Prediction of Pressure Drop in Horizontal and Near-Horizontal Multiphase Flow using Group Method of Data Handling (GMDH) approach with the aim of reducing the curse of dimensionality; A Comparative Study

By

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Dissertation submitted in partial fulfilment of

the requirements for the

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(Petroleum Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

(Dr. Mohammed Abdalla Ayoub Mohammed)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH PERAK

May 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(DELWISTIEL ANAK JAMEL)

ABSTRACT

An accurate prediction on the value of pressure drop during a multiphase flow in pipelines is greatly in need in petroleum industry. Back to 1967, the first empirical correlation was developed to predict the pressure drop in pipelines. Since then, it attracts the interest of many researchers to conduct rigorous studies on this matter. However, the correlations and models that are being used in the petroleum industry nowadays seem to be out dated. At most of the time, it tends to under predict and over predict the pressure as all the correlation have superior relation only with the data used in their experiments.

The objective of this study is to construct a model with high accuracy and low complexity, by utilizing Group Method of Data Handling (GMDH) approach. Parameters that govern the pressure drop are studied to understand their significance towards the prediction of pressure drop. Once all the parameters are outlined, a model is developed and is expected to be generalized, where it can be applied in any behavior of multiphase given. GMDH approach is well known for its ability to model the relation between multiple input parameters and an output with the mean of self-organizing. Stopping criterion will be set optimally to ensure that the model will result in accurate prediction. To achieve this, MATLAB Software will be used for coding and simulation and all the results will be further evaluated in Microsoft Excel software.

The result possess by GMDH model generated in this study will be compared with Beggs and Brill correlation, Gomez et al. correlation and Xiao et al. mechanistic model as these models are the mostly applied methods to predict pressure drop for horizontal and near-horizontal conditions.

From this study, the model generated is very successful in predicting the pressure drop in pipeline where it possess the lowest Average Absolute Percentage Error (AAPE) of 12% compared to other correlation or model. Trend analysis and statistical analysis were conducted to confirm the validity of this model.

The author believes that the model generated in this study will be able to predict the pressure drop in much convenient way in petroleum industry.

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God bless.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The study of pressure drop during a multiphase flow in pipelines is very essential to optimize the equipment designs involved during an operation. Many systems are designed based on the predicted pressure drop which includes surface equipment design, pipeline design, pumping equipment design, gas lift design and etc. Rigorous research has been conducted since half-a-decade to model or correlate the behavior of pressure drop on either horizontal or vertical multiphase flow. However, very few of them focus on the presence of inclination or elevation factors in multiphase flow. In fact, elevation of pipeline absolutely will be encountered during the installation process, connecting the platform to the oil receiving terminal. Hence, accurate prediction of pressure drop due to elevation is also important in order to optimize the design of facilities.

Among the widely used correlations and model in petroleum industry to predict pressure drop are Beggs and Brills, Dukler et al, Eaton-Flanigan, Dukler-Eaton-Flanigan, and Xiao et al. mechanistic model. All of these correlations and model were developed based on common factors such as liquid hold up, friction factor and the flow regime. Although these correlations and model were widely used, somehow, their application might be applied to certain conditions only. It means that, they might perform well prediction only on their range of application (based on experimental parameters) but might over predict or under predict the pressure drop when being applied to the real environment. Due to the limitations of these correlations and model, many researchers tend to model the pressure drop by any means that can give greater accuracy and simplicity.

Artificial Neural Network (ANN) modeling approach is one of the most popular methods being used by the researchers to come out with a new model in order to predict the pressure drop. Based on the application of this method, it was proven that ANN modeling gives better predictions with higher accuracy and lower complexity compared to the existing correlations or models. First of all, all the input parameters that are believed to have significant impact to pressure drop were defined by the user. Next, the user has to define the ratio of the network's layer in order to establish the connectivity between multiple input parameters to one output (pressure drop). This process somehow might consume a lot of time as the user will need to redefine the structure of the network until preferred result were obtained, by the mean of trial and error. This limits the application of ANN to be used in order to give a good prediction of pressure drop. Thus, Group Method of Data Handling (GMDH) has been proposed in this study to predict the pressure drop as this method is able to overcome all the limitations possess by ANN.

In contrast with ANN, GMDH is a self-organizing network where users do not need to define the structure of the network itself. It works by the same means of ANN; establish a connection between multiple input parameters and one output. GMDH approach consumes lesser time compared to ANN as the user just need to set a stopping criterion instead of repeatedly change the structure of the network by trial and error method. Although GMDH is widely known as a good modeling approach, its application in petroleum industry is still very rare and the reason is unknown. Thus, it has been chosen as the main approach to model the pressure drop in this study.

1.2 Objective of Study

The objectives of this study are as follow;

i) To predict the pressure drop during horizontal and near-horizontal multiphase flow

An accurate prediction of pressure drop during a multiphase flow is very essential for equipment design. As the elevation during a flow have a great impact to the pressure drop, it must be taken into account so that the margin of error in pressure drop prediction can be minimized.

ii) To determine all the parameters and factors that affects the pressure drop

All the parameters and factors that contribute a significant impact on the pressure drop need to be studied in detail in this study. It is very important to know the impacts of these parameters and factors so that the accuracy of the prediction can be maximized and to ensure that not a single parameters or factors are being left out during the modeling.

iii) To utilize the GMDH modeling approach

Although GMDH approach is widely known by its ability to self-organize the network to predict any value of interest, there are very few literature can be found on its application in petroleum industry. Thus, this high potential approach was chosen to predict the pressure drop during multiphase flow in pipelines.

iv) To model pressure drop prediction with high accuracy and low complexity

A simple model that does not over fit the training data with high accuracy of prediction is expected in this study. By not over fitting the training data, the model is expected to be able to handle future unseen data being introduced, thus increasing its generality to predict pressure drop. The model is also expected to be dimensionless with some coefficients being introduced.

v) To conduct trend analysis and statistical analysis in validation of model

Once the model is developed, trend analysis and statistical analysis will be conducted to ensure that the model is valid and the model possesses a very low error in prediction.

1.3 Problem Statements

Some of the problems faced when it comes to pressure drop prediction are listed as follow;

i) Complex models or correlations with low accuracy

The existing correlations that are widely used in petroleum industry are very complex, with many assumptions have to be made in order to predict the pressure drop. When assumptions have been made and some particulars are being neglected although they have significant impact on the value of pressure drop, of course it will result in a low accuracy model. Thus, deep studies need to be done to keep the model simple yet with high accuracy

ii) Great need for generalized model in petroleum industry

The existing correlation seems to over fit the experimental data that being used during the development of that particular correlation or model. This can be proved by the percentage of error that being reflected by these correlations when being applied in real environment, where at some point it can reach up to 100% of percentage error. Therefore, a model that is able to accurately predict the pressure drop in whatever conditions given is a great need in oil and gas industry.

1.4 Scope of Study

In order to achieve all the objectives mentioned in 1.2, the study must cover all the mentioned points:

1. Literature survey

A comprehensive study on any literature related to the prediction of pressure drop during horizontal and near horizontal multiphase flow must be done. The literature review in this study focus on 4 elements as follow;

a) Early development of empirical correlation and mechanistic model

b) Parameters and factors affecting pressure drop during horizontal and near-horizontal multiphase flow

c) Evaluation studies on the accuracy of existing correlations

d) Application of GMDH in petroleum industry

2. Model Simulation

After all the parameters and factors that govern the pressure drop have been identified, a model development will be conducted by using GMDH approach. The data that will be used in the development phase will be provided later on.

3. Trend analysis and statistical analysis

Prior to the completion of model in development phase, trend analysis will be first conducted to confirm the validity of the model. Next, statistical analysis will be conducted to determine the percentage of error of the predicted value compared to the actual measured data. This process will be repeated until the desired accuracy of the model is achieved.

1.5 Relevancy and Feasibility

The main objective of this study is to effectively predict the value of pressure drop with high accuracy and high simplicity model. In petroleum industry, the problem always raised where the decision to choose any correlations or models to be used to predict pressure drop is very hard. Accuracy in pressure drop prediction plays a very important role in order to make a good design of equipment with high efficiency. The cost of equipment will be reduced as we can precisely design the equipment that can compensate the required criteria, rather than buying something that over doing the job. The result of this study is expected to be very significant in petroleum industry.

The author believes that, with the developed model, the value of pressure drop can be predicted accurately thus solve all related problems faced during the equipment design. The model developed is also expected to be very feasible where the model can be used to predict pressure drop in any conditions given. However, it is recommended that a specific study must be conducted for that particular area of interest so that the accuracy of the prediction can be enhanced.

CHAPTER 2

LITERATURE REVIEW

This chapter outlines the entire outcome from comprehensive study on literatures related to pressure drop prediction. It can be divided into four subtopics which include (i) the early development of empirical correlations and mechanistic model, (ii) parameters and factors that affect the pressure drop, (iii) evaluation studies on existing empirical correlations and mechanistic models, and (iv) the application of GMDH in petroleum industry.

2.1 Overview on Multiphase Flow

Multiphase flow can be generally defined as any fluid flow that consists of more than one phase of fluid. It can be classified according to the state of the different phases which refers to gas/liquid flow, gas/solid flow, and liquid/solid flow. This study will focus on the prediction of pressure drop in horizontal and near-horizontal gas-liquid multiphase flow. Prediction of pressure gradient in multiphase flow is very important for pipe designs, and for operation and maintenance of the downstream facilities. Considering the complexity of the multiphase flow behavior as compared to single phase, it is very hard to accurately predict the pressure drop as many unknown parameters and different phase distributions or patterns are involved. Two general topologies of horizontal multiphase flow can be usefully identified at the outset, namely disperse flows and separated flows. By disperse flows, it means those consisting of drops or bubbles (the disperse phase) distributed in a connected volume of the continuous phase. Separated flows consist of two or more continuous stream of different fluids separated by interfaces.

The flow regime or flow pattern is a qualitative description of phase distribution in pipe. In horizontal gas-liquid flow, there are three main types of flow pattern which are segregated, intermittent, and distributive flows. Stratified smooth, stratified wavy and annular flow regimes are example of segregated flow. The intermittent flow pattern consists of slug flow and plug (elongated bubble) flow. Meanwhile, distributive flow regimes include bubble and mist flow. Usually the patterns are recognized by visual inspection. **FIGURE** 1 until **FIGURE** 3 shows the common type of multiphase flow. However, to some extent, the flow pattern might be hard to observe, and assumptions have to be made. In this case, flow regime maps are used to predict flow regimes in horizontal gas-liquid flow. These maps are plots of superficial liquid velocity against superficial gas velocity. Maps of Baker are among the first maps being used in oil and gas industry.

In other to predict pressure drop during the multiphase flow, model for wall shear-stress and relation for relative velocity between the phases need to be developed. The method of modeling multiphase pressure drop falls into two categories which are homogenous model and two-fluid or drift flux model. Homogeneous model includes the relation of wall shear stress and the relative velocity is developed empirically. On the other hand, two-fluid or drift flux models use separated model for wall shear stress. The empirical solution will be substituted by complete solution of each phase momentum equation.

Several parameters which govern the pressure drop in horizontal pipe multiphase flows must be identified prior to the development of a correlation or model. Sevigny (1962) suggest that the pressure gradient is greatly affected by the inclination angle of the flow. Beggs (1973) supports that angle of inclination do affect the pressure gradient through their study. In addition, Bonnecaze et al. (1971) reported that pressure drop also strongly dependent with liquid hold up during the flow. Several investigators choose to define measure and predict slip or hold up as intermediate parameter leading to the calculation of pressure drop considering energy balance which led to an interpretation of pressure gradient as a sum of three individual gradients, density, acceleration, and friction. Hong Y. and Desheng Z (2010) identify several properties that may govern the behavior of pressure gradient which are pipe inner diameters, pipe length, pipe roughness, inclination angle, oil density, oil viscosity, pressure, and temperature.

Many correlations were established to predict the pressure drop in a multiphase flow system empirically. Mechanistic models are also available and ready to be applied in any interest of study. Some of these correlations are as follow; Beggs and Brills, Dukler-Eaton-Flanigan, Dukler-Flanigan, Dukler, Eaton, Eaton-Flanigan whereas Xiao et al., Baker et al., and Gomez et al. are some of the examples of mechanistic models. All the models behave differently for different parameters set up. Therefore, deeper study is needed to identify the most suitable correlation or mechanistic model to be used in certain specified condition given. This can be achieved by comparing the accuracy of each correlation and mechanistic model.

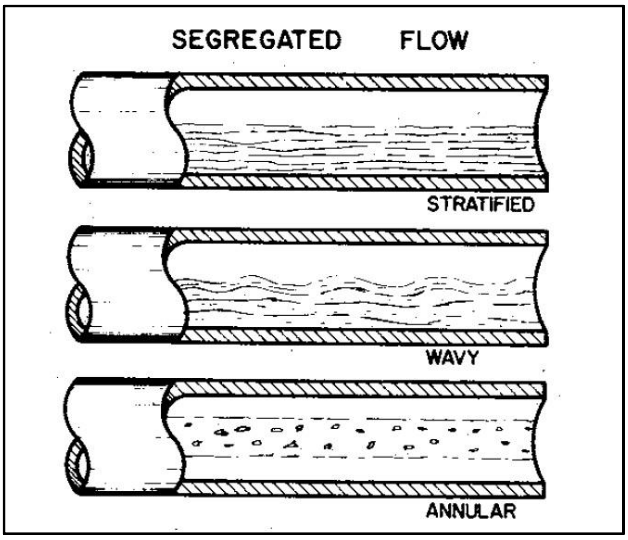

FIGURE 1: Segregated Flow

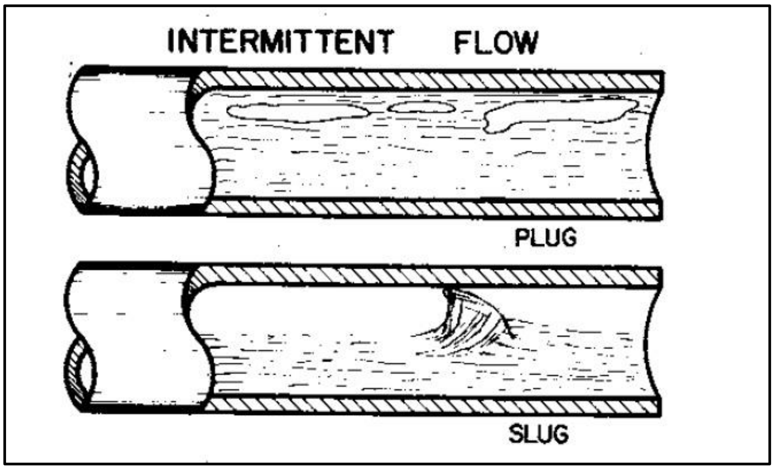

FIGURE 2: Intermittent Flow

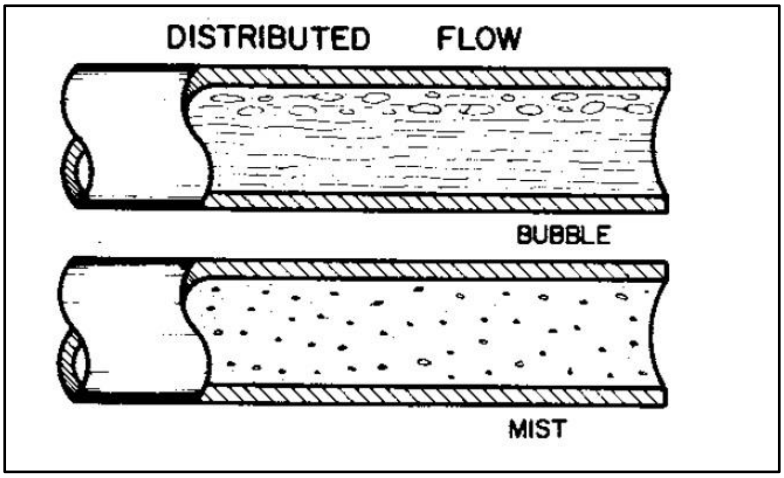

FIGURE 3: Distributed Flow

2.2 Development of Early Empirical Correlation and Mechanistic Model

There are many empirical correlations and mechanistic models that are commonly used in the petroleum industry. Most of them are among the early developed correlations back in 1967, when the first empirical correlation being introduced. Following the awareness on the importance of accurate prediction of pressure drop during a flow in pipeline systems, many researchers came out with their own method, either empirical correlation or mechanistic model. In this section, two empirical correlations and one mechanistic model development are further discussed which are Eaton, B. A, et al. (1967) and Beggs and Brills (1973) empirical correlation, and Xiao et al. (1990) mechanistic model.

2.2.1 Eaton, B. A. Et Al. (1967) Empirical Correlation

Eaton et al. (1967) aims to develop a generalized pressure loss, liquid hold up and flow pattern correlations in their current study. All the data used in this study was taken from two 1,700-feet test lines with pipe diameter of 2 – inch and 4 – inch. For 2 – inch pipe, the liquid rates varies from 50 B/D to 2500 B/D whereas, for 4 – inch pipe, the liquid rates varies from 50 B/D to 5500 B/D. Gas liquid ratio range from 0 to 132,000 scf/bbl for 50 B/D liquid rate and narrower range for higher liquid rate. Several parameters were studied and found to have significant impacts on the pressure loss, which consist of flow rate, pipe size, pipe length, flow line (system) temperature and fluid properties itself.

According to the authors, during the multiphase flow, energy might loss as the fluid flow from one point to the other point. This is due to the energy transferred from the gaseous phase to the liquid phase in the form of heat exchange or acceleration. The author applied the energy balance equation to develop the pressure loss correlation during a horizontal multiphase flow, where it was assumed that the flow is in steady-state condition. There are five terms included in the energy balance equation which are (1) change in pressure-volume energy, (2) change in potential energy due to the elevation, (3) kinetic energy change, (4) irreversible losses or change and (5) energy change due to external shaft or work done by the fluid. In this study, the second and the fifth term was eliminated as the study focus on horizontal with no elevation flow condition and there is no work done by the fluid during the flow. From the authors' point of view, after further study on some of fluid properties, it was found that the increase in liquid velocity does not necessarily cause significant increase in pressure losses and it can be neglected for viscosity value ranging from 12 to 15 cp.

The authors suggest that liquid hold up is one of the important parameters that affect the pressure loss during a multiphase flow. It permits the calculation of average linear velocity of each phase and their difference, which is known as slip velocity. Slippage of gas over liquid is responsible for energy transfer across the interface between phases. In this study, the correlation of liquid hold up was developed based on the experimental water-gas data. Viscosity effect is included as it results in the limitation value of several dimensionless group to calculate liquid hold up when the viscosity is greater than 10 to 20 cp.

Flow pattern map was proposed in this study although it is not required for pressure loss correlation. Among problems that associated with flow pattern are (1) it is hard to define the flow pattern resulted from a certain set of flow condition, and (2) it is difficult to select the correct correlation for any particular pattern as there are many correlation exist for that one particular pattern. The author manage to develop the flow pattern correlation based on two dimensionless groups which are the two phase Reynold's function and the two phase Weber function. From the study, the authors suggest that flow pattern is a dependent variable, same as the pressure loss instead of being an independent variable suggested by previous researchers. Therefore, single energy-loss correlation will suffice for all flow regimes since the flow pattern are controlled by same variables.

In conclusion, the proposed correlation is valid and can be applied to predict the pressure drop in horizontal multiphase flow only. The study also shows a good result where the standard deviation of percentage errors are as low as 0.262.

2.2.2 Beggs and Brill (1973) Empirical Correlation

Beggs and Brill (1973) had successfully developed a correlation to predict the pressure drop during horizontal or near-horizontal (inclined) multiphase flow in pipelines. 8 parameters were studied, which includes gas flow rate, liquid flow rate, average system pressure, pipe diameter, liquid hold up, pressure gradient, inclination angle and flow pattern. The correlation are devised for two parameters in order to calculate the pressure gradients in two phase inclined flow which are liquid hold up and two-phase friction factor.

Liquid hold ups are directly dependant with the type of flow patterns or flow regimes. There are three types of flow regimes, which are; distributed flow regime, intermittent flow regime and segregated flow regime. Distributed flow consists of bubble and mist flow, whereas intermittent flow consists of plug and slug flow. Stratified, wavy, and annular flows are classified as the segregated flow. Apart from the flow regime, the degree of pipe inclination also affects the value of hold up in the pipe. Therefore, the value of predicted holdup must be corrected for inclined flow. This can be achieved by normalizing the value of measured hold up, by dividing the value of hold up at any angle with the value of hold up at zero degree of inclination.

In other to estimate the friction factor for any flow with certain degree of inclination, the measured friction has to be normalized by dividing the measured data with the no-slip friction factor. It is only applicable if the velocities of the flowing fluids are the same with each other. The value of the no-slip friction factor is obtained from the Moody diagram, for smooth pipe. It was found that the normalized two-phase friction factor is in a function of input liquid content and liquid holdup.

From the study, Beggs and Brill concluded that, the inclination angle of a pipe in multiphase flow definitely affects the liquid hold up and pressure drop for most flow conditions. The liquid hold up reaches its maximum value at +50 degree of inclination whereas it could reaches its minimum value at -50 degree of inclination. At +90 degree and +20 degree of inclination, it was found that the holdup is approximately equal which explains the vertical holdup correlations can be used with some degree of success for horizontal flow.

2.2.3 Xiao, J. J. Et Al (1990) Mechanistic Model

J.J. Xiao et al. (1990) mechanistic model has been developed for horizontal and near-horizontal multiphase flow. It is able to detect the flow pattern, predict the characteristics of the flow, liquid holdup and the pressure drop for stratified, intermittent, annular and dispersed bubble flow pattern. It was found that the application of the mechanistic model perform better prediction of pressure drop compared to the other correlations used before.

Four types of flow patterns were studied prior to the development of the mechanistic model which are stratified flow (stratified smooth and stratified wavy), intermittent flow (elongated bubble flow and slug flow), annular flow (annular mist and annular wavy flow), and dispersed bubble flow. Three major flow transitions were underlined in the study; the stratified-non stratified transitions, intermittent-annular transitions and intermittent-dispersed bubble transition.

Separate models are developed accordingly to predict the pressure drop for each flow pattern. The models are stratified flow model, intermittent flow model, annular flow model and dispersed bubble flow model. The generalized one-dimensional two-fluid model by Taitel and Dukler (1976) was adapted in the study of stratified flow model. For intermittent flow model, it was assumed that the liquid level in the film zone is uniform. The liquid and gas phase in the flow also considered as incompressible. For annular flow model, two dimensional models were incorporated in the development of the model (James et al. 1987 and Laurinat et al. 1985). For liquid phase, the film thickness of liquid was assumed as average meanwhile for gas core, the droplets are assumed to travel at same velocity in gas phase. Therefore, the gas core can be treated as homogeneous fluid. The dispersed bubble flow was considered as the simplest model to be developed. As there are no slippages between the phases, pseudo-single phase model with average properties is adopted in the development of this flow pattern model.

The evaluation of the developed model was carried out for the prediction of pressure drop during the flow. Three sources of data was chosen in the study which are (1) 1988 version of the A.G.A. gas liquid pipeline data base which contains 455 data points (Crowley 1988), (2) field measurements by Mcleod et al. (1971), and (3) laboratory data from Eaton & Brown (1965) and Payne et al. (1979). Several considerations have been made to select reliable data from Crowley 1988 which include discarding all unreliable data (i.e, low pressure drop measured for very long pipelines), and did not consider any data containing free water for compositional system. This result in the selection of only 79 out of 455 data points, where 25 data points are from the compositional system. To compare the reliability of the developed model, comparative study have been conducted with reference to the commonly used correlations which include Beggs and Brill, Mukherjee and Brill, Dukler, and Dukler and Eaton correlation. J.J. Xiao concluded that the current developed mechanistic model is more reliable than the other correlation compared.

2.3 Parameters and Factors Contribute To Pressure Drop

Several parameters and factors that govern the value of pressure drop being identified from the literature. The outcome of the study on these will be further divided into two sub-topics.

2.3.1 Parameters Governing Pressure Drop

Some of the common factors that is believed to have significant impact on the value of pressure drop are

i) Wellhead Pressure

ii) Wellhead Temperature

iii) Water Flow Rate

iv) Gas Flow Rate

v) Oil Flow Rate

vi) Length of the flow line

vii) Degree of inclination

viii) Internal diameter of the flow line

2.3.1.1 Theory

The parameters outlined affect the value of the pressure in various ways. The possible outcomes of pressure drop in relation to any changes in the value of one parameter while others kept constant are being discussed further.

a) Oil flow rate

The value of the pressure drop is expected to increase with the increasing value of oil flow rate

b) Gas Flow Rate

The value of the pressure drop is expected to increase with the increasing value of gas flow rate

c) Pipeline length

The pressure drop is expected to increase with the increasing length of pipelines

d) Angle of Inclination

The positive value of inclination, upward flow from horizontal is expected to result in increasing pressure drop measured. In the other hand, downward flow from horizontal (negative inclination) is expected to result in decreasing value in pressure drop

e) Pipe Diameter

The increasing size of pipeline will result in the reduction of pressure drop. As the size of pipeline increased, the cross sectional area will increase too. Thus makes the pressure drop reduced.

2.3.2 Physical Factors Governing Pressure Drop

There are mainly three physical factors that contribute to the pressure drop during a multiphase flow in pipelines. They are (1) liquid hold up and (2) friction factor.

2.3.2.1 Liquid Hold Up

According to Beggs and Brill (1973) the liquid hold up contributes significant effect on the measurement of pressure drop. It was suggested that the value of liquid hold up is dependent on the angle of elevation. An increment in the elevation of pipe will result on the decreasing velocity of fluid due to the gravity forces acting in the liquid. Thus, the slippage increases with hold up. This will cause the pressure drop higher. When the angle is increased further, liquid bridges entire pipe and cause the slippage being reduced. At this point, the value of liquid hold up will decrease. An increase of angle in negative direction (illustrated by downhill flow) will cause the velocity increase and therefore the hold up will decreases. Pressure drop measured should be lower during this type of flow. In order to correct the value of liquid hold up due to elevation, the hold up is normalized by dividing the value of hold up at any angle divided to the value of hold up at horizontal. It is also found that the value of hold up is highly depending on the value of liquid content and Froude's Numbers.

2.3.2.2 Friction Factor

In Beggs and Brills study, the value of two-phase friction factor was normalized by dividing it with the no-slip factor, which can be obtained from Moody Diagram. It was found that the friction factor is in the function of liquid content and liquid hold up.

Jean Fabre in the study of "Modeling Stratified Gas-Liquid Flow" suggests that friction factor must be accurately predicted in order to predict the friction factor during two-phase flow system. The friction factor will be calculated based on the friction caused by oil-wall contact, gas-wall contact, and interfacial of the two-phases. Interfacial friction is strongly coupled to the motion of both phases. The higher is the interfacial friction, the higher is the pressure drop measured in gas. The author manage to correlate the wall friction factor where some equations are identified to calculate wall friction factor in gas phase, wall friction factor in the liquid phase and interfacial friction factor.

2.4 Evaluation Studies on Existing Empirical Correlation and Mechanistic Model

Many evaluation studies were conducted to determine the accuracy of each correlation and model. It can be either (1) evaluation study conducted to determine which correlation or model should be used in condition given or (2) evaluation study of new model or correlation developed against existing correlations. Both types of this study will be covered in this sub-topic.

2.4.1 Evaluation Based On Given Condition

Hong Yuan and Desheng Zhou (2010) had evaluated the commonly used two-phase flow pressure-prediction correlations and mechanistic model against the experiment data. All experiment data used in the study are obtained from publish papers (Kokal and Stanislav 1989a, 1989b). The data used were gathered from 1-, 2-, and 3-inch pipes with seven inclination angles. Oil and water were used as testing fluids. In the study, Beggs and Brill (1973), Dukler-Eaton-Flanigan, Dukler-Flanigan, Dukler, Eaton, Eaton-Flanigan correlations and Xiao et al. mechanistic model were evaluated in term of pressure drop prediction. Commercial software was used to stimulate the experimental section for 1- and 2- inch pipe diameter.

The software is a steady-state-flow simulator for single pipe or complex network system. This simulation tool can predict flow patterns, liquid hold up, temperature gradient, pressure gradient, etc. (Pipesoft-2 Manual 2007). All the results were presented as a graph of pressure gradient against Superficial Gas Velocities (SGVs) at certain Superficial Liquid Velocity (SLV). The percent error for various SGVs at each SLV were calculated based on the difference of measured pressure gradient and calculated pressure gradient. Negative value of percent error indicates that the calculated pressure gradient is larger than the measured pressure gradient. It reflects that the correlation or model over predict the pressure gradient. In the other hand, positive percent error indicates that the correlation or model under predict the pressure gradient. An absolute average error is calculated by averaging the value of percent errors at various SGVs for each SLV.

From the research, Yuan H. and Zhou D. concluded that (1) Beggs and Brill always over predict the pressure gradient, (2) Dukler-Eaton-Flanigan over predict pressure gradients except for 1-inch pipe with -1 degree of inclination at small SLVs cases, (3) Eaton and Eaton-Flanigan always underpredict the pressure gradient for 1-inch pipe with SLVs more greater than 3 ft/s, (4) Dukler behave the best for 1- inch pope with SLVs greater than 3 ft/s. For SLVs less than 3 ft/s, Xiao behave the best. (5) Xiao behave the best for 2-inch pipe cases, and (6) all correlations with Flanigan correction factor behave worse than the ones without Flanigan correction factor except for Eaton-Flanigan of 1- inch pipe.

Spedding, P. L., Benard, E., and Donelly, G. F. had conducted an evaluation study where empirical correlations were tested against reliable two phase pipe flow data for the prediction of pressure drop. The correlations were also adapted to three phase gas-water-oil flow in pipe. Among the correlations being tested are Lockhart-Martinelli correlation, Dukler-Wicks-Cleveland correlation, Beggs and Brill correlation, Friedel correlation, Beattie-Whalley correlation, etc.

From the study, it was concluded that the prediction of pressure drop made by all correlations were not successful over all flow regimes. For stratified flow, which usually occur in horizontal and near-horizontal multiphase flow, only Beggs and Brill, Dukler-Wicks-Cleveland and Beattie-Whalley correlations that are able to predict the pressure drop within 30% spread.

2.4.2 Evaluation of New Correlation Developed Against Existing Correlations

Ayoub, M. A. and Demiral, B. M. in their study “Application of Resilient Back-Propagation Neural Networks for Generating a Universal Pressure Drop Model in Pipelines” aim to generate and validate a universal pressure drop model at pipelines under three-phase flow condition by utilizing resilient back-propagation Artificial Neural Network. A total number of 335 data has been used for generating validating and testing the ANN model.

A model performance has been evaluated against the best empirical correlations and mechanistic models (Xiao et al., Gomez et al., and Beggs and Brill). The new proposed model is able to achieve the optimum performance when compared to the best available models adopted by the industry for estimating pressure drop in pipelines for all angles of inclination with correlation coefficient reach up to 98.82%. The model proposed show a very small average absolute percentage error of 12.1%.

2.5 Application of GMDH in Petroleum Industry

Semenov, A. A et al. in their study aims to develop the best mathematical model for Dolgan reservoir rock characteristics estimation using all available well logs information. Among the methods being used in their study are linear regression, neural networks, and GMDH. GMDH method had successfully obtained the best correlation in terms of statistical criteria. It is able to optimize model coefficient for predetermined mathematical equation and select optimal model complexity. As a result, full-field geomodel of Dolgan formation was created based on the result of porosity calculation with GMDH. The geomodel is then used during different processes, such as horizontal or side track wells drilling to create field development system and to predict recovery rate through model simulation.

Lee, Y. B., Liu, H. S., and Tarng, Y. S have conducted a research to predict the drill life under varying cutting conditions. Abductive network or GMDH has been adopted in order to predict the drill life in their work. Several parameters are selected as the input, which includes drill diameter, cutting speed, and feed rate. The drill life used in the abductive network is defined as the period of drilling time that the average flank wear land, VB is equal to 0.3 mm or maximum flank wear land, VBmax is equal to 0.6 mm. This criterion to define the effective life for HSS tools is recommended by the International Standard Organization (ISO). From the experimental result, it was proven that abductive network can be effectively used to predict drill life under varying conditions, with prediction error of less than 9 %. It was also proven that by using abductive network, a number of polynomial functional nodes can be self-organized and grouped into several layers to form optional network architecture by using Predicted Square Error (PSE). The principle of PSE criterion is to synthesize as accurate but less complex a network as possible.

Research on the prediction of pipeline scour depth in clear-water and live-bed conditions was conducted by Mohammad, N., Gholam- Abbas, B., and Haji, M. A. by using GMDH. Among the suggested parameters which can affect the scour depth are sediment size, geometry of pipeline, and the approaching flow characteristics. The application of GMDH in predicting the pipeline scour depth was compared with other methods of prediction including support vector machines (SVM) and commonly used empirical equations. The result is significance, where GMDH outperform the other methods. The prediction made using GMDH have lower error and higher accuracy.

Osman, E. A., and Abdel-Aal, R. E. suggest abductive or polynomial networks based on the Group Method of Data Handling (GMDH) modeling approach to be used as an alternative modeling tool that avoid many of the Neural Network limitations. The authors outlined all the limitations of artificial neural network which include restriction by neuron analogy, complexity of design space, and learning algorithm parameter need to be determined. The advantages of using GMDH approach was greatly focused on as the authors encourage more of this approach to be utilized in oil and gas industries. The authors had successfully applied GMDH in order to predict the bubble-point pressure Pb and the bubble-point oil formation volume factor Bo. As for bubble-point pressure, Pb, the abductive network model developed with coefficient of 0.9898 has successfully outperforms all other correlation. The average absolute percentage error by using GMDH is 5.62%, compared to 13% posed by other empirical correlations. In the other hand, the abductive network developed to predict the bubble-point oil formation volume factor, Bo, also manage to outperform other empirical correlations. The developed model with coefficient of 0.9959 posses an average absolute percentage error of 0.86%, where the common error varies from 1% – 2%. The results indicate that abductive network models are more accurate than other models and empirical correlations. Some of the potential applications of GMDH in oil and gas industries were also discussed.

CHAPTER 3

METHODOLOGY

This chapter covers all the methodology that will be used, project activities, key milestones, study plan, and future recommendations on this study. In general, simulation software will be greatly used in the development of the model by using GMDH approach. Further explanation on GMDH approach will be

3.1 GMDH Modeling Approach

GMDH is a further propagation of inductive self-organizing methods to the solution of more complex practical problems. By the mean of self-organizing, it consists of networks of mathematical functions that capture complex, non-linear relationships in a compact and rapidly executable form. Such networks subdivide a problem into manageable pieces or nodes and apply advanced regression techniques to solve each of simpler problems. In the other word, it works by establishing a general network that connects both the input and output variables which generally expressed by Kolmogorov – Gobor polynomial. The component of input can be either independent variable, functional forms or even finite difference terms. This method is able to find the structure of a model and the dependence of the modeled system output on the value of most significant input of the system simultaneously.

In comparison with the well-known Artificial Neural Networks (ANN), GMDH has many advantages that overcome the limitation poses by ANN. Among them are, (1) self-organization. When a user uses ANN in modeling, he/she needs to estimate the structure of the model by choosing the number of layers and the number of the transfer functions of nodes of a neural network which is very subjective. In the other hand, the number of layers and nodes in GMDH are estimated by the minimum of external criterion which is predefined by the user. (2) GMDH performs modeling faster than ANN. For ANN, the result depends from initial solution, which require user to set various algorithmic parameters by trial and error. Indeed, it consumes time to reach the finalized model. Compared to ANN, GMDH simultaneously optimize the structure and dependencies in model, not a time-consuming technique, and any inappropriate parameters will not be included automatically. It means that GMDH only model input parameters that have significant effect on the output layer.

GMDH has been successfully applied in many fields of interests which include economy system, ecology systems analysis and prediction, environment system, medical diagnostics, manufacturing, military system, etc. However, there is very few application of GMDH can be found in oil and gas field of study. Although the ability of GMDH to model the output with given input parameters is well known, the reason of why there is only few application of this method in oil and gas industries is still not known. This method has a very high potential to be applied in oil and gas industries as many uncertainties are being dealt in petroleum sectors such as during exploration, production, and transportation.

3.1.1 Basic Structure of GMDH

The connections between neurons in the network are not fixed but rather are selected during training to optimize the network. The number of layers in the network also is selected automatically to produce maximum accuracy without over fitting. The following figures are basic GMDH network using polynomial functions of two variables:

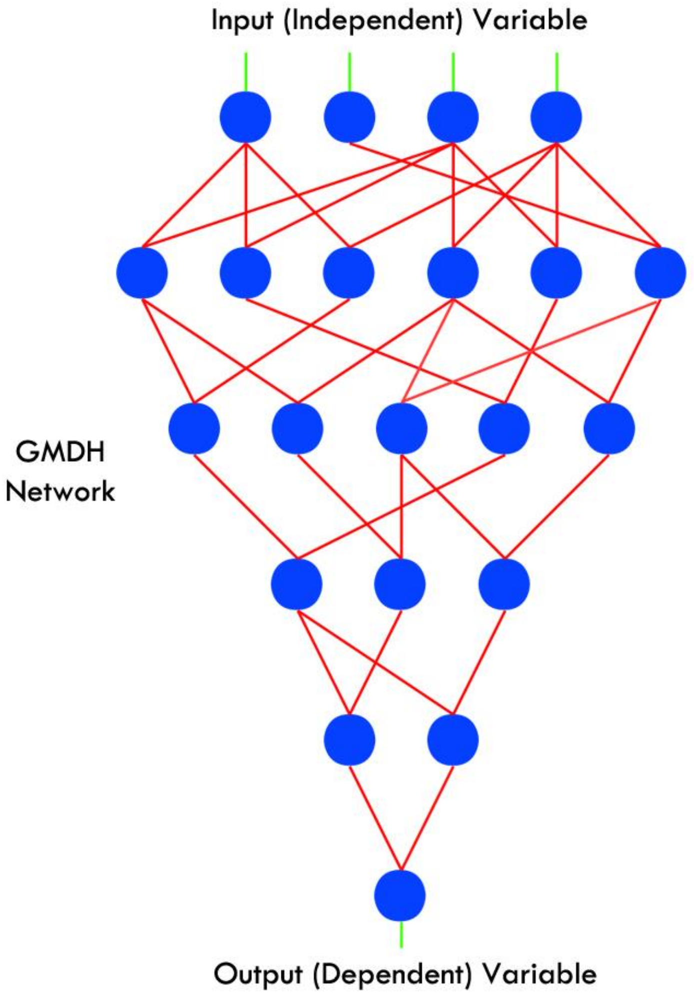

FIGURE 4: Basic Structure of GMDH Network

The first layer (at the top) presents one input for each predictor variable. Each neuron in the second layer draws its inputs from two of the input variables. The neurons in the third layer draw their inputs from two of the neurons in the previous layer; this progresses through each layer. The final layer (at the bottom) draws its two inputs from the previous layer and produces a single value which is the output of the network. Inputs to neurons in GMDH can skip layers and come from the original variables or several layers earlier as illustrated by **FIGURE** 5 below:

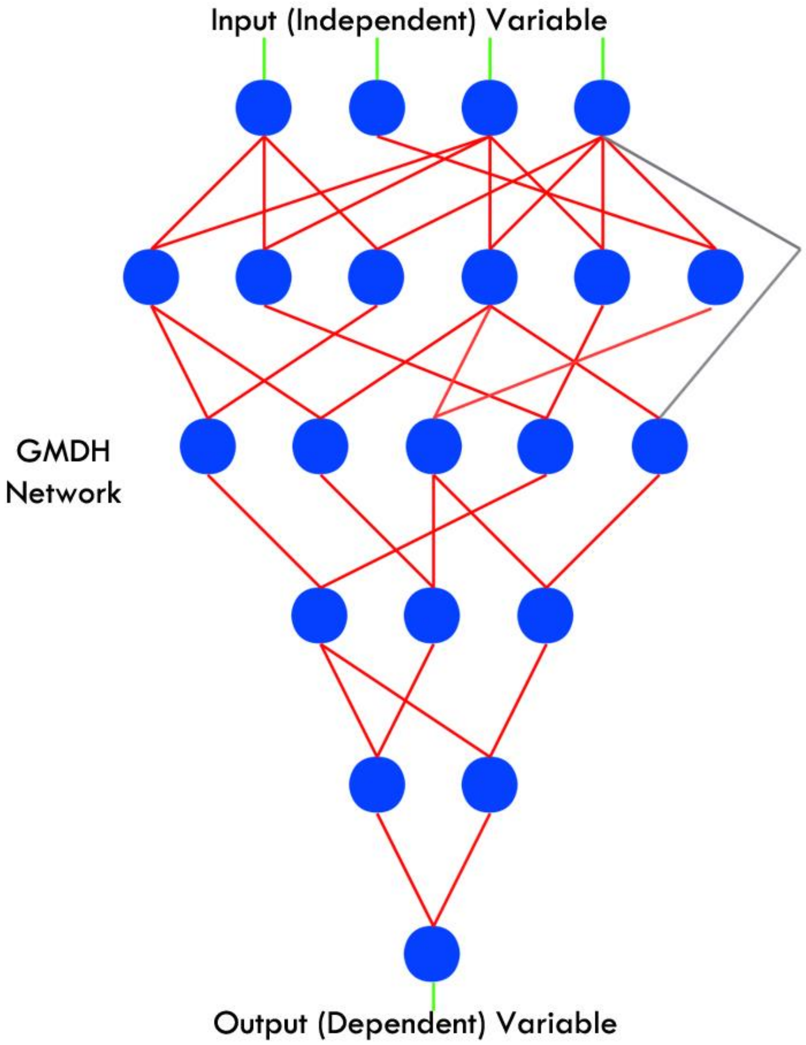

FIGURE 5: Basic Structure of GMDH Network (2)

In this network, the neutron at the right end of the third layer is connected to an input variable rather than the output of a neuron on the previous layer. Traditional GMDH neural networks use complete quadratic polynomial of two variables as transfer functions in the neurons. These polynomials have the form of:

y = p0 + p1*x1 + p2*x2 + p3*x1^2 + p4*x2^2 + p5*x1*x2

From the earlier discussion, the input parameters chosen to model the pressure drop in horizontal and near-horizontal are (1) pipe diameter, (2) oil flow rate, (3) liquid flow rate, (4) length of pipe, (5) inclination angle, (6) system temperature, and (7) system pressure.

3.1.2 Training, Validation and Testing Data Set

A set of data (which will be given later on) is chosen as a reference data prior to the development of the model. The whole data will be divided into three partitions which are for the training, validation and testing. The author suggests a ratio of 2:1:1 to be used in data partitioning, where half of the data will be used for training purposes, one quarter of the data will be used for validation purpose, and the remaining one quarter will be used for testing. The reason of choosing higher weightage on the testing data is to ensure that the model developed will have sufficient training phase.

3.1.3 Predicted Squared Error: A Criterion for Automatic Model Selection

Predicted Squared Error (PSE) is the sum of two terms: the training squared error and over fit penalty. The training squared error (TSE) is given by the average squared error of a model on n training observations. Let k be the number of coefficients in the model that are estimated to minimize TSE. The over fit penalty is given by2σ_p^2 (k⁄n), where σ_p^2 is a prior estimate of the true error variance that does not depend on the particular model being considered. Thus, PSE is given by

PSE = TSE + 2σ_p^2 (k/n)

The PSE is used at all stages of network construction to rank and select the better model structures. The network that achieves the least PSE is the final product of network synthesis. A minimum will be attained because TSE decreases with each additional coefficient but always remains nonnegative, whereas the over fit penalty linearly increases in the number of coefficients.

In conclusion, upon the development of the model, PSE plays a very important role as it is the stopping criterion for that particular model. The result of the model, either accurate and general, or accurate and over fit, will depend much on the value of PSE. Therefore, PSE must be set at a value that can result in a model that is accurate yet generalized. One of the suggested methods to do so is by using the complexity penalty multiplier (CPM) parameter. When any value greater than the default value of 1 is chosen, it leads to simpler models that are less accurate but are more likely to generalize well with previously unseen data. In the other hand, lower values of CPM produced more complex networks that may over fit the training data and degrade prediction performance with noise, especially when new unseen data were introduced to the network. Thus, the value of CPM = 1 is chosen for this study.

3.2 Trend Analysis and Statistical Analysis

Both trend and statistical analysis will be used in this study. Trend analysis is conducted to ensure that the developed model is valid theoretically. Effects of the input parameters against the pressure drop will be tested and cross checked with the theory suggested. By doing so, the wrongly developed model will be rejected and modeling should be reworked.

Statistical analysis is conducted to ensure that the pressure prediction made by the developed model is mathematical correct. The statistical parameters used are

i) Average percent relative error
ii) Average absolute percent relative error
iii) Minimum and maximum absolute percent error
iv) Root mean square error
v) Standard deviation of error

3.3 Project Activities

The project activities are divided into three phase of research development which is:

1) Early Research Development

In the early research development, the main focus is the background study of this project. It includes:

- Overview of multiphase flow
- Overview of method used, GMDH

2) Middle Research Development

In the middle research development, the author makes detailed literature studies which include:

- Early development of empirical correlation or mechanistic model
- Parameters and factors affecting pressure drop
- Evaluation studies on existing correlation
- Application of GMDH in petroleum industry

3) Final Research Development

Final research development will be covered later on when the model is developed and tested.

The breakdown of activities is shown in **FIGURE** 6 below.

FIGURE 6: Breakdown of Activities

3.4 Key Milestones

In order to ensure that the project is conducted in the provided time frame, several key milestones are suggested by the author. This also will enable the author to keep track on the progress of project. The key milestones are tabulated as follow;

KEY MILESTONE	**REMARKS**
1. Complete literature review • Early development of empirical correlation and mechanistic model • Parameters and factors contribute to the pressure drop during horizontal and multiphase flow • Evaluation studies of existing empirical correlation and mechanistic model • Application of GMDH in petroleum industry	FYP1
2. Complete theory on effect of parameters to the pressure drop	FYP1
3. Complete theory of methodology used in study (GMDH)	FYP1
4. Development of model by using GMDH	FYP2
5. Evaluation of developed model • Trend analysis • Statistical analysis	FYP2
6. Complete report on the study	FYP2

TABLE 1: Key Milestones

3.5 Study Plan

No	**Detail/ Week**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
1	Topic Selection/Proposal	🟦	🟦											
2	Chapter 1 Progress		🟦											
3	Chapter 2 Progress			🟦	🟦									
4	Chapter 3 Progress					🟦								
5	Extended Proposal Draft Review					🟥								
6	Submission of Extended Proposal						🟥							
7	Proposal Defense Preparation						🟦	🟦	🟦					
8	Proposal Defense (Oral Presentation)								🟥					
9	GMDH Familiarization (MATLAB)								🟦	🟦	🟦			
10	Simulation Planning (MATLAB)											🟦		
11	Submission of Interim Draft Report												🟥	
12	Submission of Interim Report													🟥

TABLE 2: FYP1 Gantt chart

🟦 Process 🟥 Suggested Milestone

No	**Detail/ Week**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1	Project Work Continues	🟦	🟦	🟦	🟦	🟦	🟦	🟦								
2	Submission of Progress Report							🟥								
3	Project Work Continues								🟦	🟦	🟦	🟦	🟦			
4	Submission of Draft Report										🟥					
5	Submission of Dissertation (Soft Bound)											🟥				
6	Submission of Technical Paper											🟥				
7	Pre SEDEX Poster Presentation													🟥		
8	FYP2 VIVA (Oral Presentation)														🟥	
9	Submission of Dissertation (Hard Bound)															🟥

TABLE 3: FYP2 Gantt chart

🟦 Process 🟥 Suggested Milestone

CHAPTER 4

RESULT AND DISCUSSION

In this topic, the result obtained from the simulation will be further discussed and elaborated in detail. It covers the generation of model which predicts the pressure reading on the separator and the prediction of pressure drop during the multiphase flow within the flow line (from wellhead to separator). It also includes the trend and statistical analysis for the model.

4.1 Generation of GMDH Model

Prior to generate the GMDH Model, first, the data is divided into three partitions which are for training, validation, and testing. The ratio chosen for the data partitioning is 2:1:1, where half of the data were used for training, one-quarter of the data for validation and another one-quarter for testing. There are a total of eight input parameters used for modeling, which includes (1) wellhead pressure, (2) wellhead temperature, (3) flow rate of gas, (4) flow rate of water, (5) flow rate of oil, (6) length of the flow line, (7) degree of inclination, and (8) diameter of the flow line.

There are some criteria have been set up prior to the generation of model itself in the Matlab Software. All the criteria are as follow;

i. Input selection for individual neurons

The model in this study is set to take inputs from both preceding layer and original inputs

ii. Degree of polynomials in neurons

The model in this study is set to form polynomial degree of 2.

iii. Criterion for evaluation of neurons and for stopping

The model in this study is set to use validation data as well as training data for the evaluation of neurons. In each layer, only the best neurons (based on the criterion) are retrained and the rest are discarded.

With all these criterions had been set up, the best GMDH model then is selected based on the lowest value of MSE, RMSE, RRMSE and highest value of R2.

Four parameters were found to have significant impact on separator pressure reading in the model generated. This includes;

i. Oil Flow Rate, Q_{oil}

ii. Water Flow Rate, Q_{water}

iii. Wellhead Pressure, $P_{wellhead}$

iv. Length of the flow line, L

LAYER	NO. OF NEURONS
#1	1
#2	1
#3	1

TABLE 4: GMDH Model and Neurons Number

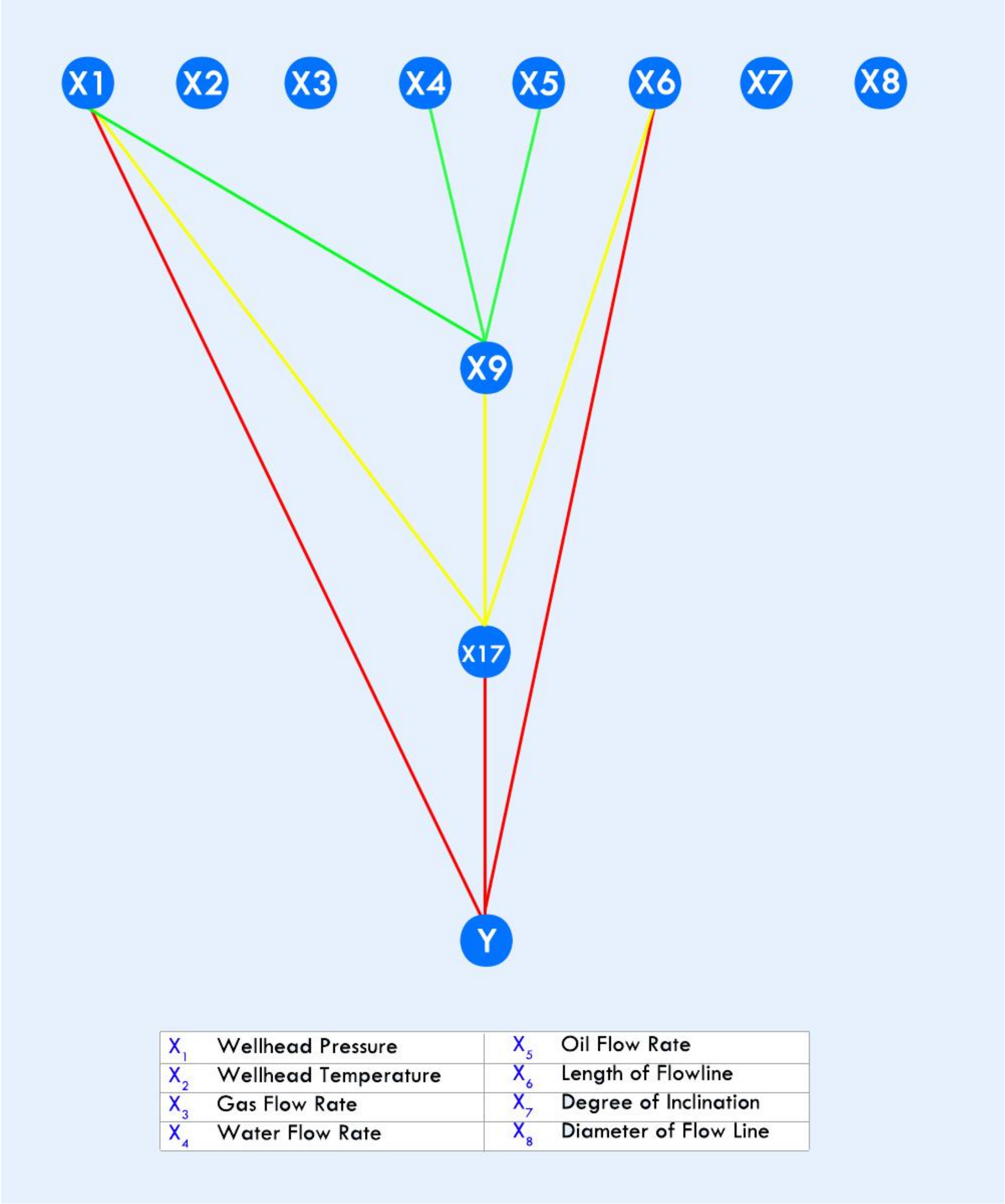

FIGURE 7: Structure of GMDH Model Developed

4.2 Prediction of Pressure Drop

By referring to the general energy equation, the pressure drop can be calculated based on three factors which are;

i) Potential energy
ii) Frictional loss
iii) Kinetic energy

The general energy equation is expressed as follow;

$$\frac{dP}{dL} = \frac{g}{g_c}\,\rho \sin\theta + \frac{f\rho v^2}{2g_c D} + \frac{\rho v dv}{g_c dL}$$

Where;

$\frac{g}{g_c}\,\rho \sin\theta$ = pressure gradient due to elevation or potential energy change,

$\frac{f\rho v^2}{2g_c D}$ = pressure gradient due to frictional losses, and

$\frac{\rho v dv}{g_c dL}$ = pressure gradient due to acceleration or kinetic energy change

P = pressure, lbf/ft2

L = pipe length, ft

g = gravitational acceleration, ft/sec2

gc = 32.17, ft-lbm/lbf-sec2

ρ = density lbm/ft3

θ = dip angle from horizontal direction, degrees

f = Darcy–Wiesbach (Moody) friction factor

υ = flow velocity, ft/sec

D = pipe inner diameter, ft

From the predicted separator pressure reading by the GMDH model, pressure drop during the multiphase flow through the flow line can be simply predicted by the equation below;

$$\text{Wellhead Pressure} - \text{Predicted Separator Pressure}$$

The GMDH model built is successful in predicting the pressure drop as it possess as low as 10% in AAPE (Average Absolute Percentage Error) for overall data and 12% in AAPE for testing data. The result is shown in **APPENDIX**.

Pressure drop predicted by GMDH Model is then compared to some of the commonly used correlation and mechanistic model which includes Beggs and Brill correlation, Gomez et al. correlation and Xiao mechanistic model. The comparisons of these models were done only for all testing data. Results are shown in **TABLE 5**.

ACTUAL	**GMDH**	**E%**	**BEGGS & BRILL**	**E%**	**GOMEZ**	**E%**	**XIAO**	**E%**
38	43	13%	51	34%	48	26%	32	15%
40	45	13%	63	57%	63	57%	37	8%
10	15	50%	12	23%	12	23%	15	48%
80	79	1%	102	28%	106	33%	111	39%
41	45	10%	45	10%	46	12%	28	31%
50	47	6%	56	12%	55	9%	32	36%
70	69	1%	81	15%	75	6%	89	27%
29	36	24%	45	56%	43	48%	29	1%
80	79	1%	93	16%	98	23%	110	37%
30	21	30%	44	47%	42	40%	27	11%
80	80	0%	86	8%	80	1%	51	36%
44	47	7%	47	6%	44	0%	30	33%
43	45	5%	57	32%	55	29%	33	23%
60	61	2%	66	9%	65	9%	38	36%
190	191	1%	210	10%	198	4%	139	27%
30	27	10%	36	21%	33	9%	21	30%
75	74	1%	102	36%	96	28%	63	16%
40	38	5%	33	19%	29	28%	19	54%
40	43	8%	46	15%	43	7%	29	27%
22	32	45%	38	75%	32	45%	16	25%
90	89	1%	108	20%	110	22%	131	46%
25	39	56%	41	64%	41	63%	26	4%
45	52	16%	44	2%	41	9%	28	37%
35	36	3%	25	29%	19	47%	10	71%
40	31	23%	45	13%	43	8%	27	32%
49	52	6%	42	15%	39	21%	27	45%
85	84	1%	109	28%	112	32%	116	36%
45	47	4%	45	0%	42	7%	29	36%
62	54	13%	46	26%	46	25%	28	54%
85	95	12%	84	2%	74	13%	53	38%
145	144	1%	197	36%	186	28%	174	20%
10	12	20%	19	91%	18	81%	13	33%
52	51	2%	71	36%	71	36%	44	16%
80	80	0%	87	8%	80	0%	52	36%
32	38	19%	43	35%	40	25%	28	14%
20	24	20%	23	16%	25	25%	28	39%
AAPE	12%		26%		24%		31%	

TABLE 5: Testing Data Results

4.3 Trend Analysis of GMDH Model

In order to confirm the model is valid, trend analysis was conducted on all four significant parameters that affect the value of pressure drop. The trend analysis was conducted by selecting one set of testing data and manipulating the value of the significant parameter individually while other parameters were kept constant.

Findings on the trend analysis of each parameter are shown as follow.

4.3.1 Effect of Oil Flow Rate on Pressure Drop

	DP	**DP**	**DP**
Q_O	**θ = -0.1**	**θ = 0.032**	**θ =0.122**
500	44	64	91
2000	48	70	93
4500	51	80	94
6000	53	84	95
7500	57	88	96
10000	58	92	97

TABLE 6: Effect of Oil Flow Rate on Pressure Drop at Different Angles

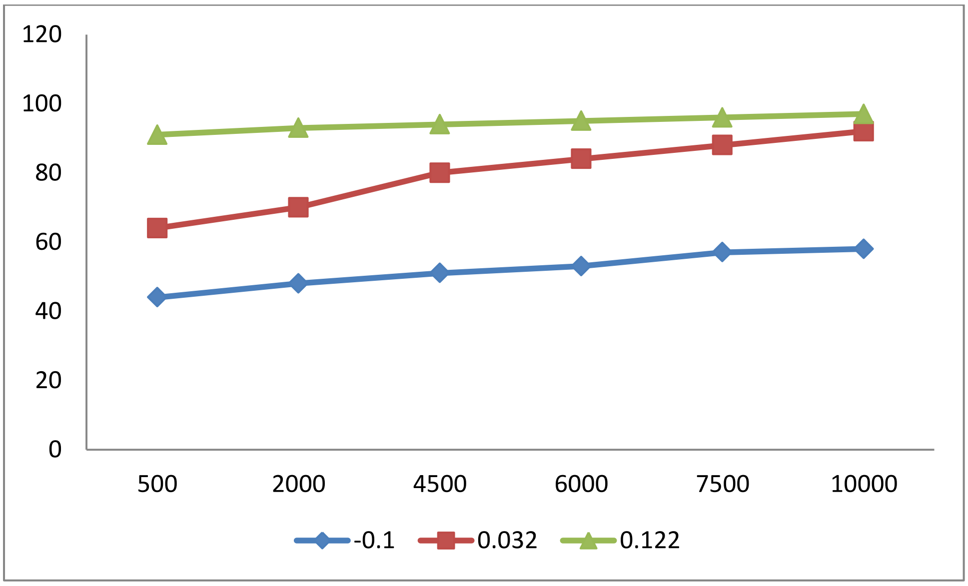

FIGURE 8: Effect of Oil Flow Rate on Pressure Drop at Different Angles

4.3.2 Effect of Water Flow Rate on Pressure Drop

	DP	DP	DP
Q_w	**θ = -0.1**	**θ = 0.032**	**θ =0.122**
4000	39	78	75
4500	43	80	76
5000	48	82	77
5450	53	84	80
6000	60	88	83
6500	65	91	87
7000	70	93	92

TABLE 7: Effect of Water Flow Rate on Pressure Drop at Different Angles

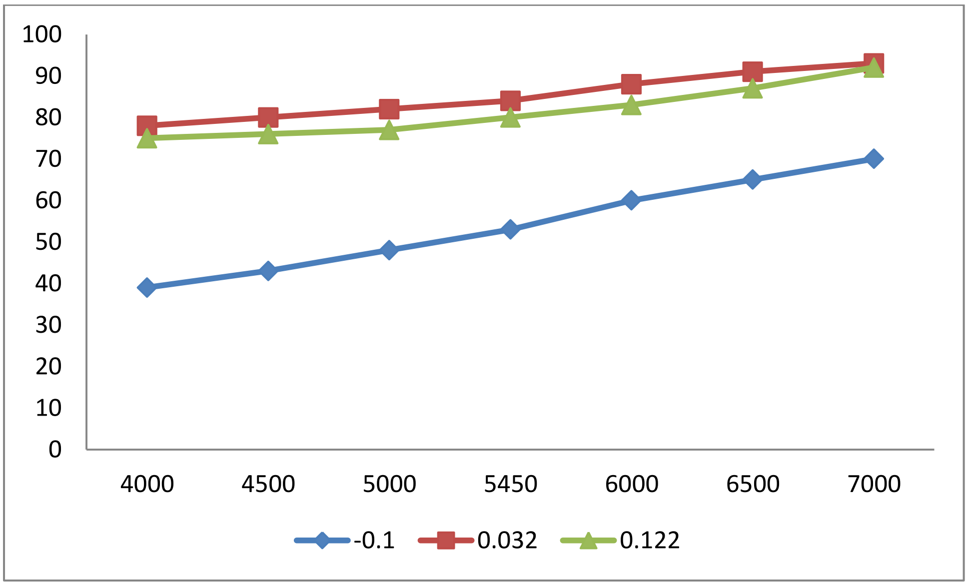

FIGURE 9: Effect of Water Flow Rate on Pressure Drop at Different Angles

From **FIGURE 8** and **FIGURE 9**, the value of pressure drop were observed increases with both oil and water flow rate. These phenomena can be explained based on the general energy equation,

$$\frac{dP}{dL} = \frac{g}{g_c}\rho\sin\theta + \frac{f\rho v^2}{2g_cD} + \frac{\rho v dv}{g_c dL}$$

The flow rate can be expressed as $Q = Av$, where A is the pipe cross-sectional area and v is the flow velocity. Similarly, the flow velocity can be expressed as $v = {}^{Q}/_{A}$.

As the pipe diameter is kept constant (result in constant cross-sectional area), increasing flow rate will increase the flow velocity. In the general energy equation, flow velocity is incorporated in the numerator of the second and the third term, which means that the value of pressure drop is directly proportional to the flow velocity. The pressure drop will increase with increasing flow velocity. Therefore, the trend reflected by the GMDH Model developed is valid for both oil flow rate and water flow rate.

4.3.3 Effect of Length of Flow Line on Pressure Drop

	DP	**DP**	**DP**
L	**θ = -0.1**	**θ = 0.032**	**θ =0.122**
500	32	31	40
2000	41	49	60
5000	51	71	84
7000	53	79	91
9000	54	83	94
12500	56	85	93

TABLE 8: Effect of Length of Flow Line on Pressure Drop

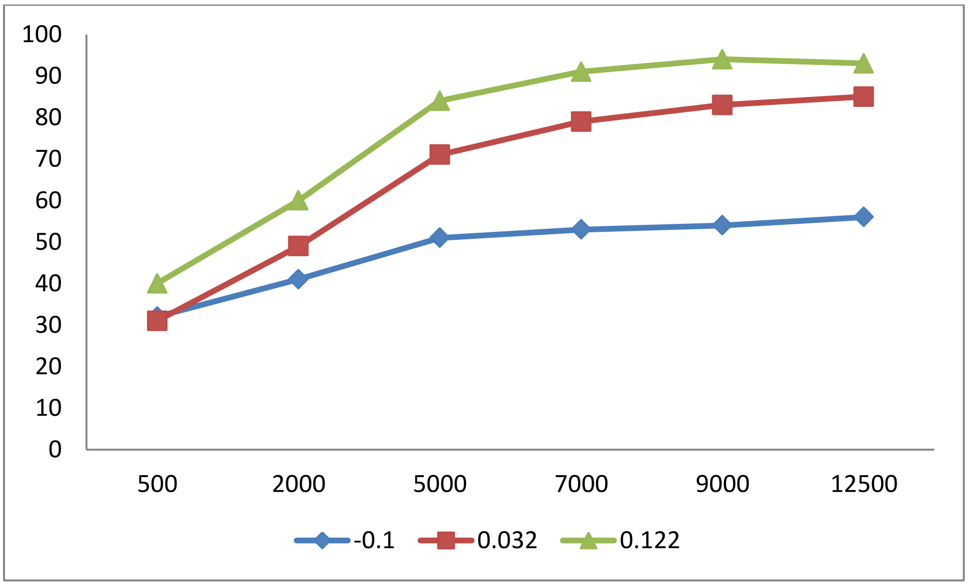

FIGURE 10: Effect of Length of Flow Line on Pressure Drop

From **FIGURE 10**, the pressure drop increases with the length of flow line. The behavior of this curve can be explained based on general energy equation;

$$dP = \left(\frac{g}{g_c}\rho\sin\theta + \frac{f\rho v^2}{2g_cD} + \frac{\rho v dv}{g_c dL}\right)dL$$

From this equation, we can see that the length of pipeline L is directly proportional to the pressure drop. It means that, when the length of the flow line increase, the value of pressure drop will increase as well, which is similar with the trend that GMDH Model posed.

4.3.4 Effect of Wellhead Pressure on Pressure Drop

	DP	**DP**	**DP**
WHP	**θ = -0.1**	**θ = 0.032**	**θ =0.122**
175	26	17	38
200	50	49	63
235	78	84	95
250	88	98	108
300	111	138	146
350	113	157	165

TABLE 9: Effect of Wellhead Pressure on Pressure Drop

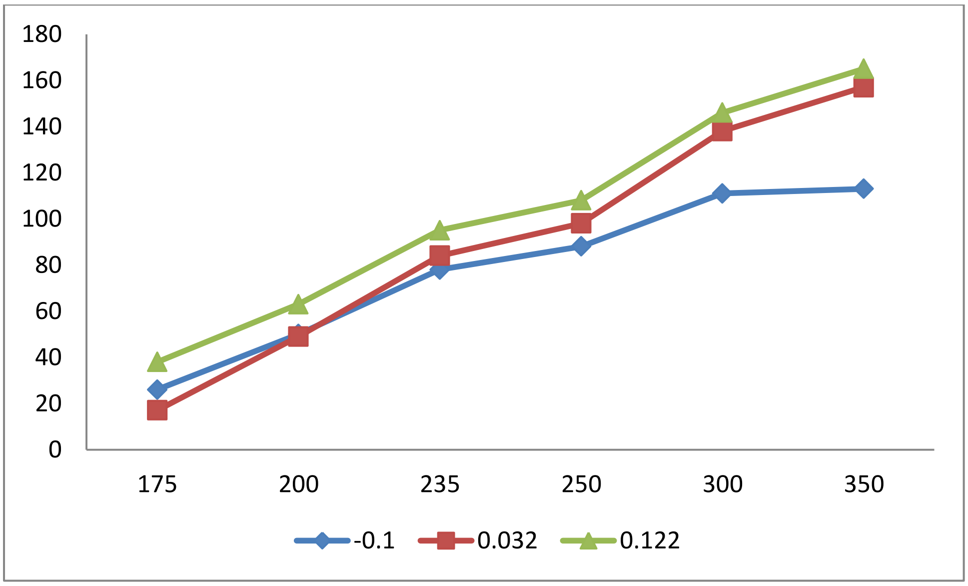

FIGURE 11: Effect of Wellhead Pressure on Pressure Drop

4.3.5 Trend Analysis of Other Correlations

In order to double confirm the validity of the model developed, further trend analysis by other correlations such as Beggs and Brills Correlation, Gomez correlation and Xiao mechanistic model were performed. Results are shown in **FIGURE 12** to **FIGURE 14** as follow.

4.3.5.1 Effect of Oil Flow Rate on Pressure Drop

QO	BEGGS & BRILL	XIAO	GOMEZ
3100	67	38	58
5000	88	57	78
10000	142	102	127

TABLE 10: Effect of Oil Flow Rate on Pressure Drop by other correlations

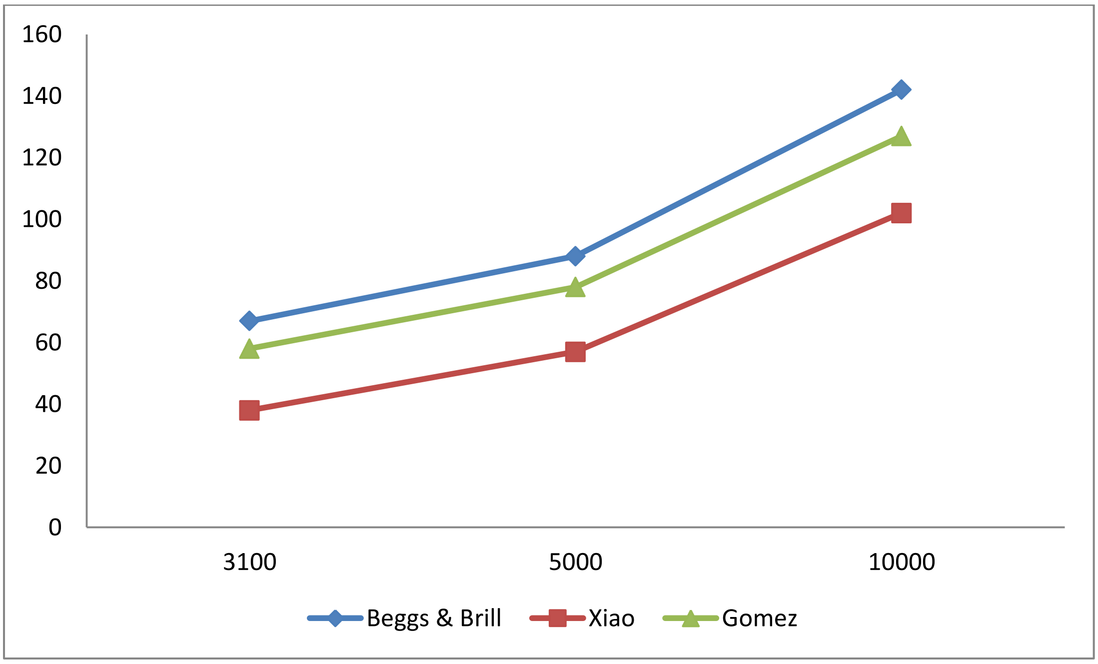

FIGURE 12: Pressure Drop vs. Oil Flow Rate (Beggs and Brill, Gomez, Xiao)

4.3.5.2 Effect of Water Flow Rate on Pressure Drop

QW	BEGGS & BRILL	XIAO	GOMEZ
4000	118	81	108
5500	137	96	126
7000	156	112	145

TABLE 11: Effect of Water Flow Rate on Pressure Drop by other correlations

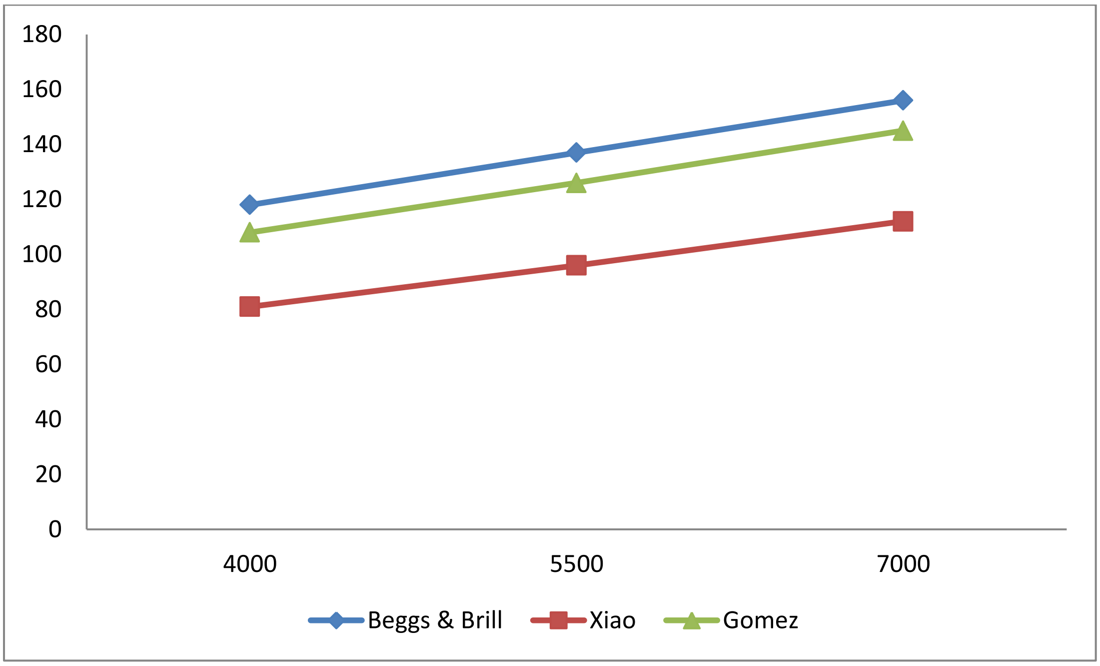

FIGURE 13: Pressure Drop vs. Water Flow Rate (Beggs and Brill, Gomez, Xiao)

The trend analysis of these three correlations satisfies the general energy equation where increase in flow rate will cause the pressure drop become higher.

4.3.5.3 Effect of Length of Flow Line on Pressure Drop

L	BEGGS & BRILL	XIAO	GOMEZ
500	5	3	4
5000	47	29	41
9000	77	49	68

TABLE 12: Effect of Flow line length on Pressure Drop by other correlations

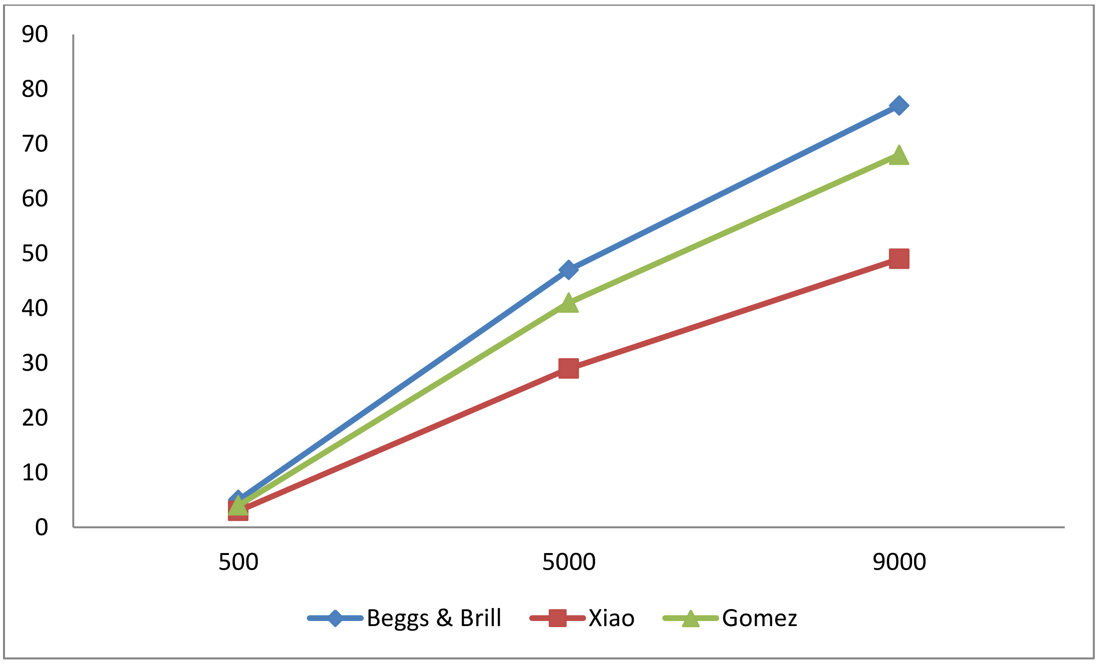

FIGURE 14: Pressure Drop vs. Length of Flow line (Beggs and Brill, Gomez, Xiao)

FIGURE 14 shows that all the correlations satisfy the general energy equation where pressure drop is expected to increase with increased length of flow line.

4.4 Cross Plots

Cross plots between the actual pressure drop and predicted pressure drop by the studied models were generated in order to interpret the precision and the consistency of all individual models. In addition, the coefficient of determination, R2 also can be shown by the linear trend line in these plots. Results are shown in graphs below.

4.4.1 GMDH Model Cross Plot

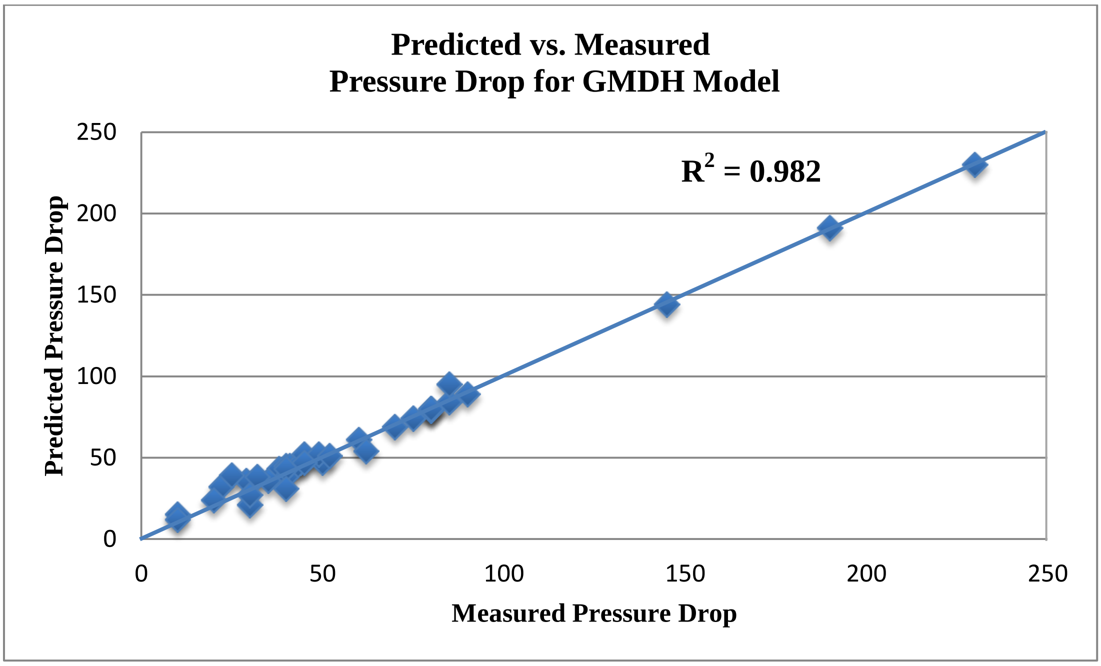

FIGURE 15: Cross plot for Testing set (GMDH Model)

4.4.2 Beggs and Brill Model Cross Plot

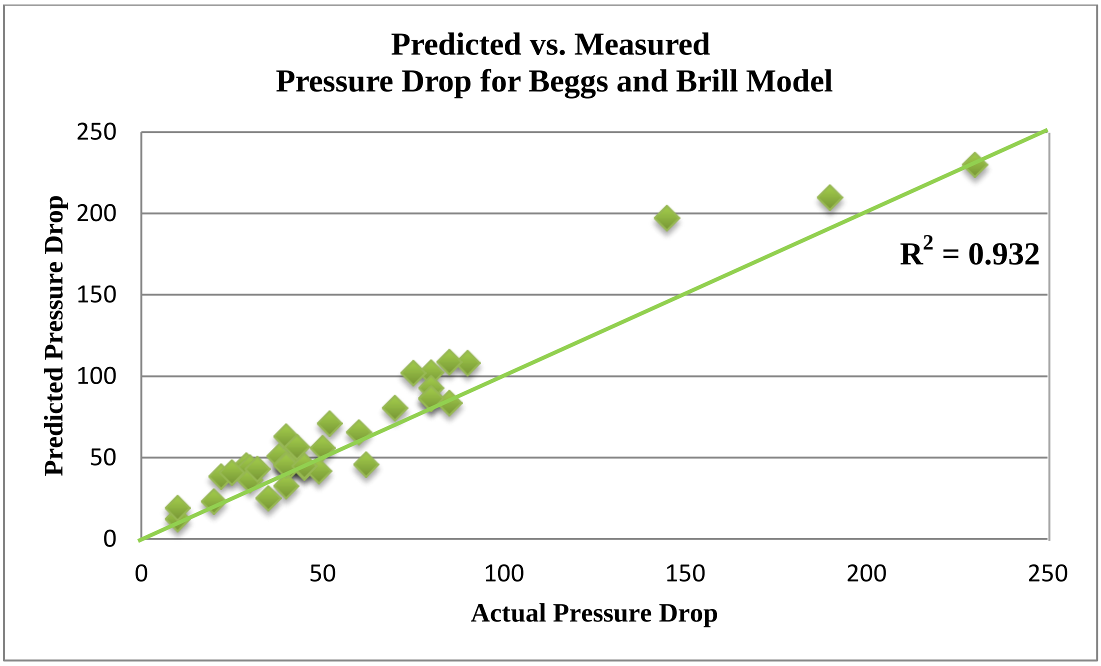

FIGURE 16: Cross Plot for Testing Set (Beggs & Brill Model)

4.4.3 Gomez Model Cross Plot

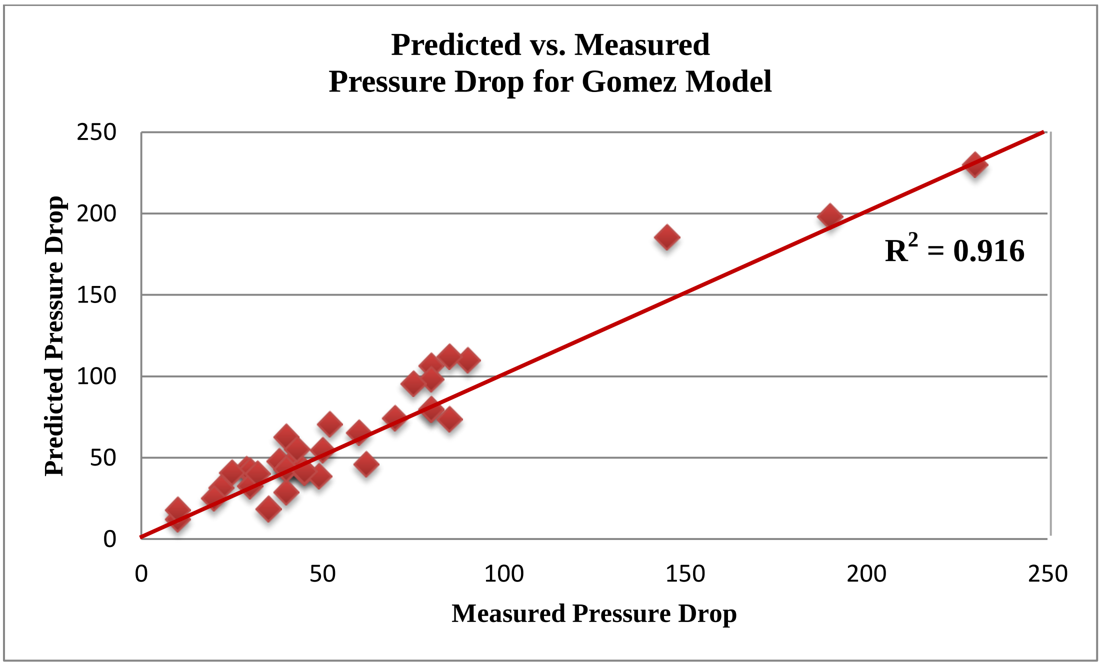

FIGURE 17: Cross Plot for Testing Set (Gomez Model)

4.4.4 Xiao Model Cross Plot

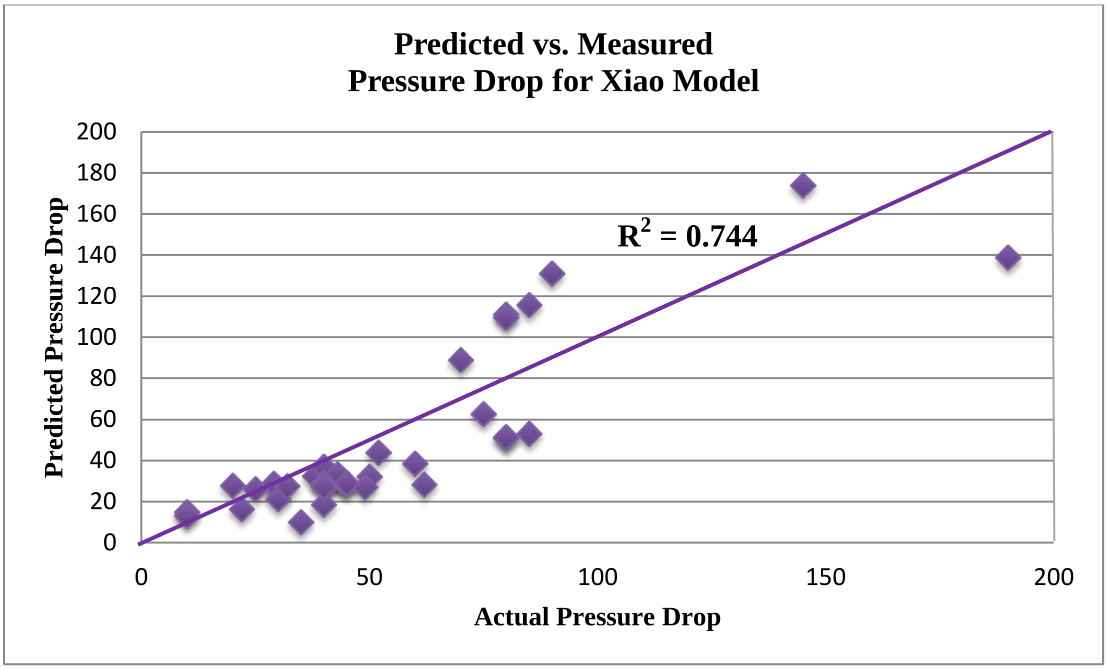

FIGURE 18: Cross Plot for Testing Set (Xiao Model)

Based on the cross plots from **FIGURE 15** to **FIGURE 18**, the following results can be drawn:

- GMDH predict the pressure drop with high accuracy as most of the points touches the line which indicates that predicted pressure drop is equal to measured pressure drop.
- Both Beggs and Brill and Gomez tend to over predict the pressure drop as most of the points plotted fall on the upper part of the line
- Xiao under predict pressure drop as most of the point scattered below the line in the cross plot
- GMDH has the highest value of coefficient of determination, R2 which is 0.982, followed by Beggs and Brill (0.932), Gomez (0.916) and lastly Xiao (0.744)

4.5 Statistical Analysis

The formula that being used to evaluate the model statistically are shown as follow;

Absolute Percentage Error (APE)

$$\text{Abs. Percentage Error} = \frac{|\text{ Predicted Pressure Drop} - \text{Actual Pressure Drop }|}{\text{Actual Pressure Drop}}$$

Average Absolute Percentage Error (AAPE)

$$\text{Average Abs. Percentage Error} = \frac{\text{Abs. Percentage Error}}{\text{No. of Data}}$$

Mean Square Error (MSE)

$$\text{MSE} = \frac{1}{\text{n}}\sum_{\text{i}=1}^{\text{n}}(\text{X}_{\text{predicted}} - \text{X}_{\text{Actual}})^2$$

Root Mean Square Error (RMSE)

$$\text{RMSE} = \sqrt{\frac{1}{\text{n}}\sum_{\text{i}=1}^{\text{n}}(\text{X}_{\text{predicted}} - \text{X}_{\text{Actual}})^2}$$

The statistical analysis was performed for all testing data in Excel files. Findings on the statistical analysis are shown in **TABLE 13** and **FIGURE 19** until **FIGURE 21.**

STATISTICAL ANALYSIS	**MODEL**			
	GMDH	**BEGGS & BRILL**	**GOMEZ**	**XIAO**
TESTING DATA				
Average Absolute Percentage Error (%)	12	26	24	31
Minimum Error, Emin (%)	0	0.27	0.11	1.34
Maximum Error, Emax (%)	56	90.50	80.70	71.43
Mean Square Error, MSE	25.97	241.73	202.81	450.79
Root Mean Square Error, RMSE	5.10	15.55	14.24	21.23
R^2	0.988	0.943	0.938	0.744

TABLE 13: Statistical Analysis of Testing Data

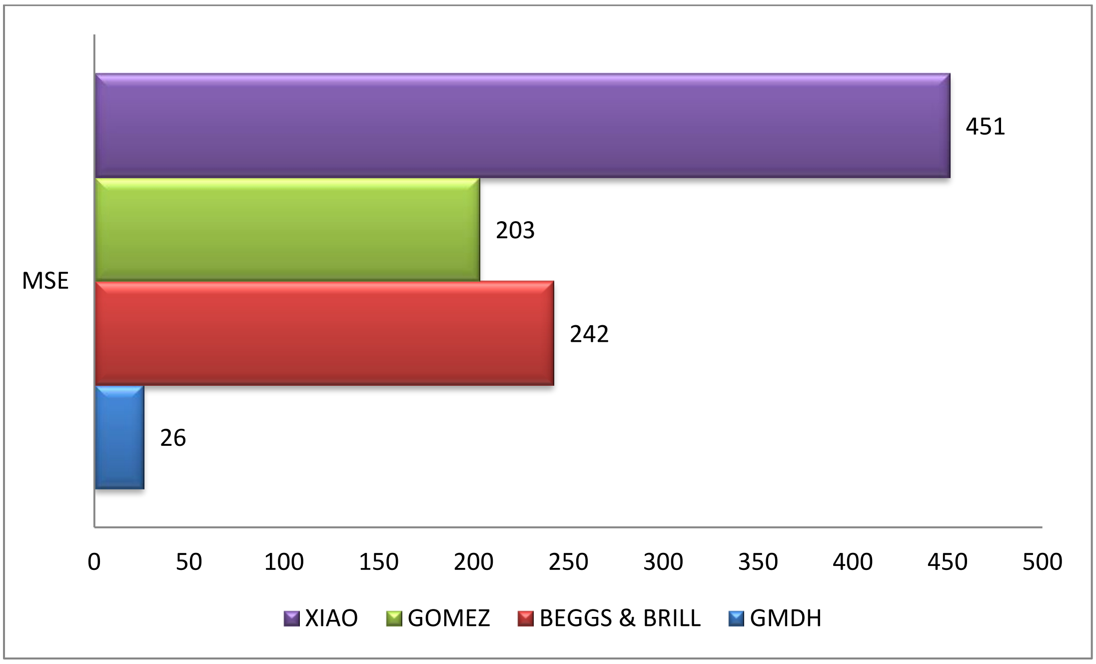

FIGURE 19: Mean Square Error

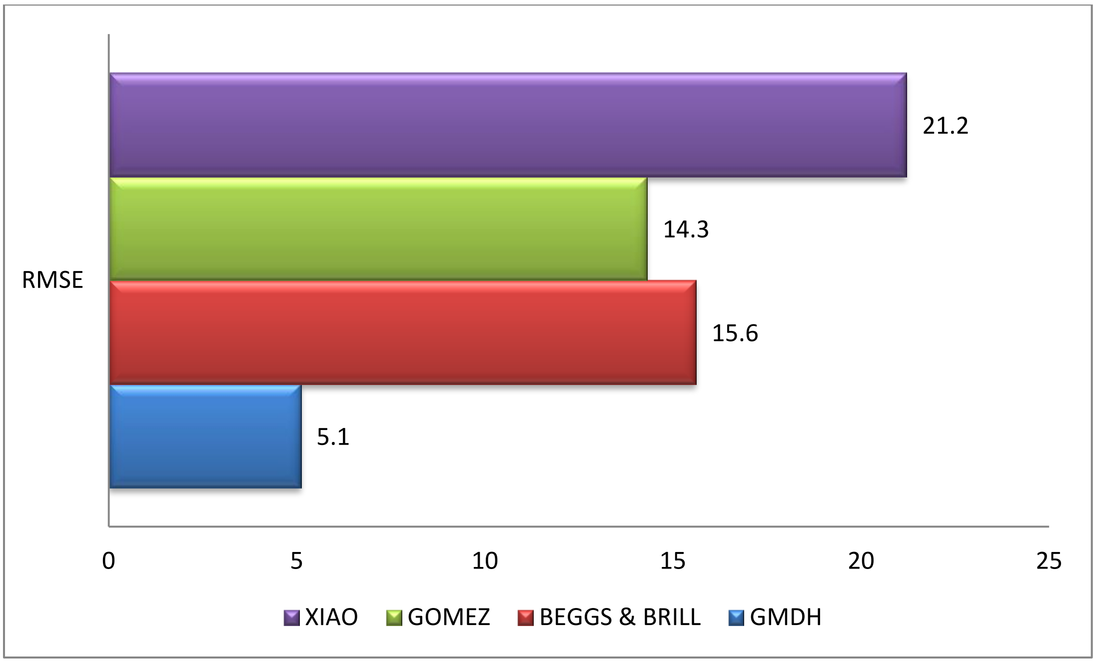

FIGURE 20: Root Mean Square Error

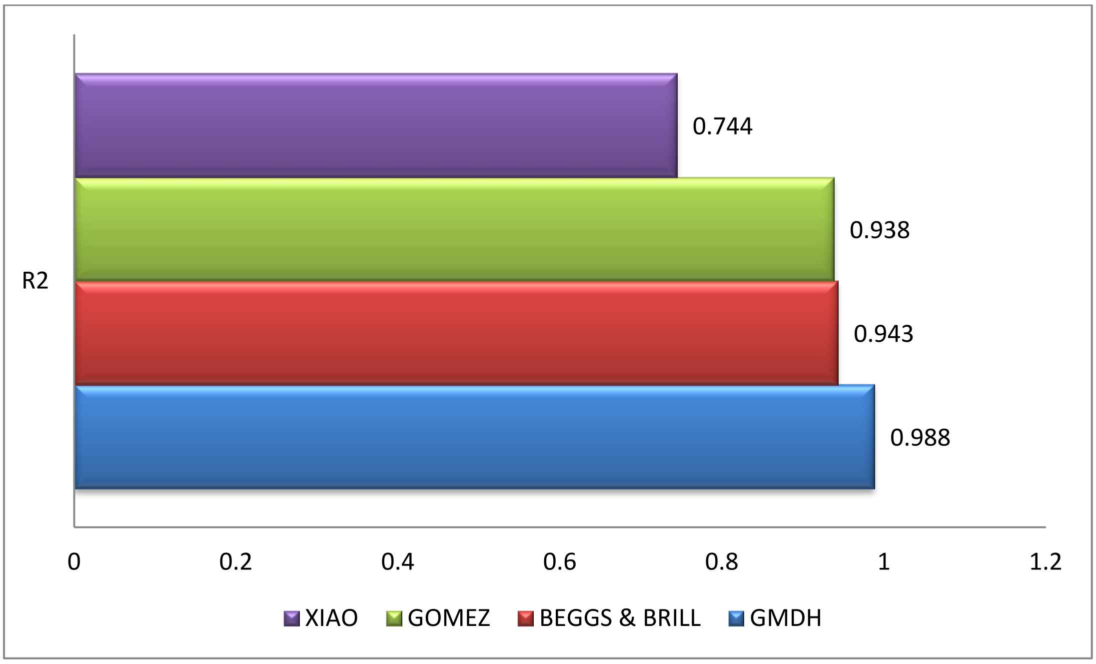

FIGURE 21: Coefficient of Determination, R^2

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

From this study, it can be concluded that the usage of Group Method of Handling Data (GMDH) approach in model development is a great success as the model developed is able to predict the pressure drop during multiphase flow within the flow line. The model develop possess high accuracy of 88% in pressure drop prediction compared with several correlations that are commonly used in oil and gas industry that posses lower accuracy.

The main objectives of this study also had been successfully achieved where this study is able to:

1. Predict the pressure drop during horizontal and near-horizontal multiphase flow with low average percentage of error (12%)
2. Determine all the parameters that affect pressure drop significantly (Oil Flow Rate, Water Flow Rate, Well Head Pressure, and Length of Flow Line)
3. Utilize GMDH Modeling approach
4. Develop a model with high accuracy and low complexity
5. Satisfy the trend of each parameter behaviors

5.2 Recommendation

The author had highlighted some problems that being faced throughout the study and recommend ways to encounter these problems so that better result can be achieved in the future study of GMDH approach.

1. **It is very difficult to develop a model that satisfies the trend of individual parameters.**

During the study, the author has to repeatedly develop a model until that model satisfies the trend posses by individual parameters. In example, a model with high accuracy can be easily achieved but it might be wrong as it may not posses the same trend that particular parameter should posses. Further studies on ways to develop an accurate model that satisfy parameters' trend in the same time must be done to enhance the credibility of the model itself.

2. **Increasing the amount of data to be used prior to model development**

The author believes that the accuracy of the model can be enhanced if the data is sufficient enough to be used to train the model. It also will result in more generalized model as the model will train itself from wide range of data.

3. **Accuracy to model pressure drop can be enhanced for one particular fields by using its own sets of data**

In order to model pressure drop in one particular field precisely, the training data used must be from the field itself. The model developed might be over fit the data, thus not being generalized to be applied to other fields. However, it is more preferable as the accuracy of pressure drop prediction can be enhanced.

4. **Complete facility in Universiti Teknologi PETRONAS to conduct experiments on multiphase flow is very much appreciated.**

   The facilities will sure being utilized to gather all necessary data needed for any simulation purposes. This will also increase the credibility of UTP as a research-based university.

5. **The input of sand production can be incorporated for more realistic pressure drop estimations.**

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