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Mathematical Model for Predicting the Development of Two-Phase Flow in a Horizontal Pipe

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Abstract: *Prediction of the flow pattern is a central problms in multi-phase flow analysis. It is a vital point for researchers to accurately predict which flow pattern category types will occur at different flow rates. For this purpose, a mathematical model using the MATLAB (R2017b) computer program is developed for the prediction of gas-liquid two-phase flow patterns in a horizontal pipe with an inner diameter of 30mm under standard conditions. The properties of the air-water two-phase, the pipe geometry, and the flow rates of phases are defined to initiate the operating conditions. The mass flow rates of air and water changed from 0.002 to 0.004 kg/s and 0.672 to 1.334 kg/s, respectively. The impact of properties of the fluid and pipe diameters on two-phase flow configuration is considered to predict the impact of fluid properties on the flow pattern. The findings indicate that as the mass flux increases, the pipe diameters decrease, affecting the configuration of the flow pattern types. The mathematical model's predicted results are validated by comparing with previous studies. In addition, good agreement is obtained when the predicted results are compared to the ongoing experiment of this research.*

Keywords*: mathematical model, flow pattern map, two-phase flow, horizontal flow, baker map, Matlab code*

Introduction

Two-phase flow is the major cause of multi-phase flows that are restricted to two-phase traveling together at the same time [1]. The interface between liquid and gas phases, which may take many various shapes relying on the interface two-phase flow patterns, is one of the most difficult elements of dealing with two-phase flow [2,3]. Various interfaces and distributions in two-phase are called "flow patterns" or "flow regimes".

The flow pattern is a characteristic of a two-phase flow that may be used to assess the flow type in the pipeline and its impact on industrial applications [4]. The complexity of two-phase flows can easily be analyzed when the two-phase flow pattern is identified. These flow patterns can be categorized according to the direction of flow relative to gravitational acceleration.

In a horizontal pipe, the two-phase flow patterns are more complex than in a vertical pipe and they are difficult to predict in an artificial environment due to the gravity acting perpendicular to the flow and causing an asymmetric distribution of the phases [2]. Several maps have been created in past studies, including Baker's map [5] which is still one of the top maps used in the field, Mandhane et al. [6], Tailel and Dukler [7], Weisman et al. [8], Breber et al. [9], Hashizume et. al. [10], Steiner et. al. [11], Ewing et al. [12], and Thome and Omer [13]. Ghazar and Tang [14] proposed the flow regime map based on the superficial Reynolds number of liquid and gas phases. Although different types of flow pattern maps are available in previous studies, defining common boundaries between the flow regimes remains difficult [15]. Still, the usage of a flow pattern maps is essential for determining flow pattern types in most investigations.

In the literature, many researchers have investigated different flow pattern observation types analytically, experimentally, and numerically focused on previous map types. Kumar et. al. [16] experimentally investigated the characterization of the two-phase flow regimes and their limitations for

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non-boiling two-phase flow via a horizontal pipe with a diameter of 0.025m and a ratio of the length to diameter (L/D) of 182. Totally 240 data points were used, with the superficial Reynolds numbers for water and air ranging from 500 to 21,000 and 560 to 35,000, respectively. Flow patterns were collected experimentally for several regimes of air-water two-phase flow and compared to those obtained by Ghajar and Tang [12]. They found that the change from stratified to slug flow causes pressure and flow rate fluctuations. Yusuf Kuntoro et. al. [17] investigated experimentally the interfacial wave characteristics of the stratified gas-liquid two-phase flows in a horizontal pipe with an inner diameter (ID) of 0.025m. To reference the experimental conditions of the stratified two-phase flow, a Mandhane map of stratified smooth and wavy boundaries was used. Their results showed satisfactory agreement with previous results. Mohammed [18] studied the effect of changing air-water velocity on the behavior and characteristics of the slug pattern in a horizontal pipe. Air mass flow rates increased from 0.8 to 7 $kg/m^2.s$, while the water mass flow rates increased between 126 and 1440 $kg/m^2.s$. Mohammed also conducted a numerical investigation using the STAR-CCM+ software. Based on the experimental setup, and chose the operating conditions for Computational Fluid Dynamics (CFD) simulations in terms of modeling the experimental two-phase flow configuration in the horizontal pipe. The experimental results were plotted on a Baker chart revealed that the tested experimental cases fell within the slug flow regime. Al-Hashimy et al. [19] studied three cases of slug flow of two-phase air-water flow in a horizontal pipe using the CFD technique. The model was generated in the STAR-CCM+ environment, and the grid was created in three dimensions (3D) using directed mesh. The simulation was validated using a Baker chart, and it accurately predicted the slug parameters. Darzi and Park [2] studied visualization experimentally and numerically simulation of two-phase flows in a horizontal tube with a diameter of 0.012m. To model the two-phase flows in a horizontal pipe using the Volume of Fluid (VOF) method, a three-dimensional CFD simulation was completed utilizing OpenFOAM and "interFoam" as the solver. All experimental data points and CFD results were compared with the Mandhane map and found to be in good agreement. Ban et al. [20] numerically researched the behavior of flow patterns in a horizontal two-phase flow pipe. They simulated seven different flow patterns for two-phase air-water flow. Meanwhile, slug transition 3D simulations for two-phase oil-gas flow have been reported in a variety of ranges. To validate the methodology, a Baker diagram and experimental data from previous studies were used. Ban et al. discovered a good agreement between their results and experimental observations for the different gas and liquid superficial velocities.

The major attention of this research is to write and develop a mathematical model using MATLAB (R2017) code to identify the pattern of two-phase flow in the horizontal pipe according to the Baker map, and to demonstrate that this program can be used with confidence to predict flow patterns. The superficial velocities of the phases, as well as the mass flow rate and mass flux for each phase, have been scripted by the program. Moreover, to research the impact of gas and liquid fluid properties on the horizontal flow pattern map.

Mathematical model

A Series of equations and empirical correlation for the two-phase flow has been utilized using the computer program MATLAB (R2017b) as follows:

The total discharge flow rate is defined as the sum of the volumetric flow rate of the liquid phase and the volumetric flow rate of the gas phase [21] and is given by

$$Q_t = Q_l + Q_g \tag{1}$$

in which, Q_t is the discharge flow rate of phases (m^3/s), and Q_l and Q_g are the discharge flow rates occupied by the liquid and gas (m^3/s), respectively. The phases' superficial velocities are known as volumetric fluxes. It is the ratio between the volumetric flow rate of a specific phase and the total cross-sectional area of the pipe. It is expressed for the liquid and gas phases individually as follows,

$$U_{sl} = \frac{Q_l}{A_t} \tag{2}$$
$$U_{sg} = \frac{Q_g}{A_t} \tag{3}$$

in which, U_{sl} and U_{sg} are the superficial velocities of the liquid and gas phases (m/s), respectively. A_t is the total cross-sectional area of the pipe (m^2). The mixture velocity of the flow (U_m) as defined in terms of the superficial velocities of the liquid and gas phases. In a two-phase flow, the mass flow rate of a particular fluid is calculated from the discharge flow rate, which gets:

$$\dot{m}_l = \rho_l Q_l \tag{4}$$
$$\dot{m}_g = \rho_g Q_g \tag{5}$$

in which, $\dot{m}_l$ and $\dot{m}_g$ are the mass flow rates of the liquid and gas phases (kg/s), respectively, ρ_l is the density of the liquid phase (kg/m^3), and ρ_g is the density of the gas phase (kg/m^3). The total mass flow rate as defined as the sum of the two-phase mass flow rates as follows:

$$\dot{m}_t = \dot{m}_l + \dot{m}_g \tag{6}$$

in which, $\dot{m}_t$ is the total mass flow rate of phases (kg/s). The mass velocity of the flow (also known as total mass flux) is the total mass flow rate divided by the total cross-sectional area of the pipe as follows:

$$G = \frac{\dot{m}_t}{A_t} \tag{7}$$

in which, *G* is the total mass flux of the flow (kg/m^{2}s). Substituting Equation 6 into Equation 7 and after rearranging yields:

$$G_l = \frac{\dot{m}_l}{A_t} \tag{8}$$
$$G_g = \frac{\dot{m}_g}{A_t} \tag{9}$$

in which, G_l and G_g are the mass velocities of the liquid and gas phases (kg/m^2. s), respectively.

On the other hand, a MATLAB (R2017b) computer software relying on the Baker map has been created to generate flow pattern maps suited for horizontal pipes and to estimate flow patterns. The Baker map was the earliest flow pattern map to predict flow regimes in a horizontal tube. He created a two-phase flow regime map according to mass flux and used the experimental results of Jenkins [22], Gazley [23], Kosterin [24], and Alves [25]. Scott [26] modified the Baker map, making changes to improve agreement with Hoogendoorn [27] and Govier and Omer [28], attempting to incorporate the impact of pipe diameter and its corresponding to the "Modified Baker's map for horizontal tube" as shown in Figure 1. Using this map at the first point, the liquid and gas mass fluxes were calculated using Equations 8 and 9. The Baker's correction factors λ and ψ are then calculated as follows [29].

$$\lambda = \left[\left(\frac{\rho_g}{\rho_{air}}\right)\left(\frac{\rho_l}{\rho_w}\right)\right]^{\frac{1}{2}} \tag{10}$$

and

$$\psi = \left(\frac{\sigma_w}{\sigma_l}\right)\left[\left(\frac{\mu_l}{\mu_w}\right)\left(\frac{\rho_w}{\rho_l}\right)\right]^{\frac{1}{3}} \tag{11}$$

in which, λ and ψ are dimensionless parameters, and ρ_{air} and ρ_w are the densities of the air and water (kg/m^3), respectively. σ_w and σ_l are the surface tension of the water and liquid (N/m), respectively. μ_w and μ_l are the dynamic viscosity of the water and liquid (Pa.s), respectively.

The fluid property values for the air-water flow are shown in Table 1. The map is adequate for the air-water and oil-gas two-phase systems. The flow regime is identified by determining the x-axis and y-axis values [x-axis, X = $G_l\Psi$ [kg/m^2.s] and y-axis, Y = G_g/λ [kg/m^2.s]].

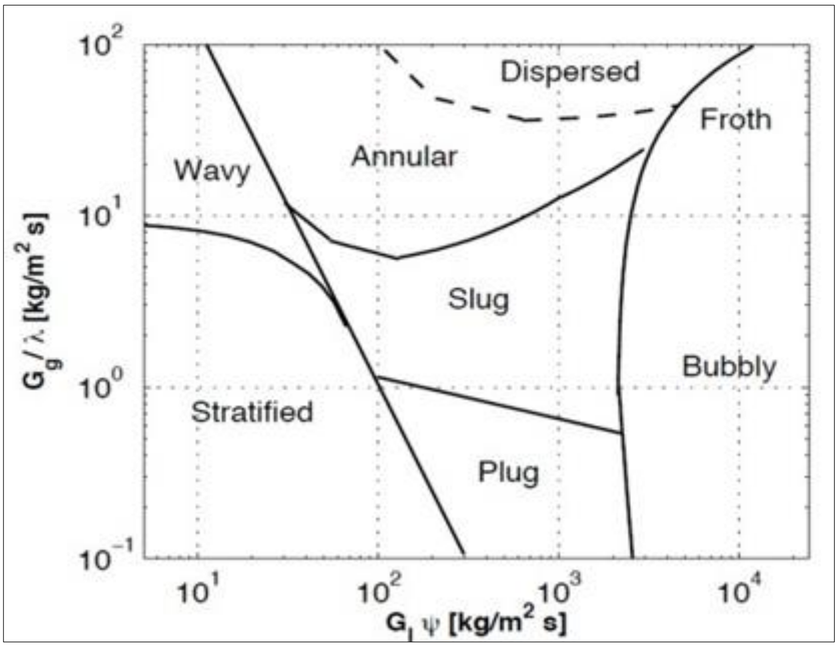

Figure 1. Modified Baker's map in a two-phase horizontal flow pipe [30]

Table 1. Physical properties of water and air

Operating phase	Density ρ (kg/m^3)	Viscosity μ (Pa.s)	Surface Tension σ (N/m)
Water	1000	0.001	0.072
Air	1.23	1.8551e-5	-

The following equations, as shown in Table 2, have been taken from their graph for its transit lines to apply the map to a computer modeling [21],

Table 2. Flow pattern types, as well as their equations and limitations

Flow pattern types and their equations	**Limitations**
For stratified flow to wavy flow $Y = -0.121X + 9.403$	$5 \leq X \leq 36.3$ and $6.2 \leq Y \leq 8.8$
$Y = -0.092X + 8.387$	$36.3 \leq X \leq 66.6$ and $2.5 \leq Y \leq 6.6$
For wavy/stratified flow to plug/slug/annular flow $Y = 1.52*10^4X^{-2.082}$	$11 \leq X \leq 300$ and $0.1 \leq Y \leq 100$
For plug flow to slug flow $Y = 3.512X^{-0.243}$	$98.8 \leq X \leq 2213$ and $0.5 \leq Y \leq 1.1$
For slug flow to annular flow $Y = 214.1X^{-0.848}$	$30.3 \leq X \leq 55.5$ and $7.4 \leq Y \leq 12.1$
$Y = 21.55X^{-0.277}$	$55.5 \leq X \leq 130.7$ and $5.8 \leq Y \leq 7.4$
$Y = 0.008X + 4.652$	$130.7 \leq X \leq 868.5$ and $5.8 \leq Y \leq 11.3$
$Y = 0.006X + 6.605$	$868.5 \leq X \leq 2975$ and $10.3 \leq Y \leq 22.7$
For annular flow to dispersed flow $Y = 1.168*10^4X^{-1.032}$	$108.6 \leq X \leq 208$ and $50 \leq Y \leq 100$
$Y = 188.5X^{-0.255}$	$208 \leq X \leq 634.4$ and $37.4 \leq Y \leq 50$
$Y = 0.002X + 34.6$	$634.4 \leq X \leq 4620$ and $36 \leq Y \leq 43.5$

For plug/slug/annular/dispersed flow to bubbly/froth flow $Y = 55.83\ln(X) - 427$	$2133 \le X \le 1.2*10^4$ and $0.25 \le Y \le 100$
$Y = 4 * 10^{43}X^{-13.08}$	$2133 \le X \le 2625$ and $0.1 \le Y \le 1.9$

Model validation against previous researches

To ensure that the program results obtained by the present study are scientifically acceptable, those results from the MATLAB code were compared to the results of previous investigations. The first validation based on the boundary conditions of the experimental and numerical works of Mohammed [18], was used to validate and compare the present solution of this study. Based on the experimental setup, Mohammed chose the operating conditions of the CFD modeling relating to representing the experimental air-water flow configuration in the horizontal pipe with an internal diameter of 0.074m. The water superficial velocities were 0.86 and 1 m/s, while the gas superficial velocity was 2.44 m/s. Mohammed's data were used as input data in the MATLAB program. The program resulted in two blue dots on the map in Figure 2, and they appear within the boundaries of slug flow as identical to the Mohammed results as it is illustrated in Figures 3a and 3b. The second validation was performed numerically on the current study using deploying the boundary conditions of Al-Hashimy et al. [19] and Ban et al. [20]. Al-Hashimy studied three cases of air-water volume fractions in a horizontal pipe of 0.074m diameter, the water flow rate was fixed to 0.0028 m^3/s and the air flow rate was alternated three times at 0.015, 0.012, and 0.015 m^3/s, as shown in Figure 3c. Ban et al. used a two-phase model to simulate the seven regimes of air-water flow as it is depicted in Table 3 and Figure 3d. Simultaneously, Ban et al. numerically simulated the twenty-four matrix data for oil-gas in a horizontal pipe with an inner diameter of 0.08m to validate the CFD procedures' correctness as it is depicted in Table 4. The superficial velocities for the oil and gas slug flow were increased from 0.05 to 0.3 m/s and 0.2 to 1.5 m/s, respectively. The previously mentioned data from Al-Hashimy and Ban were used as initial operating conditions in the program. Figure 2 portrays the output as three groups of coordinates on a map. Three orange dots represent Al-Hashimy conditions for the air-water flow, seven yellow points for air-water flow, and twenty-four matrix points for oil and gas flow. According to the results of Al-Hashimy and Ban, all groups fell within the required regime of flow patterns, as shown in Figure 2. Finally, the current program's output data and available literature data were compared, and it was discovered that the flow pattern types predicted in the previous study were identified as those expected from the program observation in this investigation.

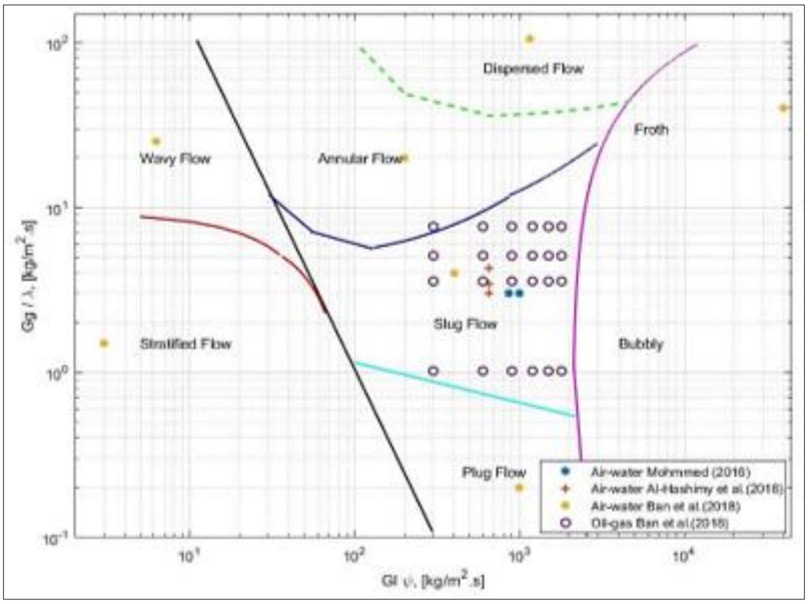

Figure 2. Predicted two-phase pattern map in the range of boundary onditions of Mohammed [18], Al-Hashimy [19] and Ban [20]

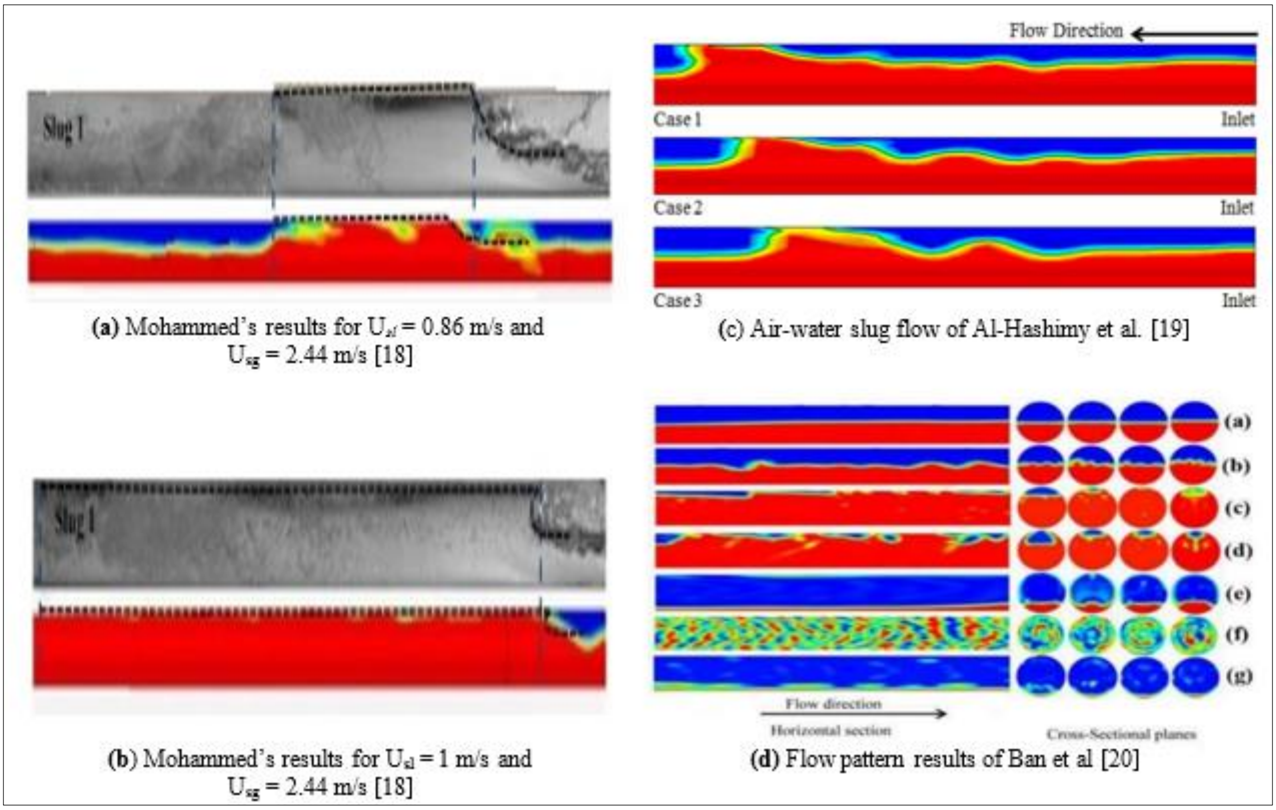

Figure 3. Previous research on two-phase air-water flow in a horizontal pipe

Table 3. Operating determines for air-water flow [20]

Flow regime	Usg (m/s)	Usl (m/s)
Stratified	1.22	0.003
Wavy	20.41	0.0063
Plug	0.16	1
Slug	3.26	0.4
Annular	16.33	0.2
Bubble	1000	40.1
Spray	85.71	1.16

Table 4. Physical properties of oil and gas flow [20]

Operating phase	Density ρ (kg/m^3)	Viscosity μ (Pa.s)	Surface Tension σ (N/m)
Oil	810.3	0.004652	0.018653
Vapor	17.1	0.0000115	-

Model validation against experimental results
Boundary conditions

The experimental system was planned and constructed in the Multi-phase Laboratory of the Department of Petroleum Engineering at the University of Zakho [31]. This study used experimental boundary conditions as input data to validate the program code based on the air-water properties discussed in section 2. The pipe diameter was 0.03m, and the volumetric flow rates of water and air were changed from $0.66*10^{-3}$ to $1.33*10^{-3}$ m^3/s (40 to 80 LPM) and $1.66*10^{-3}$ to $3.3*10^{-3}$ m^3/s (100 to 200 LPM), respectively, measured by the Rotameter in the lab.

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Outcomes from a mathematical model

The following sections, divided into two parts, describe and display the MATLAB programmer results and compare them to the experimental data,

Two-Phase flow conditions

The first part of the program, MATLAB (R2017b) determines the basic parameters for an air-water phase in a horizontal pipe as a function of the mass velocities of the water and air phases for a given set of inlet flow parameters. The findings of the superficial water and air velocities are displayed in Table 5, which varied from 2.36 to 4.72 m/s and from 0.94 to 1.84 m/s, respectively. The range of superficial velocities of phase is included in the range flow pattern of slug flow [6], which was predicted in the last column. The water and air mass flow rates were increased from 0.672 to 1.334 kg/s and 0.002 to 0.004 kg/s, respectively. The brief results of mass velocities of phases, and the x-axis and y-axis values for each run at various flow rates were presented in Table 5. The slug flow pattern was estimated under water and air flow rate conditions for each run.

Flow pattern structure

The transition boundaries between the various flow pattern areas from Table 2 were created in the second part program using MATLAB (R2017b). The resulting map is divided into four zones, stratified and wavy zones, plug and slug zones, annular and dispersed zones, and bubbly with a froth zone as presented in Figure 4. The flow map is the best method to predict the flow types. The calculated mass velocities of phases from Table 5 were plotted as flow pattern map result in a log-log coordinate system utilizing $X = G_l\Psi$ and $Y = G_g/\lambda$ as eighteen coordinates. Figure 4 demonstrates that the operation condition points fell in the slug flow regime and displays the impact of increasing the air and water flow rates of the phases on the flow pattern type.

Table 5. Typical output results of the program

Q_l	Q_g	U_{sl}	U_{sg}	m_l	m_g	m_t	G	G_l	G_g	X	Y	Predicted Flow Pattern
LPM		m/s		Kg/s			Kg/m. s			Kg/m. s		
40	100	0.94	2.36	0.67	0.002	0.672	946. 0	943.2	2.9	943.2	2.9	Slug
	120		2.83		0.002	0.672	947. 6		3.48		3.48	
	140		3.3		0.003	0.673	947.2		4.06		4.06	
	160		3.77		0.003	0.673	948.8		4.64		4.64	
	180		4.24		0.004	0.674	948.4		5.22		5.22	
	200		4.72		0.004	0.674	949. 9		5.8		5.8	
60	100	1.41	2.36	1	0.002	1.002	1418.6	1414.7	2.9	1414.7	2.9	Slug
	120		2.83		0.002	1.002	1418. 2		3.48		3.48	
	140		3.3		0.003	1.003	1419.8		4.06		4.06	
	160		3.77		0.003	1.003	1419. 6		4.64		4.64	
	180		4.24		0.004	1.004	1420.9		5.22		5.22	
	200		4.72		0.004	1.004	1421. 5		5.8		5.8	
80	100	1.84	2.36	1.33	0.002	1.332	1889.2	1886.3	2.9	1886.3	2.9	Slug
	120		2.83		0.002	1.332	1890. 7		3.48		3.48	
	140		3.3		0.003	1.333	1890.3		4.06		4.06	
	160		3.77		0.003	1.333	1891. 9		4.64		4.64	
	180		4.24		0.004	1.334	1892.5		5.22		5.22	
	200		4.72		0.004	1.334	1892. 1		5.8		5.8	

In addition, the program's results were compared to visual observations captured by a camera at high speed in the lab, as indicated in Figure 5. By comparing Table 5, Figure 4, and Figure 5, it is evident that the eighteen matrix point results for predicting the flow pattern shown on the map and expected on the table were identical to the experimental visualization.

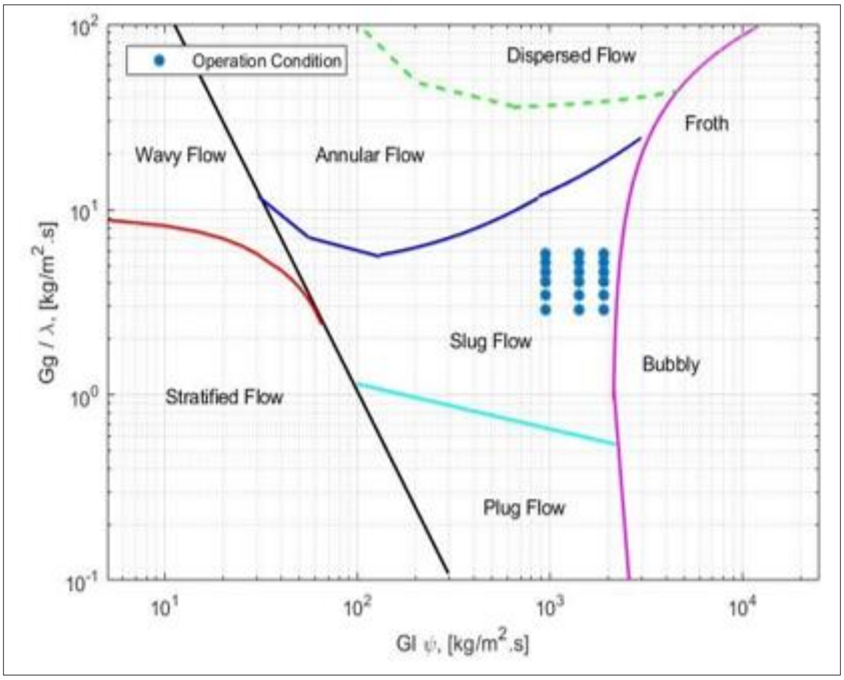
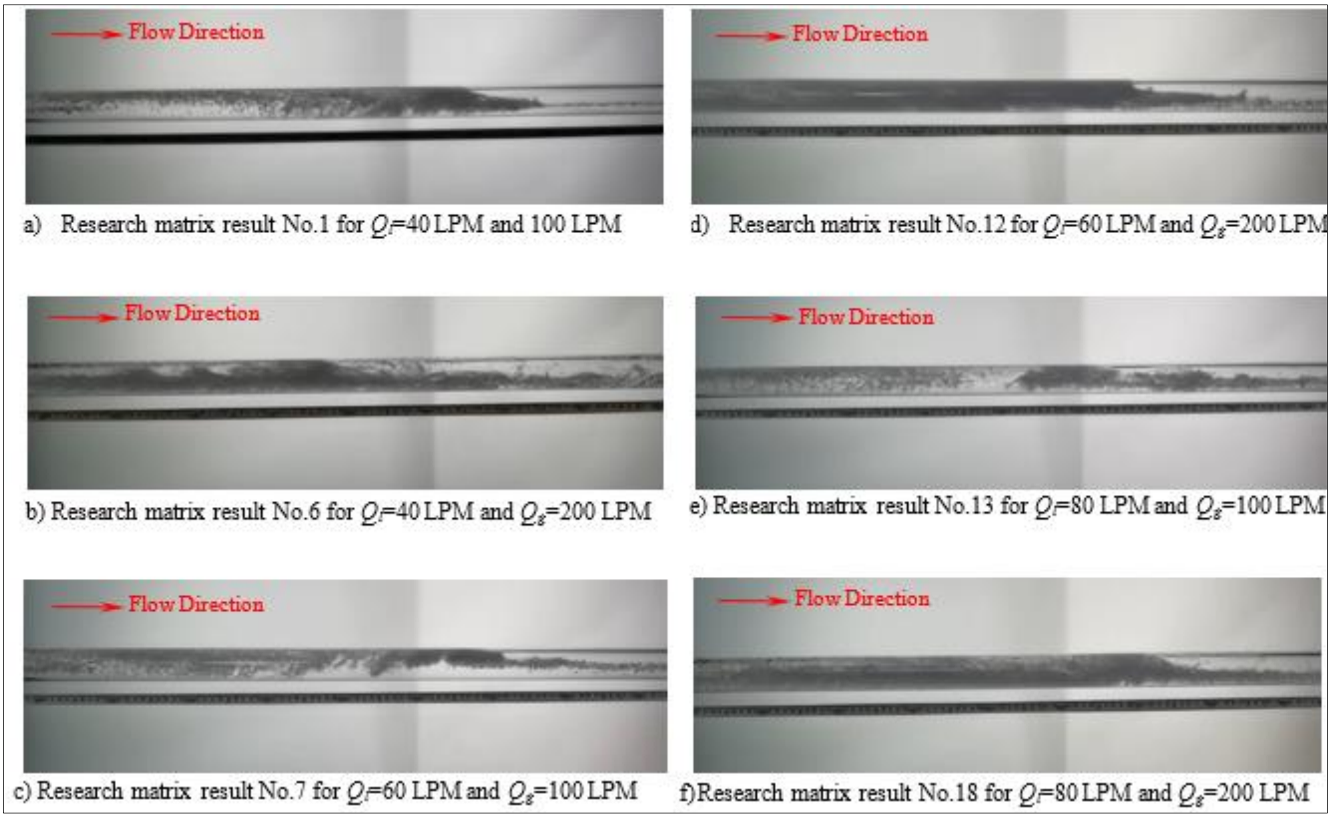


Figure 4. Flow pattern map produced by the program based on experimental operating conditions



a) Research matrix result No.1 for Q_l=40 LPM and 100 LPM

d) Research matrix result No.12 for Q_l=60 LPM and Q_g=200 LPM

b) Research matrix result No.6 for Q_l=40 LPM and Q_g=200 LPM

e) Research matrix result No.13 for Q_l=80 LPM and Q_g=100 LPM

c) Research matrix result No.7 for Q_l=60 LPM and Q_g=100 LPM

f) Research matrix result No.18 for Q_l=80 LPM and Q_g=200 LPM

Figure 5. Visual studies of air-water flow regimes

Impact of fluid properties and pipe geometry on the fow pattern types

Primary parameters have long been recognized as the key criteria influencing the occurrence of a flow pattern in two-phase flow, although fluid characteristics and pipe diameter also play an essential role [32]. The impact of fluid properties and diameters of the pipe on the configuration of two-phase flow in the horizontal pipe was investigated without significantly affecting the discharge flow rates of gas and liquid, which were set to $1.66*10^{-3}$ m^3/s and $0.66*10^{-3}$ m^3/s, respectively. The impact of air-water and oil-gas flow properties was observed on five different pipe diameters of 2.54, 4, 6, 8, and 10 cm, as well as on the flow pattern types. The program's output is depicted in Figure 6, illustrating the effect of phases mass flux and Baker's correction factors on the map. The values of λ and ψ in the air-water two-phase case are equal to one. Due to the change in phases density in the oil-gas phase, the values of λ and ψ will be greater than one, affecting map's mass flux and flow pattern types. In the air-water two-phase case, λ and ψ are both equal to one. The values of λ and ψ were greater than one due to the change in phase density in the oil-gas phase, affecting the map's mass flux and flow pattern types. The flow pattern produces slug flow and froth flow when the pipe diameter is 2.54 cm for air-water and oil-gas, respectively, and the flow pattern gradually changes from froth to plug and stratified flow as the diameter increases. More specifically, it is evident from Figure 6 that the impact of fluid properties on the diameter of the pipe, the figure proves that a slight change in the x-axis, due to the small difference between the density of water and oil, in contrast to the y-axis shows an obvious difference due to density differences of air and gas. The figure also shows that decreasing pipe diameters cause an increase in phase mass fluxes, which affects the configuration of the flow pattern types. In addition to that, the results are effectively limited by the froth flow and stratified flow range, which can provide stratified, plug, or slug, and froth flow.

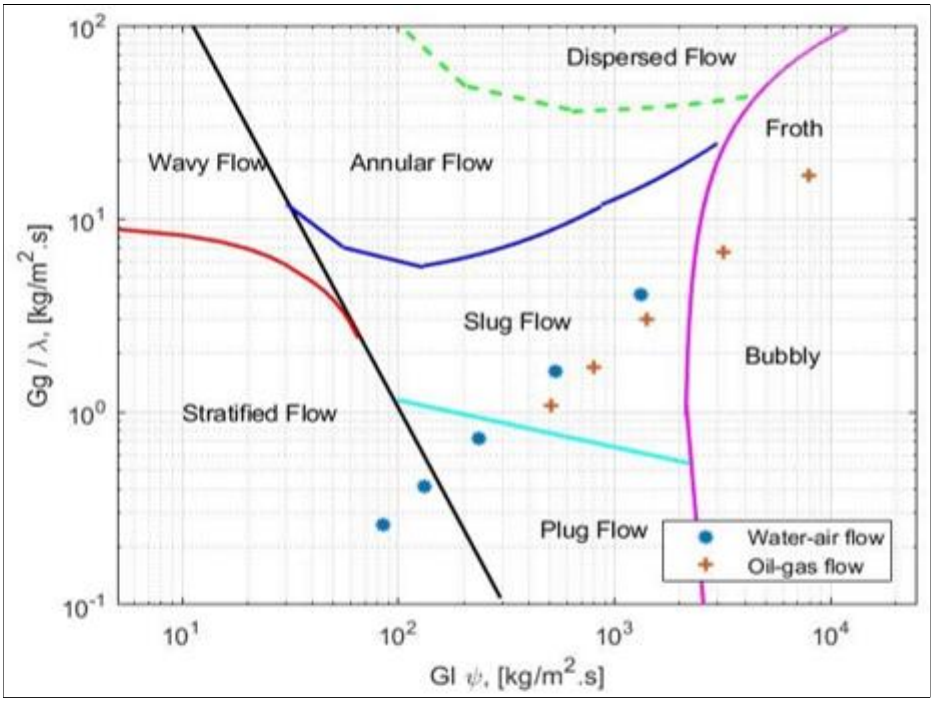


Figure 6. Impact of pipe diameters and fluid properties on flow pattern map

Conclusions

A mathematical model based on Baker map conditions has been improved using MATLAB (R2017) code to estimate the flow pattern map in a horizontal pipe. To estimate the types of flow patterns, the parameters of pipe diameter, volumetric flow rates of phases, and phase properties are used as input data.

The program results are compared to the previous investigations results as well as current experimental captured results. The following conclusions can be summarized:

The program was used with confidence and shows the most accurate method for predicting flow patterns. The results demonstrated a high level of agreement with previous and current studies. Also, the results obtained by predicting the program results and visualizing the experimental results were identical.

The superficial velocities were varied for water from 2.36 to 4.72 m/s and for air from 0.94 to 1.84 m/s, as determined by the program results, and were included in the range flow pattern of slug flow.

The fluid properties and pipe diameters have a considerable impact on the two-phase flow pattern. When the liquid and gas properties changed causes obvious changes in the flow pattern types that change from the stratified flow to the froth flow range, which can provide stratified, plug, or slug, and froth flow, effectively limiting the results. Furthermore, the pipe diameters decrease, and phase mass fluxes increase, influencing flow pattern type configuration.

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Appendix, A MATLAB (R2017b) Code Supplementary
MATLAB (R2017b) program code for this article is available in the online version at ResearchGate ResearchGate https://www.researchgate.net/profile/Safa-Ibrahim-6

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