow pattern between the liquid (oil + water) and the gas phases.

For the first part of their three-phase flow pattern determination, they identified either oil based, or water based flows; for the second part dispersed, separated, or separated–dispersed liquid–liquid flow; for the third part they identified six possible patterns: stratified, wavy, plug, slug, annular, and dispersed. Acikgoz et al [20] reported similar patterns as outlined in (Table 3 and Figures 5 (a and b)) for three-phase horizontal pipe. Keskin et al [25] in a three-phase oil, water, gas experiment proposed twelve flow patterns similar to that proposed by Acikgoz et al [20] and Taitel et al. [24]

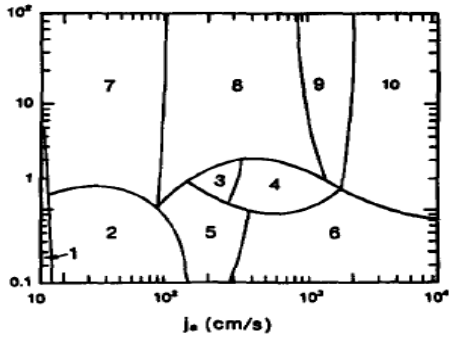

Figure 5a: Flow patterns for three-phase, oil, water and gas in horizontal pipes [20]

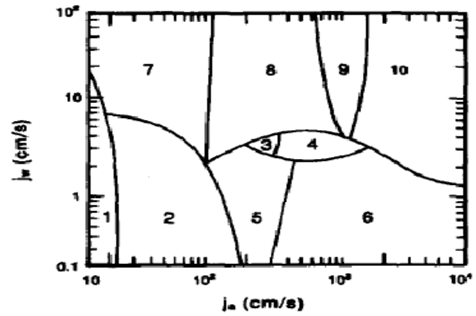

Figure 5b: Flow patterns for three-phase, oil, water and gas in horizontal pipes [20]

Taitel and Dukler [16] also proposed transition from stratified flow for three phase oil-water-gas especially when the liquid level is unstable as

$$U_G - U_O > \left(1 - \frac{h_L}{D}\right)\sqrt{\frac{(\rho_O - \rho_G) g A_G Cos\beta}{\rho_G S_j}} \quad (28)$$

They stated that slug flow will exist for high liquid holdup and annular flow for low liquid holdup i.e. h_L .

Table 3: Three-Phase Flow Pattern Classifications

Region	Flow Regime
1	Oil-based dispersed plug flow
2	Oil-based dispersed slug flow
3	Oil-based dispersed stratified/wavy flow
4	Oil-based separated stratified/wavy flow
5	Oil-based separated wavy stratifying-annular flow
6	Oil-based separated/dispersed stratifying-annular flow
7	Water-based dispersed slug flow
8	Water-based dispersed stratified/wavy flow
9	Water-based separated/dispersed incipient stratifying-annular flow
10	Water-based dispersed stratifying-annular flow

6.0 Conclusion

In this work a review of multiphase flow pattern models has been carried out. Many of the relevant methods found in the literature to model the multiphase flow in pipelines is presented. It includes the traditional simplified and mechanistic models as well as empirical models. Though there are a number of models found in the literature, however no single model is able to reproduce all the existing multiphase flow patterns in pipeline given varied conditions. Some gaps were reported by a number of authors as regards model validation which bothered on non availability of experimental data. It highlighted the significant of experimental work in the identification of flow patterns in pipeline. Though some authors argued that visual observations in flow pattern recognition is subjective which has been based largely on individual interpretation. Some instrumental methods of analysis have been proposed by some workers, these are not simple to use and therefore did not find widespread applications. Experimental data are without doubt very useful especially for model development, testing and validation of mechanistic models.

7.0 References

[1] Lin P.Y. and Haranty T.J. ''Effect of Pipe Diameter on Flow Patterns for Air – Water Flow in Horizontal Pipe'' International Journal of Multiphase Flow, Vol. 13, No. 4, Page 549 – 563, 1987.

[2] Taitel Y. ''Flow Pattern Transition in Two-Phase Flow'' 2nd Annual Meeting of Multifluid of Science and Technology, March 1999.

[3] Hurlburt, E.T. and Haranty T.J. ''Prediction of the Transition from Stratified to Slug and Plug Flow for Long Pipes'' International Journal of Multiphase Flow, 28 (2002), 707 – 729.
[4] Li, X., Miskimins, J.L., Sutton, R.P. and Hoffman, B.T. "Multiphase Flow Pattern Recognition in Horizontal and Upward Gas-Liquid Flow Using Support Vector Machine Models" SPE Annual Technical Conference and Exhibition, 27-29 October, Amsterdam, The Netherlands, 2014.
[5] Deng, C., Adams, K. and MacFarlane, T. " The Effects Of Flow Pattern Transitions Of Three-phase Flows On Corrosion" NACE, CORROSION, 16-20 March, New Orleans, Louisiana, 2008.
[6] BRATLAND, O., " Pipe Flow 2 - Multiphase Flow Assurance". First ed. Ovi Bratland.
[7] Barnea, D. ''A Unified Model for Predicting Flow Pattern for the Whole of Pipe Inclinations'' International Journal of Multiphase Flow, Vol. 13, Page 1 – 12, 1987.
[8] Chen, X. and Guo, L. ''Flow Patterns and Pressure Drop in Oil-Air-Water Three Phase Flow through Helically Coiled Tubes'' International Journal of Multiphase Flow, Vol. 29, Page 1053 – 1072, 1999.
[9] Oliemans, R.V.A. ''Multiphase Science and Technology for Oil/Gas Production and Transport'' SPE Paper Number 27958, August 1994.
[10] Oddie, G. ''Experimental Study of Two and Three Phase Flows in Large Diameter Inclined Pipes'' International Journal of Multiphase Flow, Vol. 13, No. 4, Page 527 – 558, 2003.
[11] Mandhane, J.M., Gregory, G.A. and Aziz, K. ''A Flow Pattern Map for Gas – Liquid Flow in Horizontal Pipes'' International Journal of Multiphase Flow, Vol. 1, pp 537 – 553, 1973.
[12] Govier, G.W. and Aziz K. ''The Flow of Complex Mixtures in Pipes'' Van Nostrand Reinhold, New York, 1972.
[13] McQuillan, K.W. and Whalley, P.B. ''Flow Patterns in Vertical Two-Phase Flow'' International Journal of Multiphase Flow, Vol. 11, Issue 2, pp 161 – 175, 1985.
[14] Zainon, M.Z., Zubir, M.A. and Ramli, R. '' Velocities Effects on the Void Distribution in a Vertical Gas-Liquid Two-Phase Flow Channels'' Advanced Material Research, Vol. 889 – 890, pp 369 – 373, 2014.
[15] Jana, A.K., Das, G. and Das, P.K. ''Flow Regime Identification of Two-Phase Liquid-Liquid Up-flow through Vertical Pipe'' Chemical Engineering Science, Vol. 61, Issue 5, pp 1500 – 1515, 2006.
[16] Taitel, Y. and Dukler, A.E. ''A Model for Predicting Flow Regime Transition in Horizontal and Near Horizontal Gas-Liquid Flow'' American Institute of Chemical Engineers Journal, Vol. 22, Issue 1, pp 47 – 55, 1976.
[17] Beggs, D.H. and Brill, J.P. ''A Study of Two-Phase Flow in Inclined Pipes'' Journal of Petroleum Technology, Vol. 25, Issue 5, 1973.
[18] Taitel, Y. Barnea, D. and Dukler, A.E "Modelling Flow Pattern Transitions for Steady Upward Gas-Liquid Flow in Vertical Tubes", American Institute of Chemical Engineers Journal, 26, 345-354, 1980.
[19] Bonizzi, M. and Issa, R.I. ''On the Simulation of Three-Phase Slug Flow in Nearly Horizontal Pipes Using the Multi-Fluid Model'' International Journal of Multiphase Flow, Vol. 29, pp 1719 – 1747, 2003.
[20] Acikgoz, M., Franca, R.T. and Lahey, Jr. ''An Experimental Study of Three-Phase Flow Regimes'' International Journal of Multiphase Flow, Vol. 18, Issue 3, pp 327 – 336, 1992.
[21] Stapelberg, H.H. and Mewes, D. ''The Pressure Loss and Slug Frequency of Liquid-Liquid-Gas Slug Flow in Horizontal Pipes'' International Journal of Multiphase Flow, Vol. 20, Issue 2, pp 285 – 303, 1994.
[22] Lee, A.H., Sun, J.Y. and Jepson, W.P. ''Study of Flow Regime Transitions of Oil-Water-Gas Mixtures in Horizontal Pipelines'' The Third International Offshore and Polar Engineering Conference, Singapore, June 1993.
[23] Spedding, P.L., Donnelly, G.F. and Cole, J.S. ''Three Phase Oil-Water-Gas Horizontal Co-Current Flow: Experimental and Regime Map'' Chemical Engineering Research and Design, Vol. 83, Issue 4, pp 401 – 411, 2005.
[24] Taitel, Y. Barnea, D. and Brill, J.P. "Stratified three phase flow in pipes", International Journal of Multiphase Flow, Vol. 21, pp 53-60, 1995.
[25] Keskin, C. and Zhang, H. ''Identification and Classification of New Three-Phase Gas/Oil/Water Flow Patterns'' Society of Petroleum Engineers SPE 110221, 2007