Development of A New Correlation for Estimating Pressure Gradient of Oil- Water Two Phase Flow in A Horizontal Pipe

Yasha Hasanzadeh, Seyed Ali Alavi Fazel*, Zoha Azizi, Seyed Mohsen Peyghambarzadeh, Alireza Azimi
Department of Chemical Engineering, Mahshahr Branch, Islamic Azad University, Mahshahr, Iran
E-mail: yasha.hasanzade@gmail.com, alavifazel@gmail.com, azizi.zoha@gmail.com,
*Corresponding author

Received: 23 April 2021, Revised: 23 August 2021, Accepted: 26 August 2021

Abstract: Pressure gradient of a two phase mixture in a horizontal pipe were experimentally investigated for water/super viscose oil mixtures. The mixture contained oil having a viscosity of 67 cp and density of 0.872 g/cm^3, and pure water, flowing through an acrylic pipe having a length and diameter of 6 m and 20 mm, respectively. A high speed digital camera has been used to record visual information. Superficial velocities of water and oil were in the range between 0.18–1.2 m/s and 0.18–0.95 m/s, respectively. The experimental pressure gradient has been compared to the Al-Wahaibi correlation and two-fluid model. The absolute average error for the "two-fluid model" and Al-Wahaibi correlation have been calculated for 30% and 12%, respectively. In this investigation, a new modified correlation is developed on the basis of the Al-Wahaibi correlation, that predicts the values of pressure gradient with an absolute average error of about 9%. The pressure gradient correlation was validated extensively against 11 independent data sources. To our knowledge, this is the best pressure gradient furmola that is published for oil–water flow which includes wide range of operational conditions including fluid properties, pipe diameters and pipe materials. One of the advantages of the new proposed formula is that it also performs well for super viscosity oils.

Keywords: Flow Pattern Map, Oil Viscosity, Oil–Water Flow, Pressure Gradient

How to cite this paper: Yasha Hasanzadeh, Seyed Ali Alavi Fazel, Zoha Azizi, Seyed Mohsen Peyghambarzadeh, and Alireza Azimi, "Development of A New Correlation for Estimating Pressure Gradient of Oil- Water Two Phase Flow in A Horizontal Pipe" , Int J of Advanced Design and Manufacturing Technology, Vol. 14/No. 4, 2021, pp. 51–58.
DOI: 10.30495/admt.2021.1928725.1279

Biographical notes: Yasha Hasanzadeh is a PhD candidate of Chemical Engineering at Mahshahr branch, Islamic Azad University, Mahshahr, Iran. He received his MSc in Chemical Engineering from Mahshahr branch, Islamic Azad University, Mahshahr, Iran in 2011. His field of research is two phase flow in pipe and fluid mechanic. **Seyed Ali Alavi Fazel** is associate professor at the department of Chemical Engineering, Mahshahr branch, Islamic Azad University, Mahshahr, Iran. He received his PhD in Chemical Engineering from Science and Research branch, Islamic Azad Univesity, Tehran, Iran in 2008. In His current research includes genetic algorithm-based optimization model for pool boiling heat transfer on horizontal rod heaters at isolated bubble regime. **Zoha Azizi** is assistant professor of Chemical Engineering at the department of Chemical Engineering, Mahshahr branch, Islamic Azad University, Mahshahr, Iran. She received his PhD in Chemical Engineering from Shiraz Univesity, Shiraz, Iran in 2015. Her main research interests are transport phenomena and solvent extraction. **Seyed Mohsen Peyghambarzadeh** is associate professor of Chemical Engineering at the department of Chemical Engineering, Mahshahr branch, Islamic Azad University, Mahshahr, Iran. He received his PhD in Chemical Engineering from Tehran Univesity, Tehran, Iran in 2012. His main research interests are transport phenomena, convection heat transfer and particulate liquids. **Ali Reza Azimi** is assistant professor of Chemical Engineering at the department of Chemical Engineering, Mahshahr branch, Islamic Azad University, Mahshahr, Iran. He received his PhD in Chemical Engineering from Tarbiat Modarres Univesity, Tehran, Iran in 2010. His main research interests are energy and modelling.

1 INTRODUCTION

Two phase liquid-liquid flow widely occurs in oil and chemical industries. When a mixture of two immiscible liquids simultaneously flows in a channel or pipeline, the two fluids can distribute themselves in numerous configurations. This flow strongly depends on the physical properties of the fluids and the operating parameters. For instance, flow configurations of two immiscible liquids with large density difference are expected to defer from those of same density difference. In many applications such as artificial lift methods such as corrosion technology and production strings in oil wells, understanding the oil–water flow behaviour has significant importance. The understanding of oil–water flow in pipes can be crucial in determining the amount of free water in contact with the pipe wall that could cause corrosion problems. The performance of separation facilities and multiphase pumps is a strong function of the flow pattern.

Understanding the flow structure and pressure drop in liquid–liquid flow in horizontal pipes will go a long way in developing predictive models that could aid the design and construction of flow equipment. During the simultaneous concurrent flow of oil and water, several configurations can be formed which are generally grouped into separated flow where both phases retain their continuity and dispersion, where one phase is continuous and the other is in the form of dispersed fragments.

In separated (segregated) flow, the two phases can either be completely separated, occupying the top and the bottom of the pipe respectively (stratified flow), or there may be inter dispersion of one phase into the other (dual continuous flow), i.e., oil drops are present in the water-continuous layer and water drops are present in the oil-continuous layer. At certain conditions, one phase occupies the core of the pipe with the other is flowing in the annulus around it (annular flow). Quiet large number of studies have been reported the occurrence of separated oil–water flow (stratified and dual continuous flows) in horizontal pipes; several attempts have been made to predict the pressure gradient in the separated flow.

There has been little investigation of horizontal two-phase liquid-liquid flows compared with vertical flows in the literature. The highly asymmetric void distribution in horizontal flow, which is due to the effect of the buoyancy force, provides more difficulties in experimental studies. Consequently, previous work on vertical flow cannot be directly extended to horizontal flow [1]. Angeli et al [2] studied the pressure gradient in horizontal liquid-liquid flows. They have been reported that the material of the tube wall can strongly affect the pressure gradient during two-phase liquid-liquid flow. Pressure gradients under all conditions were higher in the steel than in the acrylic tube for the same mixture velocities and flow volume fractions, Rodriguez et al [3] experimentally studied on oil–water flow in horizontal and slightly inclined pipes. Extensive results of holdup and two-phase pressure gradient as a function of superficial velocities, flow pattern and inclinations have been reported. Bannwart et al [4] have performed experimental investigation on liquid–liquid–gas flow; flow patterns and pressure-gradient have been studied. An important observation in this study was the occurrence of core-annular flow in all pipe sizes and inclinations due to the practical importance in production and transportation of heavy oil.

In the experiments herein reported water was always in contact with the pipe wall (hydrophilic-oilphobic pipe material), which guarantees the lubrication process and keeps the oil from sticking the pipe wall. Hanafizadeh et al [5]. considered the influence of the flow regimes on the performance of an airlift pump experimentally. The data were obtained for air–water two-phase flow in a vertical pipe. The three main flow regimes namely slug, churn and annular were visually detected in their works. Hanafizadeh et al. [6] have performed experimental investigation of oil-water two phase flow regime in inclined pipes. They have reported various flow patterns comprising: bubbly, slug, smooth stratified, wavy stratified, churn, annular and dual continuous flow. From the obtained results, it can be inferred that non-stratified flows such as bubbly and slug flows are dominant flow patterns in the upward flows and stratified flows are dominant flow patterns in the downward flows.

Oddie et al [7] experimentally studied on two and three phase flows in large diameter inclined pipes. They express the effects of the flow rates of different phases and pipe deviation on holdup have been evaluated. Detailed flow pattern maps were generated over the entire range of flow rates and pipe inclinations for all of the fluid systems. Mandal et al [8] have studied the oil-water flow through different diameters of pipes. A new flow pattern namely rivulet flow appearing in the 0.012 m pipe have been designated. Design of the mixer section also appears to influence the downstream distribution of the two liquids and the flow pattern map may change its appearance remarkably merely by changing the way of introducing the two fluids in the test rig.

Xiao-Xuan Xu [9] studied the oil–water two-phase flow in horizontal pipelines. In recent papers, Angeli and Hewitt [2], Chakrabarti et al. [10], Rodriguez and Oliemans [3], and Yiping et al. [11] employed the two-fluid model and Al-Wahaibi correlation [12] to predict the pressure gradient using plane and curve interface. Large discrepancies were obtained between the measured and predicted values especially in dual continuous flow. As the Al-Wahaibi correlation [12], to be of limited value in the prediction of liquid–liquid pressure gradient for some systems in horizontal pipe flow, an empirical pressure gradient correlation for separated horizontal oil–

water flow is developed in the present work based on the pressure gradient published data of oil–water flow.
The accuracy of the correlation is evaluated by comparing its predictions with experimental data and with the Al-Wahaibi correlation. This study is based on pressure drop data in different experimental conditions especially super viscose oil for predict pressure drop of oil–water flow in horizontal pipes. The correlation obtained in this work can be one of the best correlations for predicting the pressure drop of two-phase flow with any conditions in horizontal pipes. In the present article, pressure drop has been studied as the major flow characteristics under different flow conditions in horizontal pipe. Pressure gradient of oil-water two-phase flows is investigated experimentally at various superficial velocities. Database for frictional pressure gradient in separated horizontal oil–water flow has been presented in "Table 1".

Table 1 Database for frictional pressure gradient in separated horizontal oil–water flow

source	D mm	Pipe roughness	Pipe material	$\frac{\mu_o}{\mu_w}$	$\frac{\rho_o}{\rho_w}$
Valle and Kvandal [13]	37.5	1 * 10-5	Glass	2.3	0.794
Nädler and Mewes [14]	59	1 * 10-5	Perspex	28	0.841
Angeli and Hewitt [2]	24	1 * 10-5	Acrylic	1.6	0.801
Angeli and Hewitt [2]	24.3	7 * 10-5	St. steel	1.6	0.801
Elseth [15]	56.3	1 * 10-5	Acrylic	1.64	0.79
Chakrabarti et al. [10]	25.4	1 * 10-5	Acrylic	1.3	0.787
Rodriguez and Oliemans [3]	82.8	7 * 10-5	St. steel	7.5	0.783
Al-Wahaibi et al. [16]	14	1 * 10-5	Acrylic	5.5	0.828
Yiping et al. [11]	26.1	7 * 10-5	St. steel	3.5	0.840
Al-Yaari et al. [17]	25.4	1 * 10-5	Acrylic	1.57	0.780
Yousuf [18]	25.4	1 * 10-5	Acrylic	12	0.875

2 EXPERIMENTAL SET-UP

The experimental studies on flow patterns and pressure drop were carried out in the liquid–liquid flow facility shown schematically in "Fig. 1".

Fig. 1 Schematic diagram of the experimental facility with the acrylic test section.

Pure water and oil with density of 0.872 g/cm^3 and viscosity of 67 cP were used as test the fluids. The separation and storage of the the fluids take place in three separator tanks. Each fluid was transferred from their storage tank with a pump to the test section which was a 200 mm in diameter acrylic pipe. Oil and water are led by centrifugal pumps from the bottom of the storage tank into the test section. Two centrifugal pumps (VID-001008004, head=33 m, Q =5.4 m^3/hr) were used. Flow rates of the oil and water were controlled just before entering into the test section.

Oil viscosity have been measured by SVN3001 kinematic viscometer. The two fluids entered into the test section from two pipes via a Y like-junction, which ensures low degree of mixing. The water phase was allowed to enter from the bottom while the oil joined from the top to reduce the mixing effect.
Two flow meters (model lzm-25g) with maximum capacity of 60 L/min were attached to each of the flow lines. The mixture returns via a PVC pipe to a separator tank, which allows the two phases to separate and subsequently return to their respective storage tanks. Test section was set to horizontal orientation. Pressure drop was measured in the acrylic horizontal pipe at 3.80 m from the inlet and the pressure ports were placed over a distance of 2.20 m. The pressure drop was measured with differential pressure transmitter –SmartLine ST700 (Honeywell). The temperature was controlled at 25°C with Samwon temperature controllers SU-105DA-N. The uncertainties of the data being collected from pressure transmitters were up to 0.2% based on the manufacturer. The measurement uncertainties are listed in the form of standard deviation in "Table 2". The superficial oil and water velocity were in the range of 0.18-0.95 m/s and 0.18-1.2 m/s, respectively.

Table 2 Uncertainty of the measurements

Measured parameter	Uncertainty
Pressure	± 0.2%
Pipe diameter	±0.2mm
Oil and water density	±0.3kg/m^3
Oil and water flow rates	±0.06 L/min
Temperature	± 0.1C^0

3 CORRELATION DEVELOPMENT

In liquid–liquid flow, several empirical correlations have been proposed for the prediction of two-phase frictional pressure loss in horizontal pipe flow. Examples of these are Angeli et al [2], of Al-Wahaibi correlation [12]. All correlations are normally expressed as friction factors where they are usually calculated based on the Reynolds number of the mixture. The equation is expressed as follows:

$$\frac{dp}{dx} = 2.4\left(\frac{f\rho_m U_m^2}{2D}\right)^{0.8} \quad (1)$$

Where $\frac{dp}{dx}$ is the pressure gradient, f_m is the two-phase friction factor, ρ_m is the mixture density, U_m is the oil–water mixture velocity and D is the pipe diameter.
The mixture density was given as:

$$\rho_m = H_w\rho_w + H_o\rho_o \quad (2)$$

Where, ρ_w and ρ_o are the water and oil density, respectively. H_w and H_o are the water and oil hold-up and they are given by:

$$H_w = \frac{Q_w}{Q_w + Q_o} \quad (3)$$

$$H_o = \frac{Q_o}{Q_w + Q_o} \quad (4)$$

Where, Q_w and Q_o are the water and oil volumetric flow rate respectively and Al-Wahaibi correlation.

$$\frac{1}{\sqrt{f_{cor}}} = -2\log\left(\frac{\varepsilon/D}{0.25} - \frac{4.518}{Re_m}\log\left(\frac{6.9}{Re_m} + \left(\frac{\varepsilon/D}{0.25}\right)^{1.11}\right.\right. \quad (5)$$

Where, ε is the wall roughness, Re_m is the Reynolds number of the oil–water mixture that is defined as:

$$Re_m = \frac{U_m\rho_m D}{\mu_m} \quad (6)$$

Average mixture viscosity (μ_m):

$$\mu_m = H_w\mu_w + H_o\mu_o \quad (7)$$

4 RESULTS AND DISCUSSION

Pressure gradient due to friction was measured in this study superficial water and oil velocities ranging from 0.18 to 1.2 m/s and 0.18 to .95 m/s, respectively. The results are presented in "Fig. 2".

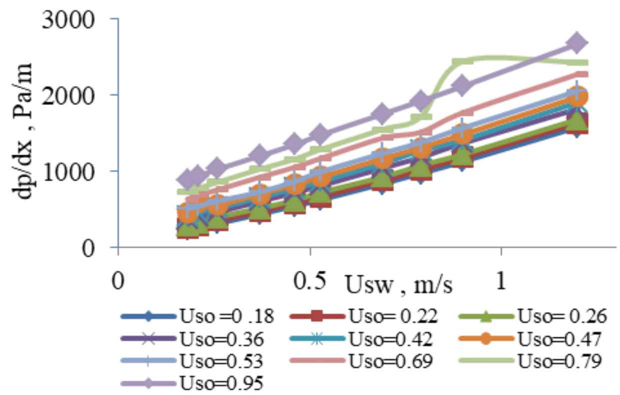


Fig. 2 Effect of increasing superficial water velocity on pressure gradient at different superficial oil velocities.

Additionally, they are classified into six patterns namely; stratified (stratified smooth, SS, and stratified wavy, (SW), bubbly (BB), dual continuous (DC), annular, (AN), dispersed water in oil (DW/O) and dispersed oil in water (DO/W) in "Fig. 3". Stratified (stratified smooth, SS, and stratified wavy, (SW): where the two fluids flow in separate layers at the top and bottom of the pipe according to their densities. Dual continuous (DC): where both oil and water form continuous layers at the top and bottom of the pipe respectively but drops of one phase appear into the continuum of the other phase. Annular (AN): where water forms an annular film at the wall and oil flows in the pipe core. Bubbly (BB): where the oil appears in the form of elongated drops (slightly longer than the pipe diameter) within water continuum. Dispersed oil in water (DO/W): where the pipe cross-sectional area is occupied by water containing dispersed oil droplets. Dispersed water in oil (DW/O): where oil is the continuous phase and water is presented as droplets across the pipe cross-sectional area.

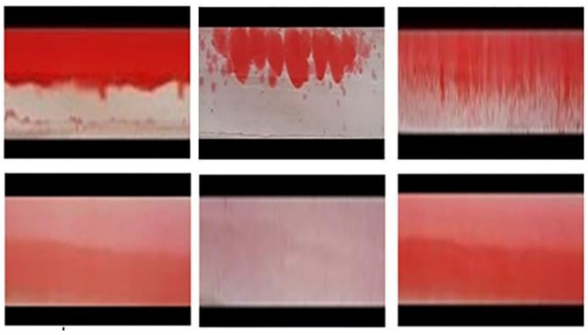


Fig. 3 Flow pattern map constructed for this study respectively (stratified (stratified smooth, SS, and stratified wavy, SW), bubbly (BB), dual continuous (DC), annular (AN), dispersed water in oil (DW/O) and dispersed oil in water (DO/W)).

Superficial oil velocity (Uso), superficial water velocity (Usw), and pressure gradient measurements corresponding to 471 experimental points collected from the literature for separated oil–water flow in horizontal pipes were used in this study. The collected database covers wide range conditions, pipe diameters and oil viscosities. Al-Wahaibi correlation has been proposed for predicting the pressure gradient in various superficial water and oil velocities ranging condition.

4.1. Modeling

In this study, to estimate the pressure gradient, a new correlation has been developed based on Al-Wahaibi correlation [12]. Two-fluid model has been proposed for predicting the pressure gradient in various superficial water and oil velocities. However, the proposed model does not provide reasonable values for the tested oil–water flow in horizontal pipes. Therefore, it was necessary to propose new correlation that is more accurate in comparison with the existing correlations. The results - particularly in “Fig. 4” - indicate that the Al-Wahaibi correlation [12] is more accurate in comparison with the other existing correlations. However, the AAPE was calculated to about 12%. In this study, mathematical and statistical calculations prove that substituting some of mentioned correlation exponents leads to improvement of the predicting ability. It is important that correlations other than Al-Wahaibi correlation [12] that are not mentioned in this work had an unacceptable deviation in comparison with the experimental data and are excluded from “Fig. 4”.

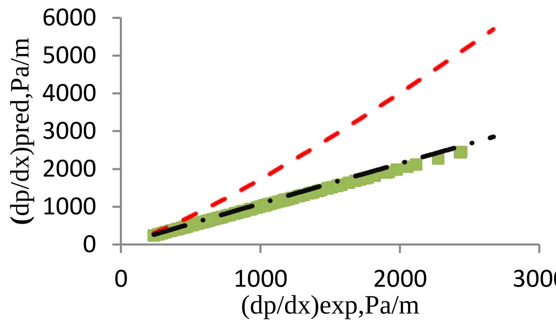


Fig. 4 Experimental data compared to the obtained result of existing correlations.

$$\frac{dp}{dx} = \left(\frac{f\rho_m U_m^2}{2D}\right)^{g6} \quad (8)$$

$$f_{cor} = g_0\left[g_1 \log(g_2(\tfrac{\varepsilon}{D})^{g_3} + g_4(Re_m)^{g_5})\right]^{-2} \quad (9)$$

Table 3 Equation coefficients

g_0	9.41323
g_1	4.27863
g_2	1.20103
g_3	0.773575
g_4	3.43975
g_5	-0.864562
g_6	0.823698

5 MODEL EVALUATION

The accuracy of the predictions was measured by calculating the average absolute percent error (AAPE) which can be seen in “table 4”. The average absolute percent error is defined as:

$$AAPE = \left[\frac{1}{n}\sum_{k=1}^{n}\left|\frac{\left(\frac{dp}{dx}\right)_{pred} - \left(\frac{dp}{dx}\right)_{exp}}{\left(\frac{dp}{dx}\right)_{exp}}\right|\right] \times 100 \quad (10)$$

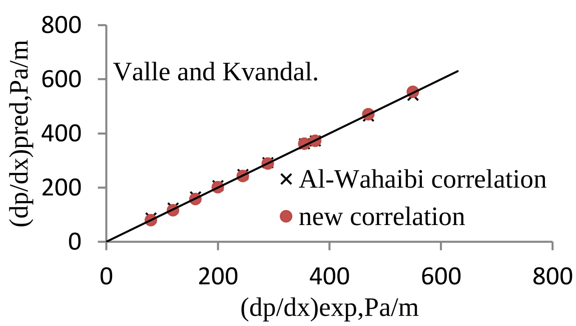
Where, subscripts ‘‘pred’’ and ‘‘exp’’ represent the predicted and experimental values, respectively. In general, the new proposed correlation (“Eq. (8)”) was found to better predict the experimental database as shown from the one indicators values. The comparison also revealed that the new correlation (“Eq. (8) ”) has better capability than the Al-Wahaibi correlation to predict the experimental data as shown from the average absolute percent error values (9.7 and 12.2 for “Eq. (9)” and Al-Wahaibi correlation, respectively).

Table 4 Comparison of the accuracy of pressure gradient prediction of the developed correlation and the Al-Wahaibi correlation against experimental database obtained from different sources.

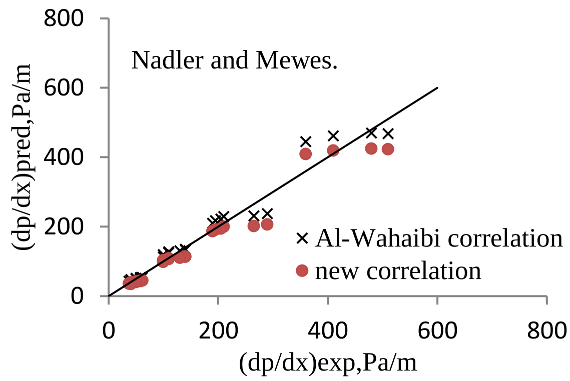
Source	Proposed correlation Eq. (8) AAPE	Al-Wahaibi correlation AAPE
Valle and Kvandal [13]	1.08	2.6
Nädler and Mewes [14]	11.9	10.9
Angeli and Hewitt [2]	6.2	6.8
Angeli and Hewitt [2]	16.4	16.7
Elseth [15]	3.5	5.9
Chakrabarti et al. [10]	15.5	20.5
Rodriguez and Oliemans [3]	15.5	15.1
Al-Wahaibi et al. [16]	24	20.7
Yiping et al. [11]	8.6	10.6
Al-Yaari et al. [17]	8.6	10.9
Yousuf [18]	11.2	10.3
This work	2.01	9.09
All experimental data points	9.7	12.2

6 COMPARISON WITH PUBLISHED DATA

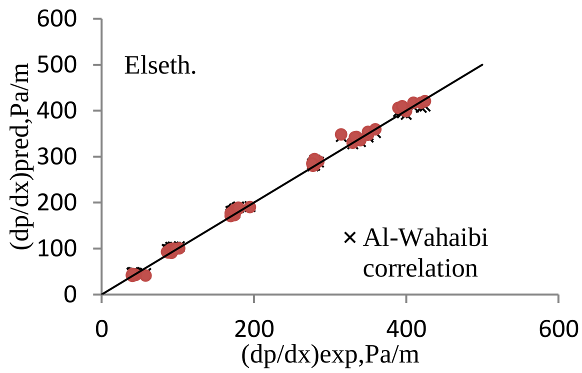
The experimental pressure gradient database (see “Table 1”) was also compared with the Al-Wahaibi correlation and new proposed correlation as shown in “Fig. 5(a)”. The comparison in “Fig. 5” revealed that the correlation was able to predict the pressure gradient reasonably well for wide range of superficial oil (Uso = 0.18– .95 m/s) and water velocities (Usw = 0.18– 1.2 m/s), viscosity values (1–67 cp), pipe diameters (14–82.8 mm) and different pipe materials.



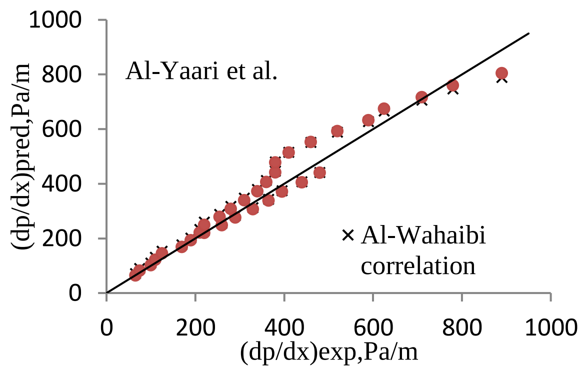
(a)



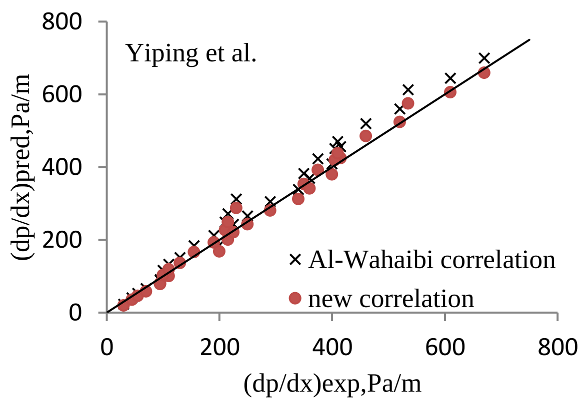
(b)



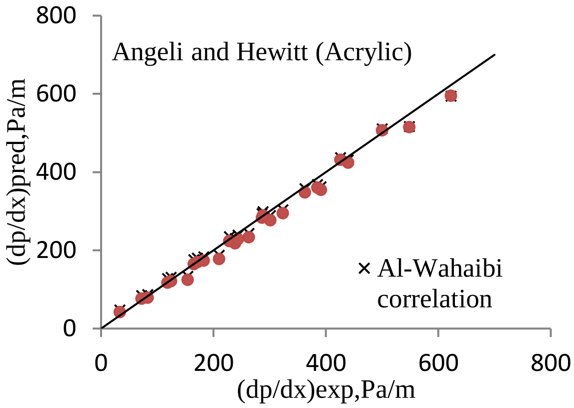
(c)



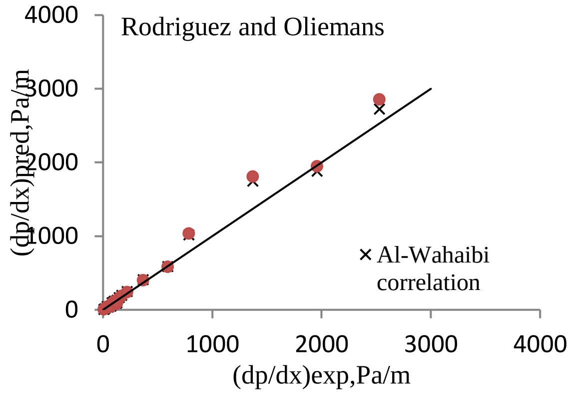
(d)



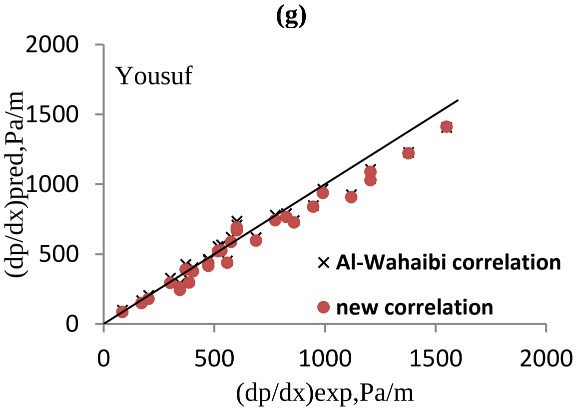
(e)



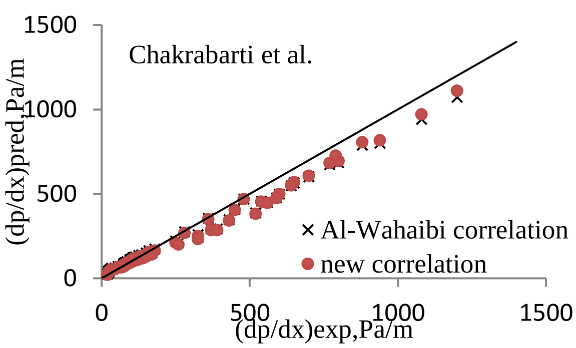
(f)



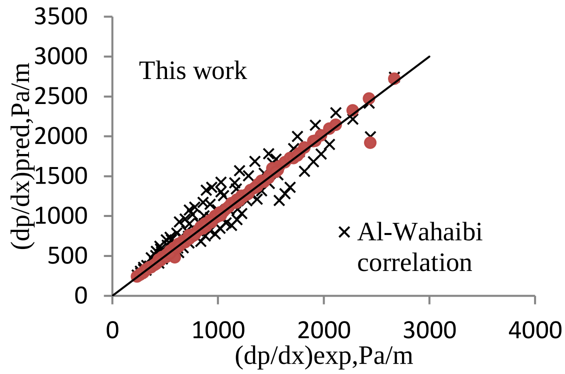
(g)



(h)



(i)



(k)

Fig. 5 Evaluation of the proposed correlation with 12 experimental data.

7 CONCLUSION

Most commonly used earlier correlations were unable to predict the values of a two phase mixture in a horizontal pipe. Furthermore, a new correlation has been developed using optimization and mathematical method, providing reasonable values compared to other correlations with the absolute average percentage error (AAPE) of 9.7%. The prediction of the correlation was validated against 11 experimental data set of oil–water separated flow over wide range of operating conditions, viscosity ratio, pipe diameters and pipe materials. The predicted pressure gradients agreed reasonably well with the experimental results. Excellent agreement was obtained between the predicted and Valle and Kvandal [13], Elseth [15], Chakrabarti et al. [10], Al-Yaari et al. [17], Yiping et al. [11], Nädler and Mewes [14], Rodriguez and Oliemans [3]and experimental data results. The worst agreement was found for Yousuf [18], and Al- Wahaibi et al. [16] data.

8 NOMENCLATURE

D	Pipe diameter(mm)
f_m	Two-phase friction factor
$\frac{dp}{dx}$	Pressure gradient
ρ_m	Mixture density($g.cm^{-3}$)
U_m	Mixture density($g.cm^{-3}$)
ρ_w	Water density($g.cm^{-3}$)
ρ_o	Oil density($g.cm^{-3}$)
H_w	Water hold-up
H_o	Oil hold-up
Q_o	Oil volumetric flow rate($m^3.s^{-1}$)
Q_w	Water volumetric flow rate($m^3.s^{-1}$)
ε	Wall roughness
μ_w	Water viscosity(cp)
U	Velocity ($m.s^{-1}$)

AAPE Average absolute percent error
μ_m Average mixture viscosity(cp)
μ_o Oil viscosity(cp)
Re_m Reynolds number

REFERENCES

[1] Kong, R., Kim, S., Characterization of Horizontal Air–Water Two Phase Flow, Nuclear Engineering and Design, Vol. 312, 2017, pp. 266- 276, DOI: 10.1016/j.nucengdes.2016.06.016.

[2] Angeli, P., Hewitt, G. F., Pressure Gradient In Horizontal Liquid–Liquid Flows, International Journal of Multiphase Flow, Vol. 24, 1999, pp. 1183- 1203, DOI: 10.1016/S0301-9322(98)00006-8.

[3] Rodriguez, O. M. H., Oliemans, R. V. A., Experimental Study On Oil–Water Flow in Horizontal and Slightly Inclined Pipes, International Journal of Multiphase Flow, Vol. 32, 2006, pp. 323- 343, DOI: 10.1016/j.ijmultiphaseflow.2005.11.001.

[4] Bannwart, A. C., Rodriguez, O. M. H., Trevisan, F. E., Vieira, F. F., and Carvalho, C. H. M. de, Experimental Investigation On Liquid–Liquid–Gas Flow: Flow Patterns and Pressure-Gradient, Journal of Petroleum Science and Engineering, Vol. 65, 2009, pp. 1- 13, DOI: 10.1016/j.petrol.2008.12.014.

[5] Hanafizadeh, P., Ghanbarzadeh, S., and HassanSaidi, M., Visual Technique for Detection of Gas–Liquid Two-Phase Flow Regime in The Airlift Pump, Journal of Petroleum Science and Engineering, Vol. 75, 2011, pp. 327- 335, DOI: 10.1016/j.petrol.2010.11.028.

[6] Hanafizadeh, P., Hojati, A., and Karimi, A., Experimental Investigation of Oil- Water Two Phase Flow Regime in an Inclined Pipe, Journal of Petroleum Science and Engineering, Vol. 136, 2015, pp. 12-22, DOI:10.1016/j.petrol.2015.10.031.

[7] Oddie, G., Shi, H., Durlofsky, L. J., Aziz, K., Pfeffer, B., and Holmes, J. A., Experimental Study of Two and Three Phase Flows in Large Diameter Inclined Pipes, Journal of Petroleum Science and Engineering, Vol. 29, Apr, 2003, pp. 527- 558, DOI: 10.1016/S0301-9322(03)00015-6.

[8] Mandal, T. K, Chakrabarti, D. P., and Das, G., Oil Water Flow Through Different Diameter Pipes–Similarities and Differences, Chemical Engineering Research and Design, Vol. 85, 2007, pp. 1123- 1128, DOI: 10.1205/cherd06036.

[9] Xu, X., Study On Oil–Water Two–Phase Flow in Horizontal Pipelines, Journal of Petroleum Science and Engineering, Vol. 59, 2007, pp. 43- 58, DOI: 10.1016/j.petrol.2007.03.002.

[10] Chakrabarti, D. P., Das, G., and Ray, S., Pressure Drop in Liquid–Liquid Two Phase Horizontal Flow: Experiments and Prediction, Chemical Engineering Technology, Vol. 28, 2005, pp. 1003- 1009, DOI: 10.1002/ceat.200500143.

[11] Yiping, L., Hua, Z., Shuhua, W., and Jing, W., Prediction of Pressure Gradient and Holdup in Small Eötvös Number Liquid–Liquid Segregated Flow, Chinese Journal of Chemical Engineering, Vol. 16, 2008, pp. 184- 191, DOI: 10.1016/S1004-9541(08)60060-9.

[12] Al-Wahaibi, T., Pressure Gradient Correlation for Oil–Water Separated Flow in Horizontal Pipes, Experimental Thermal and Fluid Science, Vol. 42, 2012, pp. 196- 203, DOI: 10.1016/j.expthermflusci.2012.04.021.

[13] Valle, A., Kvandal, H., Pressure Drop and Dispersion Characteristics of Separated Oil/Water Flow, Two-Phase Flow Modelling and Experimentation, Vol. 42, 1995, pp. 583- 592.

[14] Nädler, M., Mewes, D., Flow Induced Emulsification in The Flow of Two Immiscible Liquids in Horizontal Pipes, International Journal of Multiphase Flow, Vol. 23, 1997, pp. 55- 68, DOI: 10.1016/S0301-9322(96)00055-9.

[15] Elseth, G., An Experimental Study of Oil–Water Flow in Horizontal Pipes, Fakultet for Ingeniørvitenskap og teknologi, PhD. Thesis, The Norwegian University of Science and Technology, Porsgrunn, 2001.

[16] Al-Wahaibi, T., Smith, M., Angeli, P., Effect of Drag-Reducing Polymers On Horizontal Oil–Water Flows, Journal of Petroleum Science and Engineering, Vol. 57, 2007, pp. 334- 346, DOI: 10.1016/j.petrol.2006.11.002.

[17] Al-Yaari, M., Soleimani, A., Abu-Sharkh, B., Al-mubaiyedh, U., and Al-sarkhi, A., Effect of Drag Reducing Polymers On Oil–Water Flow in A Horizontal Pipe, International Journal of Multiphase Flow, Vol. 35, 2009, pp. 516- 524, DOI: 10.1016/j.ijmultiphaseflow.2009.02.017.

[18] Yusuf, N., Al-Wahaibi, Y., Al-Wahaibi,T., Al-Ajmi, A., Olawale, A. S., and Mohammed, I. A., Effect of Oil Viscosity On The Flow Structure and Pressure Gradient In Horizontal Oil–Water Flow, Chemical Engineering Research and Design, Vol. 90, 2012, pp. 1019-1030,DOI:10.1016/j.cherd.2011.11.013.