

**UTILIZATION OF MACHINE LEARNING FOR FLOW ASSURANCE IN THE OIL  
AND GAS SECTOR: A FOCUS ON ANNULAR FLOW PREDICTION**

A thesis presented to the Department of Petroleum Engineering

African University of Science and Technology

In partial fulfilment of the requirements for the degree of

**MASTER OF SCIENCE IN PETROLEUM ENGINEERING**

By

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**July, 2021**

## **CERTIFICATION**

This is to certify that the thesis titled “**UTILIZATION OF MACHINE LEARNING FOR FLOW ASSURANCE IN THE OIL AND GAS SECTOR: A FOCUS ON ANNULAR FLOW PREDICTION**” submitted to the school of postgraduate studies, African University of Science and Technology (AUST), Abuja, Nigeria for the award of the Master's degree is a record of original research carried out by IDRIS-IDAHA KAWU MUSA in the Department of Petroleum Engineering.

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By

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A THESIS APPROVED BY THE PETROLEUM ENGINEERING DEPARTMENT

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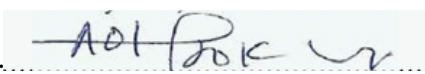
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## ABSTRACT

There is insufficient literature for annular flow and applications of Machine Learning in the petroleum industry; thus, this thesis is centred on annular flow prediction.

Liquid holdup and flow behaviour during annular flow was accurately predicted using the Neural Network toolbox on MATLAB (Machine Learning). The experimental data contained measurements of liquid holdup at three different probes across an air – water system, over a period of 15 seconds. Measurements were noted at intervals of 0.001s; thus, a total number of 15,000 time steps. The superficial gas velocity within the system was changed 17 times (ranging from  $6.17 \text{ ms}^{-1}$  to  $16.05 \text{ ms}^{-1}$ ), while the liquid superficial velocity was constant in all cases ( $0.02 \text{ ms}^{-1}$ ); data exists for 17 different velocities, for the 3 different probes.

Effective neural networks that yielded  $>90\%$  validation accuracy were noted to occur when the architecture was designed to have 10 hidden neurons and greater than 50 delays. An efficient architecture was further solidified by analysis of the “Autocorrelation error” chart; all non-zero lags should be within the confidence limit. This exceptional performance was ascertained via the calculation of average liquid holdup values. The average liquid holdup of experimental and simulated values was noted to be the same or greatly similar, proving accuracy of the implemented neural network design.

This research has proved that the trend in annular flow time series data can be identified by a neural network; further research could be carried out to determine the relevant variables that are needed for accurate liquid holdup computations with time.

Keyword: Neural network, Flow Assurance, Liquid holdup.

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## **DEDICATION**

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# CHAPTER ONE

## INTRODUCTION

### 1.1. Preamble

The term, “Flow assurance”, originated from the Portuguese word; *Garantia do Escoamento*. It has a literal translation of “guarantee of flow”; the guarantee that petroleum would flow efficiently (Total, 2020).

Although Flow Assurance had originally focused on problems associated with solids formation in pipelines, numerous existing literatures now portray Flow Assurance as anticipating and providing or planning for solutions in advance, to any possible problem that could prevent the successful flow of petroleum or its associated forms to a desired point. This subject has gained traction since the 1990s, due to the profitability of petroleum projects being centred on the ability of the desired product to reach a point (Oil & Gas IQ Editor, 2018). Research efforts have intensified as signified by the increasing partnerships between the industry and academia.

*“Cold-flow technology could save the offshore energy industry billions of dollars by preventing flowline blockages that holdup production and prolong the economic life of many field” (Petroleum Economist, 2006)*

*“Companies spend billions of dollars each year to rectify corrosion on offshore platforms, pipelines, and processing facilities” (Jacobs, 2020)*

“To any possible problem” commences from the onset of production from a well, in the Petroleum Industry. As production commences, there thus exists various times where produced fluids are of different states; appropriate management of such times is critical to recovery from reservoirs and thus, profitability of projects. Literatures has thus strongly associated “multiphase flow” to flow assurance. The different phases translate into a flow having different geometric configurations over the period of flow. Such configurations are known as “flow patterns”; annular flow is a type of flow pattern (Oil & Gas IQ Editor, 2018).

The common negative occurrences that occur from the onset of petroleum production include formation of hydrates, formation of asphaltenes, formation of scale, emulsions, wax, sand production, erosion, corrosion.

Various strategies have been developed to guarantee flow. An efficient strategy would include a risk assessment plan as its first step, where the aforementioned possible negative occurrences are tested for. Such a concept is similar to most problem solving methods. Other steps for such a detailed risk assessment plan would include; Sampling, Analysis, Scenario modelling.

Sampling involves fluid data collection. Fluid data is collected from the reservoir and other depths via different methods like logging, coring. Important properties of fluid would include; Pressure, Volume, Temperature, Viscosity, Density (Oil & Gas IQ Editor, 2018).

Analysis involves comprehending the fluid data collected. The company analyses the data for details like water composition, impurities present, salinity levels etc. A PVT (Pressure, Volume and Temperature) test is carried out to enable the observation of the fluid's behaviour under different conditions. Such information would aid the scenario modelling process.

The final step of scenario modelling involves utilisation of the processes data to model possible flow assurance scenarios. The fluid's existing behaviour is obtained and the established parameters are then used to predict the fluid's behaviour at different conditions. The predictions enable anticipating negative situations that could happen and how they would be minimised or avoided (Oil & Gas IQ Editor, 2018).

Sequel to completing a risk assessment plan; developing prevention, remediation and optimisation strategies are the next steps.

Prevention strategies are ideal solutions, as they totally avoid the technical problem (wax, hydrates, scale etc.) and other financial problems could further emanate. An example of such a strategy is the utilisation of chemicals in pipelines. Specific anti-corrosion chemicals have been known to contribute towards sustainable production from oilfields (Oil & Gas IQ Editor, 2018).

Remediation strategies are utilized upon occurrence of the problem. They are designed into an operation from the onset of planning. An example: if this problem happens, a chemical should be released in the pipeline system.

Optimisation strategies involve optimising flow via technologies or processes. Such include the utilisation of automation technologies, engineering simulations, control systems.

All solutions to ensuring flow in the petroleum industry can thus be classified underneath one of the above strategies (Oil & Gas IQ Editor, 2018).

The concept of technological disruption is one that extends to Flow Assurance. Technological disruptions promise increased efficiency and reduced costs. A major technological subject being discussed nowadays is “Machine Learning”.

Machine Learning (ML) is a section of Artificial Intelligence that involves the utilization of a system to implement algorithms in finding trends in data and then automatically making predictions in the future, using that trend obtained. The more training data fed into the algorithm, the more accurate the predictive model could be. A ML model is the result generated when the ML algorithm has been trained (Theobald, 2017).

A rather simple example of ML application is an e-commerce site. Upon viewing a product or reading reviews, other similar products are thus recommended in form of promotions or advertisements. An existing ML model consumes one’s browsing activity and then predicts what the individual could also like (Theobald, 2017).

ML has been generally split into two categories; supervised and unsupervised learning. The difference being that the former involves the training machine via the use of an expected answer, while the later allows for the machine to find some form answer by itself (Theobald, 2017).

A combination of ML and Flow Assurance would enrich the existing literature on all forms of Flow Assurance strategies. ML could be used to accurately predict formation of hydrates, scales, emulsion, multiphase flow behaviour etc.

## **1.2. Problem Statement**

There exists substantial literature on most flow patterns, but not annular flow. Specific research on annular flow and its impact is limited. Utilizing the Neural Network Toolbox in MATLAB to accurately predict liquid holdup and flow behaviour during annular flow would increase available annular flow literature and thus, understanding. In addition, it would provide a foundation for more extensive research to be carried out.

The utilized framework can also be modified as appropriate to fit prediction for other flow patterns.



### **1.3. Aims and Objectives**

#### *Aim*

The research work aims to utilise MATLAB to predict liquid holdup and flow behaviour during annular flow, subsequent to feeding existing multiphase flow data and implementing the design of a neural network system.

#### *Objectives*

The aforementioned aim will be achieved via the below objectives;

- i. Training a neural network via MATLAB using multiphase flow data, to predict liquid holdup during annular flow.
- ii. Validation of outputs against targets to establish accuracy.
- iii. Calculation of frequencies and structure velocities.

### **1.4. Research Justification**

- i. Billions of dollars being expended in the flow assurance due to the uncertainties in anticipating flow patterns. There is thus a need for accurate predictions during the risk assessment planning.
- ii. The ability of MATLAB to predict liquid holdup and flow behaviour during annular flow would be a great positive, as the annular flow pattern could then be forecasted and researched further. This thus enables strategic investments to ensure the relevant data concerning these features are collected and processed appropriately.
- iii. Absence of substantial research on annular flow prediction.

### **1.5. Scope**

The scope of this research entails the utilization of annular flow time series data for algorithm training and then subsequently predicting the liquid holdup and flow behaviour across different time points. The data includes liquid holdup at different times, from fluid flow experiments at the laboratory. MATLAB is utilized as the software for training due to its efficiency and dynamism. Also, liquid holdup is measured by three different probes placed at different points across the conduit.

## **1.6. Organisation of Thesis**

The entails the below chapters;

- Chapter 1 represents the introduction of the Thesis. It answers why this research is being carried out, what will be carried out and the scope of the research.
- Chapter 2 represents a review of existing literature of Machine Learning. Reviews ensure the research gains the best lessons from previous research and attempts to solve actual gaps.
- Chapter 3 represents a review of existing literature on Flow Assurance. Reviews ensure the research gains the best lessons from previous research and attempts to solve actual gaps.
- Chapter 4 represents the methodology utilized in training the MATLAB algorithm to understand the trend in the provided data and thus predict for other different time points.
- Chapter 5 represents the results and discussion of the results obtained from the prediction procedure.
- Other chapters contain conclusion and recommendations.

## CHAPTER TWO

### REVIEW OF MACHINE LEARNING LITERATURE

#### 2.1. Definition of Machine Learning

Machine learning is defined as the process whereby algorithms are utilized to learn from existing data. The ultimate goal of such a process is that a model be developed to accurately understand and eventually predict the data's trends (Theobald, 2017).

The data is popularly known as a "dataset", containing rows and columns. The columns represent features of the data, while the rows represent each data point or observation. Data sets are usually split into three sub-sets; Training set, Test set, validation set. The algorithm is trained on the Training set, its efficiency is tested on the "Test set" and then its accuracy further tested and validated using the "Validation set" (Theobald, 2017).

Algorithms already exist that seek trends in data, subsequently predicting trends from related data. These algorithms have been developed from the knowledge of statistics and mathematics (Theobald, 2017).

Ben-David et al. (2014) referred to ML as "Automated Learning"; programming a machine so that it learns from input data. They also described "learning" as the conversion of experience into knowledge. The learning algorithm is trained by feeding it data; the experience process. The output is "knowledge", which is a program that can carry out the desired task:

Another contributor to existing literature is Nilsson (1998). Nilsson describes ML as a terminology that is difficult to be precisely defined, like "learning". According to him, ML is said to occur when a machine changes its structure in an attempt to improve its performance in the future. A given example is speech recognition device which improves in its function after being fed speech samples: ML is important for the following reasons (Nilsson 1998);

- The inability of humans to define exact relationships between inputs and outputs. It would thus be advantageous if Machines could continuously adapt to determining outputs, when fed inputs.
- It is also possible that relationships observed within datasets, are not the only existing relationships. ML methods are capable of mining such relationships.

- Certain features of the working environment might not be inculcated during the design stage. ML methods enable a machine to adapt to the conditions of its working environment.
- There is a constant update in knowledge concerning tasks and is thus not feasible to constantly redesign machines. ML enables machines to adapt at a faster rate.

## **2.2. Types of Machine Learning**

Ben-David et al. (2014) classified ML into two groups; Supervised Learning, Unsupervised Learning. Their classification systems stem from the concept of the usual learning, which comprises of a learner and the environment.

Supervised learning occurs when the training data contains relevant information, from which new information could also be found for “test examples”. In this case, the environment is the teacher that guides the learner towards the required information (labels) (Ben-David et al., 2014). Unsupervised learning, on the other hand, does not require a difference between the training data and test data. The learner is fed the entire dataset and it then clusters the various groups of data, based on similarities between them (Ben-David et al., 2014). Extra description of unsupervised learning is also provided by Marsland (2015); the algorithms learn from unclassified or unlabelled data. The algorithm goes into a mirage of data without structure; thus being trained by such structure-less data. It then infers a function that could be used to make predictions. Ben-David et al. (2014) also highlighted another type of learning; Reinforcement learning. This involves feeding training data which have a lot of information into algorithms and then extracting a lot more information than originally provided for test examples. Supervised learning has been further classed into two types; regression and classification.

### ***Classification***

In classification, a new dataset is labelled according to the learnings of past datasets. The algorithm learns to recognize certain correlations and is thus able to classify constituents of a data set as appropriate. Examples include; animal detection, fruit classification (Alpaydin, 2010).

## ***Regression***

In regression, the algorithm is trained to identify correlations from previous data sets and then make predictions of numerical results. Examples include; height prediction, real estate price prediction (Alpaydin, 2010).

### **2.3. Machine Learning Algorithms**

Ali et al. (2019) defines algorithms as the step-by-step procedure followed to solve a problem. It involves executing actions in an organized manner, to attain a solution. Computer programs are algorithms. The word “Algorithm” itself is derived from the name of the Arab mathematician, Mohammed Ibn-Musa al-Khwarizmi, who was a major contributor to the field of Algebra.

*“To solve a problem on a computer, we need an algorithm.”* (Alpaydin, 2010)

Alpaydin (2010) defines algorithms in a similar light; steps carried out to process the input to output.

ML Algorithms are procedures that are used to solve ML problems. Some of the algorithms described in this thesis include Linear Regression, Logistical Regression, Random Forest; Gradient Boosted Trees, Support Vector Machines (SVM), Neural Networks, Decision Trees, Naive Bayes.

#### ***Linear Regression***

Linear Regression is a form of supervised learning. The Linear Regression algorithm predicts an output (dependent variable) from a set of independent features and their outputs. It obtains a linear relationship between the dependent variable and independent features.

In training a Linear Regression model, univariate input training data and their corresponding outputs (labels) are fed into the algorithm. The algorithm then obtains the best fit regression line, which provides the best intercept and coefficient values for the equation below:

$$y = \Theta_1 + x \cdot \Theta_2 \quad (2.1)$$

$x$  = univariate input training data

y = outputs

$\Theta_1$  = intercept,  $\Theta_2$  = coefficient

$\Theta_1$  and  $\Theta_2$  are constantly updated to obtain y, the predicted value. The difference between y and its true value from the labelled data (cost function) is minimum. The cost function of linear regression is expressed as seen below:

$$J, \text{ cost function} = \frac{1}{n} \sum_{i=1}^n (\text{predicted } y \text{ value} - \text{actual } y \text{ value})^2 \quad (2.2)$$

For linear regression, the cost function is also known as the Root Mean Squared Error (Gupta, 2018).

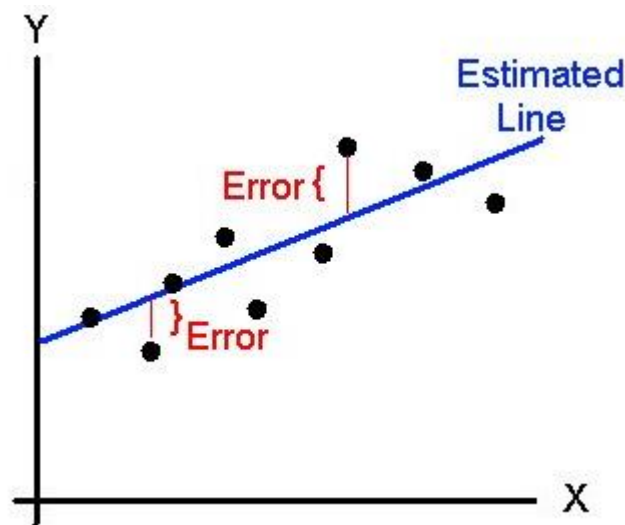


Figure 2.1 – Line of best fit

### **Multiple Regression**

Real life situations have multiple independent variables and such necessitate for a concept of multiple regression. Multiple linear regression algorithm exists to obtain the relationships between multiple independent variables and a dependent variable, by fitting a regression to the dataset. The population regression line for a T number of dependent variables is seen below. It describes how the mean response,  $\gamma_y$ , varies with independent variables.

$$\gamma_y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \dots \dots \beta_T x_T \quad (2.3)$$

The multiple regression model needs to include the variation ( $\epsilon$ ) that results from varying the dependent variable about its means,  $\gamma_y$ . The model thus becomes;

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} + \dots \dots \beta_T x_{iT} + \epsilon_i \quad (2.4)$$

A similar concept of minimizing the error, as in simple linear regression, is then employed (Yale University, 1998).

### *Naïve Bayes Classifier*

This is an algorithm that is based on the Bayes Theorem. It assumes independence amongst the features of a dataset. The presence of a feature has no effect on the presence of another feature; although both contribute towards the result.

The common use of the Naïve Bayes Classifier include; text classification, sentiment analysis, face recognition, weather forecast, text and news classification, google search classification, email spam filtering (Wasserman, 2004).

The Bayes Theorem is described mathematically as;

$$P(A|B) = \frac{P(B|A) \times P(A)}{P(B)} \quad (2.5)$$

$P(A|B)$  is the probability of event A occurring, given event B has happened. Some underlying concepts of the Bayes theorem according to Wasserman (2004) are;

- Probability of an event occurring stems from a belief and is not limited by frequency of occurrence of an event. Therefore, an infinite number of events could be described via probability. The probability of a flow being annular at some point, is determined by the belief that it could be true; not by how many times it has occurred.
- Although fixed, parameters / attributes / features, could also be described using probabilistic statements.
- From a probability distribution, point and interval estimates can be extracted.

In carrying out inference via the utilization of the Bayesian concept, a probability density of a desired attribute is first chosen. This is called the prior distribution. A model that describes the parameter, given the occurrence of another parameter is then chosen. The initial prior distribution is then updated, after other parameters have also been observed. The Bayesian concept thus has a strength of being relevant, with prior information, but its subjective notion of probabilities slightly weakens it (Wasserman, 2004).

## **Advantages**

- It is relatively easy to implement and has high performance when used for multi-class prediction.
- In comparison to other classification algorithms, it requires lesser training data.
- It also performs highly according to Wasserman (2004) when categorical input variables are compared to numerical variables.

## **Disadvantages**

- Underlying assumption of independency amongst parameters or features (Wasserman, 2004).

## ***Support Vector Machine (SVM)***

The SVM is a supervised machine learning algorithm that is used for classification. Subsequent to providing the SVM model with training data, it is able to appropriately categorise the data as appropriate. It was developed in 1992 by Vapnik and has gained traction in modern machine learning, due its high classification performance on moderately sized datasets. The computation of a SVM becomes inefficient, when provided with large training examples.

An SVM, when provided with an appropriately sized dataset, develops a hyperplane that separates the dataset. The hyperplane is a line that optimally separates data points and is also popularly referred to as; the decision boundary. An optimal hyperplane minimises the margins from the different categories. Scattered data points could be linearly inseparable; a new dimension is added, creating a three-dimensional space. The prior mentioned concept could get completed, thus the introduction of “kernels”. The SVM avoids employing the actual vectors but uses the dot products between them, ensuring efficient computations. This concept according, to Marsland (2015), is also used with other classifiers.

## ***Decision Tree***

The Decision tree algorithm is known to uniquely solve regression and classification problems. The basic concept entails an algorithm that predicts a continuous or discrete class or value via learning from decision rules, extracted from training data. Decision trees have been thus grouped into; Categorical Variable Decision Tree and Continuous Variable Decision Tree. The earlier mentioned system of classification is based on the goal or target of prediction. A categorical variable decision tree aims to predict a categorical variable (Yes or No, Annular



Flow or Slug Flow etc.), while the continuous variable decision tree aims to predict a continuous variable (Chauchan, 2020).

The common words associated with the Decision Tree algorithm include;

- Root Node; the entire sample that eventually gets divided into multiple homogenous tests.
- Splitting; the process via which a node is divided into other sub-nodes.
- Decision Node; a decision node is a sub-node that has been divided into other sub-nodes.
- Leaf/Terminal Node; these are nodes that are not divided or split.
- Pruning; the opposite of splitting. Sub-nodes are removed, until a single decision node is left.
- Branch / Sub-tree; A portion of the entire decision tree.
- Parent and Child Node; parent nodes are nodes that are divided into sub-nodes, while child nodes are the sub-nodes resulting from splitting a parent node.

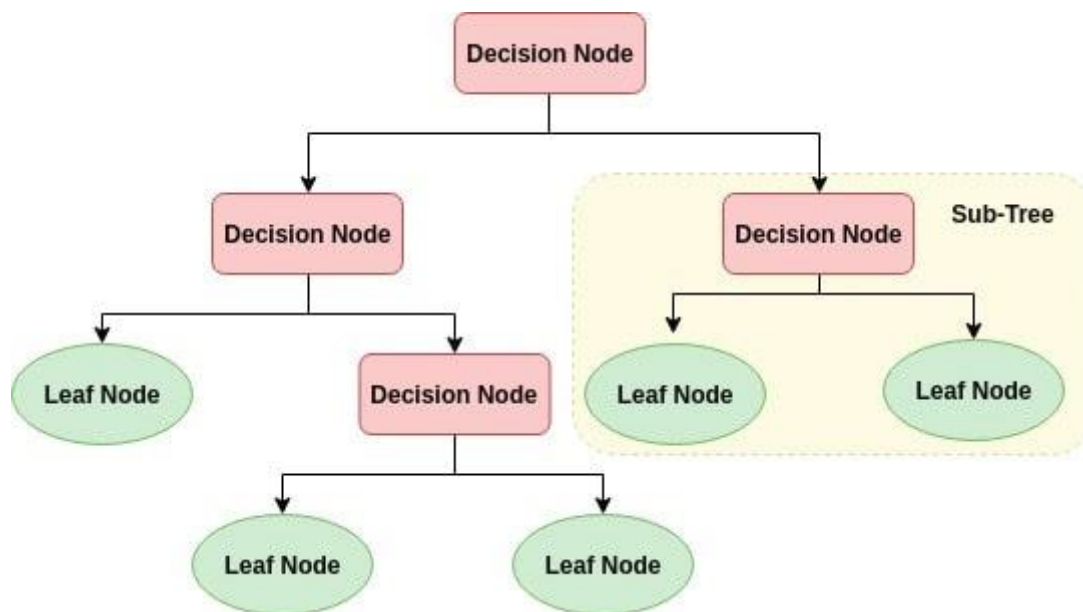


Figure 2.2 – Decision Tree

In Decision Trees, the below assumptions are made;

- Consideration of the entire dataset as the root at commencement of the ML process.
- Its more desired features are categorical. Continuous values are usually discretized.

- Statistical approaches are the mechanisms via which features or attributes are placed as root or internal nodes of the decision tree.
- Recursion is imperative for the distribution of records.

Decision Trees utilise the Sum of Product (SOP) representation, also known as Disjunctive Normal Form. At a leaf node, all branches of the same class are a product of values. A sum results when different branches end in that class (Chauchan, 2020).

Attributes selection is the process via which the appropriate features or attributes are selected as root nodes, at each level. Several measures exist to facilitate such a process. Multiple algorithms exist, that are used to develop sub-nodes. As more child nodes are created, the homogeneity of resulting child nodes increase. The decision trees selects the split of nodes that creates the most homogeneous child nodes. Beyond the need for homogeneity, algorithms are also selected according to the type of target variables. An example is the ID3 algorithm (Chauchan 2020).

### ***ID3 algorithm***

The ID3 algorithm develops a decision tree, via a one-way top-down search approach. It takes the best decision at that point in time, without extensive consideration of past decisions. It commences with the development of a root node, which is the original set. It then iterates through each feature of the set, calculating entropy and information gain of the feature. The feature with the highest information gain or lowest entropy is selected. The original set is then split, to produce subsets via the feature selected in the first step. Recursion is then used by the algorithm on each subset, not taking into consideration previously selected features (Chauchan, 2020).

### **Attribute Selection**

Selecting an attribute is a complicated process. Researchers have recommended the certain criteria discussed.

- Entropy

Entropy refers to the degree of randomness within data. The ease of analysis of data increases with decreasing entropy. The ID3 algorithm operates based on the entropy notion; a branch having an entropy of zero is considered as the “leaf node” and splits branches with entropies of more than zero (Chauchan, 2020).

$$E(S) = \sum_{i=1}^c -p_i \log_2 p_i \quad (2.6)$$

S = current state

$p_i$  = Probability of an event  $i$  of state S or Percentage of class  $i$  in a node of state S.

For multiple features,

$$E(T, X) = \sum_{c \in X} P(c) E(c) \quad (2.7)$$

- Information Gain

The Information Gain is a statistical tool used to measure how effective a specific feature splits the training examples, based on the goal. Information gain according, to Chauchan (2020) corresponds to a reduction in entropy. The ID3 algorithm also uses Information gain. Mathematically,

$$IG = E(\text{Before splitting}) + \sum_{j=1}^k E(j, \text{after}) \quad (2.8)$$

- Gini Index

The Gini Index is a cost function utilised for evaluation of a dataset after it has been split.

$$Gini = 1 - \sum_{i=1}^c (p_i)^2 \quad (2.9)$$

From the mathematic function above, the Gini function will be biased towards classes with higher probabilities. Homogeneity is directly proportional to the Gini Index.

The Gini function is the primary tool utilised by another Decision Tree algorithm, CART (Classification and Regression Tree), in splitting nodes (Chauchan 2020).

- Gain Ratio

The Gain Ratio is an advancement over Information gain. It corrects for its tendency to be biased towards features having distinctly large values. It considers the branches that would result from splitting, before splitting (Chauchan, 2020).

$$GR = \frac{IG}{\text{Split information}} = \frac{E(\text{Before splitting}) - \sum_{j=1}^k E(j, \text{after})}{\sum_{j=1}^k w_i (\log_2 w_i)} \quad (2.10)$$

- Variance Reduction

Reduction in variance algorithm is usually used for regression. The best split of a dataset is chosen, by reducing the variance to minimum (Chauchan, 2020).

$$\text{Variance} = \frac{\sum (x - \bar{x})^2}{n} \quad (2.11)$$

- Chi-square

CHAID is the abbreviation for Chi-squared Automatic Interaction Detector. It represents the statistical significance between the differences in the parent node and child node. The significance is equal to the sum of squares of the differences between the actual target features and forecasted. This is usually applied for categorisation problems (Chauchan, 2020).

Mathematically,

$$\chi^2 = \frac{\sum (O - E)^2}{E} \quad (2.12)$$

A common problem with Decision Trees is over fitting. This results in inaccuracies when attempting to predict from unknown datasets, not originally part of the training dataset. Solutions include; Pruning and utilization of an advanced algorithm called “Random Forest” (Chauchan, 2020).

### ***Random Forest***

The Random Forest is an algorithm that could be used for both regression and classification, although it is mostly used for classification. Breiman is reported to have created this algorithm. The Random Forest algorithm creates multiple decision trees from a dataset, then makes a prediction based on the most responses provided by the decision trees. As earlier stated, it solves the problem of over-fitting in decision trees. Another accurate definition of random forest is; a classifier “consisting of a collection of decision trees, where each tree is constructed by applying an algorithm A on the training set S and an additional random vector where the

vector is sampled from some distribution”. The prediction of the random forest is obtained by a majority vote over the predictions of the individual trees.

The motivation for such a concept is that a decision tree would create good predictions, but multiple decision trees would create better. If one decision tree produces errors in prediction, the predictions of other decision trees would eventually eliminate the error of that tree. The name “Random” results from the random nature in which trees are built and the randomness of subsets when nodes are split. The randomness with which trees are created, sparks the continuous interest in this algorithm. There exist two methods via which the randomness is ensured: Bagging (also known as Bootstrap Aggregation) and Random feature selection (Yiu, 2019).

- Bagging

This is the process where every individual decision tree would develop trees based on random sampling from the original dataset while, on the other hand, also taking replacements. The original dataset does not break up into smaller subsets, and each tree is developed from each sub-set. All decision trees created, on the contrary, are fed, according to Yiu (2019), a training sample from the original dataset with a replacement.

- Random Feature Selection

Different decision trees by this method are created from an original dataset after randomly testing its sub-features; this thus results in increased diversity between decision trees. There is an increase in randomness via this method, as the trees can only select from the subsets. It is also quicker, as there are lesser attributes to iterate over (Yiu 2019). Both earlier mentioned methods intend to minimize variance, while also evading overfitting. Furthermore, shortening is circumvented. More trees can be formed till the decrease in prediction error is minimal (Yiu, 2019).

### ***Deep Learning (DL)***

Deep Learning is perhaps the most stimulating branch of Machine Learning. It is implemented in numerous technologies, like self-driving cars, software translators. Via DL, extreme accuracy in predictions is possible. Several Deep Learning models include; Artificial Neural

Networks, Convolutional Neural Networks, Recurrent Neural Networks (RNN), Deep Boltzmann machines, Auto Encoders.

### Artificial Neural Networks (ANN)

Artificial Neural Networks or ANN is a model that aims to mirror information processing by the brain. Neural networks are also called perceptron. It is made up of “neurons” linked to each other. Neurons are simple and made up of a cell and wires. They await incoming signals from other neurons, through the appropriate wires. Such wires are called dendrites (terms are borrowed from biology). Upon receiving signals, neurons may sometimes be “activated” resulting in signals being transmitted to other neurons. The wires via which outgoing signals are transmitted, are known as axons. Thus, they receive input and process for output. The point of connection between axon and dendrite is called “synapses”. The strength of an ANN model depends on the connections between its neurons (Hagan et al., 2014).

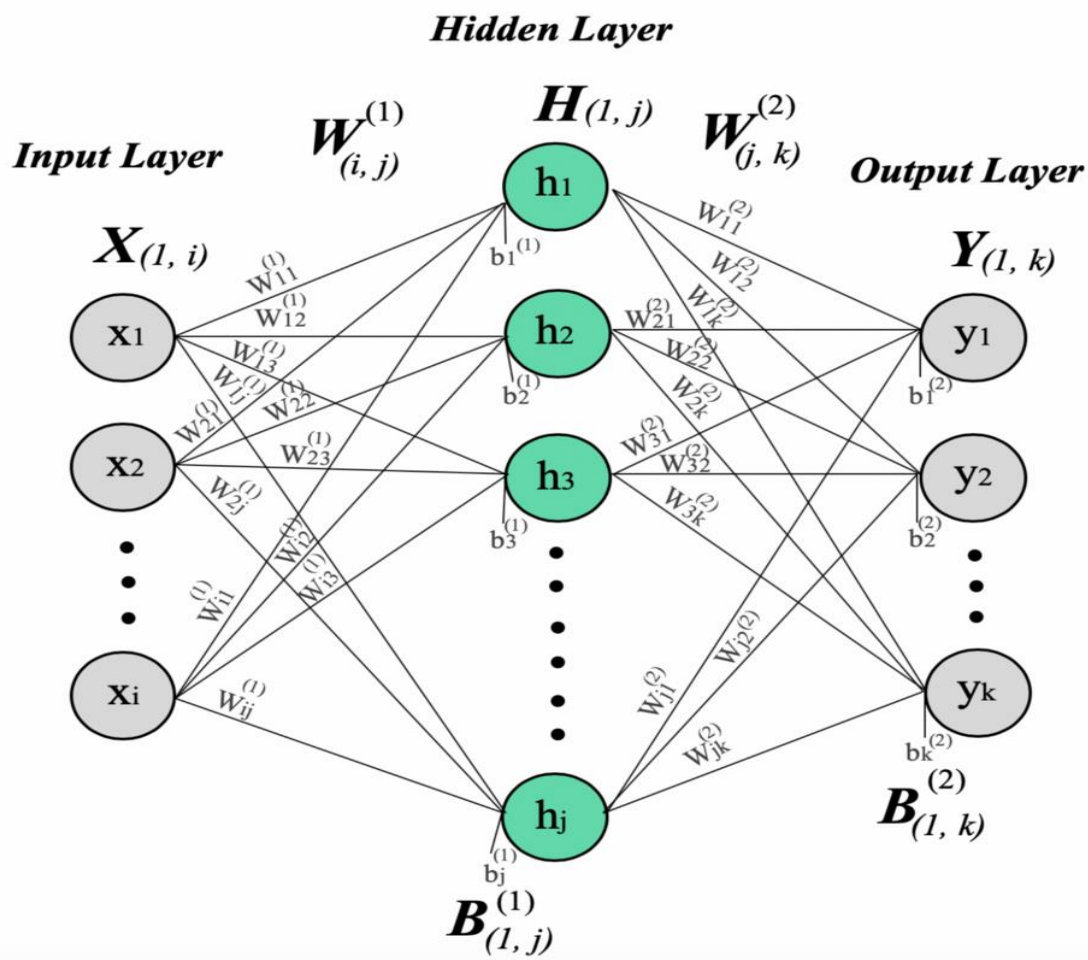


Figure 2.3 – ANN Architecture

## **Activation Function**

The Activation Function of a neuron determines if the neuron will be “fired” or not. In detailed terms; if the neuron would pass on a signal. This occurs via a calculation of the weighted sum and adding some bias to the result. The bias is added, to introduce non-linearity into the signal that is transmitted. Without the bias, a linear function would result from the neuron and would not be able to model complex data. Rather, the one-dimensionality would restrict it to simple or easy data (Izaugarat, 2018).

- Threshold activation function

For this type of activation function, a decision on transmitting a signal is dependent on a certain threshold. If the input signal is above the threshold, the neuron is “fired” and outputs the exact signal to the next layer (Luhaniwal, 2019).

- Sigmoid Activation function

The Sigmoid Activation function is a mathematical function used for problems that require its solutions, in forms of probabilities. The Sigmoid function itself is S-shaped, having a maximum of 1 and minimum of 0 (Luhaniwal, 2019).

- Hyperbolic Tangent function

The Hyperbolic Tangent function is also a mathematical function like the sigmoid function but ranges from 1 to -1 (Luhaniwal, 2019).

- Rectified Linear Units

This is the most efficient activation function, ranging from 0 to infinity. This function is only applied to hidden layers, while outputs could utilize other functions (Luhaniwal, 2019).

## **Methods of Adjusting Weights**

- Brute-force Method

It is optimal when used in a single-layer feed-forward network. The optimal weight is selected, after elimination of all other weights; the most minimal weight (the weight situated at the

bottom of the curve) is the optimal weight. This method is easily affected by Dimensionality (Mayo, 2017).

- Batch-Gradient Descent

The Batch-Gradient Descent is a first-order algorithm that iterates through the data using various angles of the function line. For a negative slope, it goes down the curve and for a positive slope, it goes upwards. It is only effective, for a convex-shaped curve (Mayo, 2017).

- Stochastic Gradient Descent

For non-convex shaped curves, the Stochastic Gradient is used instead. Rather than iterating through the entire data as in the Batch-gradient Descent, a portion of the original sample is selected based on random probability. It is faster than the Batch-Gradient Descent (Mayo, 2017).



## CHAPTER THREE

### REVIEW OF FLOW ASSURANCE LITERATURE

This research work focuses on the “Multiphase Flow” aspect of Flow Assurance.

#### 3.1. Definition of Multiphase Flow

There exist various definitions across literature, albeit similar. Michaelides et al. (2017) defined multiphase flow as the simultaneous flow of more than one fluid phase through porous media. Karen Tay defines multiphase flow as the simultaneous flow of materials with very distinct velocity fields in each phase (Tay, 2017).

An analysis of the various definitions from existing literature insinuates the constant presence of terminologies like “distinct phases”, “simultaneous flow”. In this thesis, multiphase flow is simply defined as flow consisting of different phases. Such a scenario would intuitively be difficult to predict or model, due to the different characteristics of various phases. Moreover, occurrences below the surface have always been characterised by a huge degree of uncertainty. An example is a flow consisting of gas, crude oil (liquid), water (liquid) and sand particles (solid); it thus becomes important to understand the various characteristics of the phases, at various operating conditions. The solid phase is usually transported by other phases of the flow, in form of lumps and particles. Its flow is thus dependent on the size of the solids and the motion of other phases. The liquid phase could either be a continuous or discontinuous phase, depending on velocity. As a continuous phase, other elements are dispersed in it. The liquid is suspended in other phases, if it's the discontinuous phase. The gas phase is also similar to the liquid phase, with the distinct difference being the high compressibility of gas (Sun, 2017).

#### 3.2. Important Concepts in Multiphase Flow

##### *Superficial Velocity*

Superficial Velocity of a fluid is defined as the volumetric flow rate of the fluid divided by the cross-sectional area in which the fluid is contained. The term “superficial” is similar to

“hypothetical”; it assumes the fluid being described is the only fluid in discussion. This term was invented due to the difficulty in calculating velocities of multiphase flows across different points. Superficial velocity is simpler to calculate and assumed to be constant over a distance (Sun, 2017).

### ***Liquid Holdup***

Geocities (2015) defined liquid holdup as the percentage or fraction of a pipe occupied by the liquid phase, at the same instant. Liquid holdup is an essential calculation, due to it being required for other calculations; heat transfer, mixture density, effective viscosity. The value thus ranges from 0% or 0 (in single-phase gas flows) to 100% or 1 (in single-phase liquid flows). Liquid holdup is measured via several experimental methods; resistivity probes, capacitance probes, trapping a segment of the flow stream between quick closing valves and measuring the volume of liquid trapped (Geocities, 2015).

“Void fraction” is a term that is used instead of “Liquid Holdup”, usually. It represents the fraction of pipe occupied by gas. It is thus the “Liquid Holdup” subtracted from 1.

Geocities (2015) further explicitly states that liquid holdup cannot be determined analytically. Liquid holdup is a function of the following variables; flow pattern / regime, pipe characteristics (roughness, diameter), fluid properties (gas & liquid).

### ***Flow Patterns***

Flow patterns refer to the geometric distribution of individual phases in a multiphase flow. Various flow patterns have been identified via different methods, visual inspection, advanced technologies. The differences in the geometric distributions of the individual phases result in differences in properties like velocity, void fraction, holdup. Numerous attempts have been made to classify the different flow patterns.

The determination of flow patterns in the Oil and Gas Industry is of utmost importance. Flow patterns are used to determine the pressure drops for flows from the reservoir through the wellbore, to the surface and beyond. Numerous efforts have thus been made to identify such patterns (Azzopardi, 2010).

- Visual observation

Fluid flow is observed in transparent tubes and the arrangements / configurations are identified. It is inevitable that infinite different configurations or arrangements would be noted from observing flows in a tube. This is thus a subjective method and has always resulted in confusion. Some arrangements would be repetitions; others could be a type of other configurations. Pragmatism and a detailed level of understanding requires agreements in descriptions.

Other limitations of this method are the fluid velocity and diameter of the tube. Flow can be reliably observed if the fluid velocity is moderate but becomes less reliable at higher fluid velocities. Also, only the flow near the wall of the tube can be observed if the tube is wide. Innovations like high-speed photography have been used to aid observation at high fluid velocities (Azzopardi, 2010).

- X-rays

X-ray tomography are used to measure the void fractions over a period, at a point of the cross-sectional area of the pipe. A frequency of the occurrence of each void fraction recorded is then plotted; also known as Probability Density function graph. Various flow patterns have their established PDFs.

It has been noted that certain flow patterns exist in horizontal flow, but not in vertical flow and vice versa. A classification system according to the direction of flow is thus commonly utilised (Azzopardi, 2010).

### ***Vertical Flow in Pipes***

- Bubbly flow

This a flow pattern characterized as having the liquid as its continuous phase and the gas (bubbles) as the dispersed phase. These bubbles are of varying sizes and their motions are difficult to characterize. Furthermore, bubble flow has sometimes been split into two sub-patterns: wall-peaking and core-peaking flows. The former is said to occur when the bubbles congregate at the walls of the pipe, while core-peaking flows are said to occur when the bubbles congregate at centre of the pipe.

Bubbly flow has also been divided into discrete bubbly and dispersed bubbly. Discrete bubble occurs at low liquid velocities, with the bubbles being generated at the gas distributor or in the

process of nucleate boiling. Dispersed bubbly occurs at high liquid velocities, with large bubbles breaking down into smaller bubbles (Azzopardi, 2010).

- Plug flow

Plug flow is also known as slug flow. It occurs when bubbles coalesce and thus, result in an increase in the size of the bubbles. The resulting bubbles are shaped like bullets. These bubbles are called Taylor bubbles. The Taylor bubbles occupy most of the pipe and are surrounded by films of liquids. Smaller bubbles are also located in the liquid slug between the huge Taylor bubbles. Recent literature shows that plug flow is limited to relatively small diameter pipes (< 150 mm), rather flow transitions from bubble to churn flow (Azzopardi, 2010).

- Churn flow

A churning flow pattern is noted at higher velocities. It is usually characterized by oscillatory fluid motion resulting from breakdown of Taylor bubbles. It is sometimes referred to as semi-annular flow when it occurs at higher gas velocities. Plug and churn flow patterns are often collectively referred to as intermittent flow (Azzopardi, 2010).

- Annular flow

Azzopardi (2010) described annular flow as the flow pattern where liquid travels as a film on the walls of the pipe. In some cases, the liquid also exists as drops in the central gas core. Such a pattern is also referred to as mist flow. “Wispy annular flow” is also used in certain cases; at high liquid flow rates, the concentration of liquid droplets in the central gas core is extremely high resulting in tendrils of the liquid being evident.

Another description of annular flow is provided below.

Annular flow, also known as channel flow, is a type of multiphase flow that is said to occur in a pipe when the lighter fluid occupies the centre of the pipe and the denser fluid flows occupies the walls of the pipe as thin film. In the context of oil and gas, gas would be at the centre while water or oil flows as a thin film over the walls of the pipe. In a scenario where flow core

contains entrained liquid droplets, the flow is usually referred to as “annular-dispersed” flow, while it is called “pure annular” flow in the absence of entrained liquid droplets. Also, both flows of the near-wall liquid film and gas core are characterized as concurrent and countercurrent. The void fraction of annular flow has been known to be greater than 75-80% (Azzopardi, 2010).

### ***Horizontal Flow in Pipes***

The flow patterns noted in vertical flows, in addition to stratified flow patterns, are the flow patterns noted in horizontal flows.

- Stratified flow

In the Stratified flow pattern, the densities of the phases is at the bottom of the pipe; density of the phases is the property that determines how the phases are configured. The stratified-flow pattern is further divided into two sub-patterns; stratified-smooth and stratified-wavy.

Stratified-smooth is characterized by a gas-liquid interface that is smooth. It occurs at lower gas rates than the stratified-wavy pattern. In the stratified-wavy flow pattern, the interface is wavy due to the higher gas rates (Azzopardi, 2010).

- Intermittent flow

In horizontal flow, intermittent flow is made up of two categories: slug and elongated bubble patterns. The elongated bubble pattern is known to contain large sized bubbles in the upper zone of the liquid phase, while the slug flow pattern is characterized by having both large and small bubbles of gas (Azzopardi, 2010).

Costigan and Whalley (1997) combined the PDF concept and segmented impedance electrodes to establish six flow patterns: discrete bubble, spherical cap bubble, stable slug, unstable slug, churn and annular flow. The descriptions of the flow patterns are stated below;

- The discrete flow is portrayed by a PDF having single peak at low void fraction.
- The spherical cap bubble is portrayed by a PDF that has a single peak at low void fraction and then a tail that extends.

- The slug flow is portrayed by a PDF that has two peaks. One peak is at a low void fraction and the other is at a higher void fraction.
- The churn flow is portrayed by a PDF that has a single peak at high void fraction and then a tail that extends.
- The annular flow shown in Figure 3.1 is portrayed by a PDF that has a single peak at high void fraction.

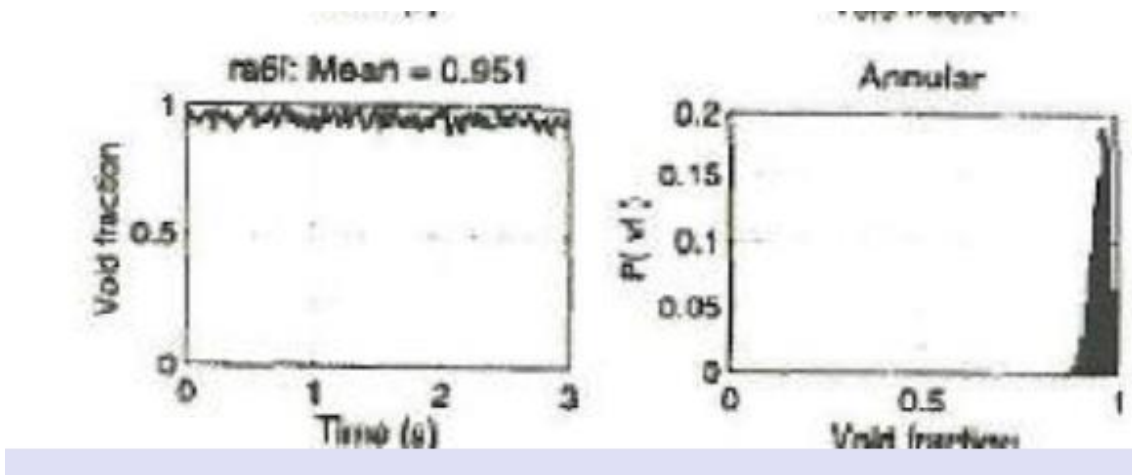


Figure 3.1 – Annular Flow PDF

### *Flow Pattern Maps*

- Hewitt and Roberts

Hewitt and Robert developed a flow pattern map shown in Figure 3.2 using water/air flows in small diameter pipes. The original map was developed under various pressure conditions (See Table 3.1) and in British Units. It has since been changed to SI units by several authors (Hewitt et al., 1969).

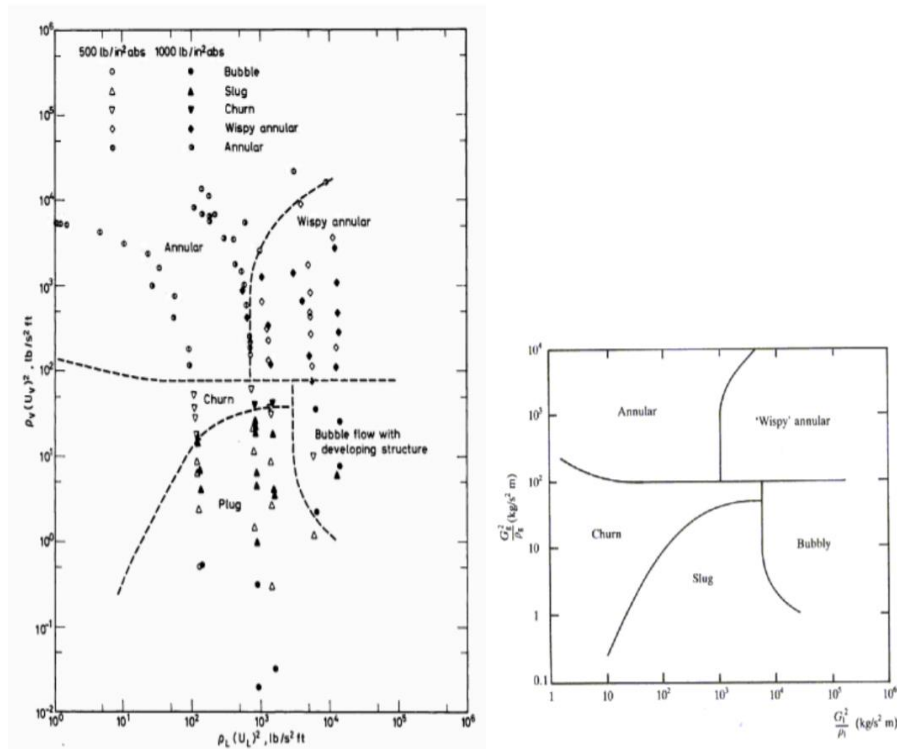


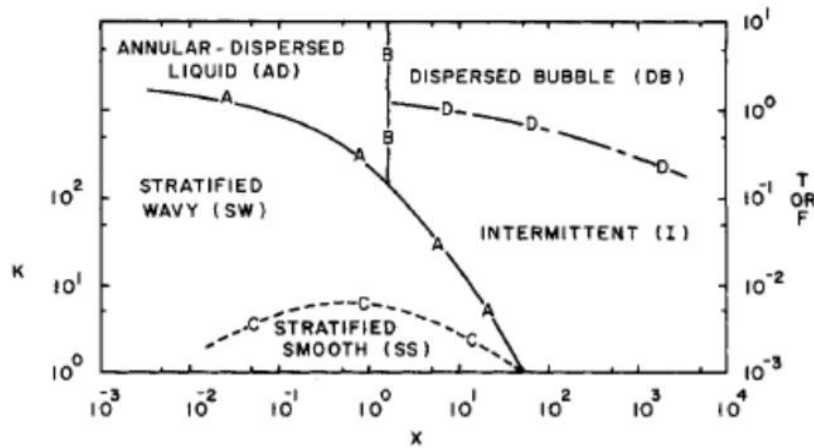
Figure 3.2 – Hewitt and Roberts Flow Pattern Map

Table 3.1 – System Characteristics

Pipe characteristics	
Length of pipe, m	0.3
Diameter of pipe, mm	31.75
Pressures at mixing zone	
Absolute pressure, Pa	$14.27 \times 10^4 - 54.26 \times 10^4$
Relative pressure, Pa	$4.14 \times 10^4 - 44.13 \times 10^4$
Temperature Range	
Gas Temperature, °C	18.9 – 25.3
Liquid Temperature, °C	20.8 – 32.5
Range of Flow rates	
Gas, kg/h (Air / Steam)	1.36 – 544.3
Liquid, kg/h (Water)	226.8 – 8164.7
Range of Densities	
Gas, kg/m <sup>3</sup> (Air / Steam)	1.68 – 6.4
Liquid, kg/m <sup>3</sup> (Water)	992.2 – 997.8

- Taitel and Dukler (1976)

The Taitel and Dukler map shown in Figure 3.2 was developed in 1976 and is the most common flow pattern map for horizontal two-phase flows. It is of a semi-theoretical origin and thus more difficult to use in comparison to other maps. On the x-axis is the Lockhart–Martinelli parameter and the y-axis, K and F (empirical constants) (Taitel et al., 1976).



Taitel and Dukler's map for horizontal tubes (Taitel and Dukler, 1976).

$$X = \left[ \frac{\frac{4C_L (u_{LS} D)^{-n} \rho_L (u_{LS})^2}{D (v_L)}}{\frac{4C_G (u_{GS} D)^{-m} \rho_G (u_{GS})^2}{D (v_G)}} \right]^{1/2} = \left[ \frac{|(dP/dx)_{LS}|}{|(dP/dx)_{GS}|} \right]^{1/2}$$

$$F = \sqrt{\frac{\rho_G}{\rho_L - \rho_G}} \frac{u_{GS}}{\sqrt{Dg \cos \alpha}}$$

$$K = F \left[ \frac{D u_{LS}}{v_L} \right]^{1/2} = F [Re_{LS}]^{1/2}$$

Figure 3.2 – Taitel and Dukler Flow Pattern map

This map was developed for Newtonian liquid-gas mixtures and constants used repeatedly are for turbulent liquids and gases. Also, the hydraulic gradient in the liquid is assumed to be negligible at transition conditions (Taitel et al., 1976).

- Griffith and Wallis's (1959) map

Griffith and Wallis's developed a map shown in Figure 3.3 in 1959, although specifically targeted for slug flow in vertical conduits. It is reliable for such conditions presented in Table 3.2, but unreliable for others due to lack of other experimental points. On the x-axis of this map is  $N_{f_{fm}}$  and a ratio of flow rates on the y-axis.



$$x - axis ; \frac{(Q_l + Q_g)^2}{gD_p} \quad (3.1)$$

$$y - axis ; \frac{Q_g}{Q_l + Q_g} \quad (3.2)$$

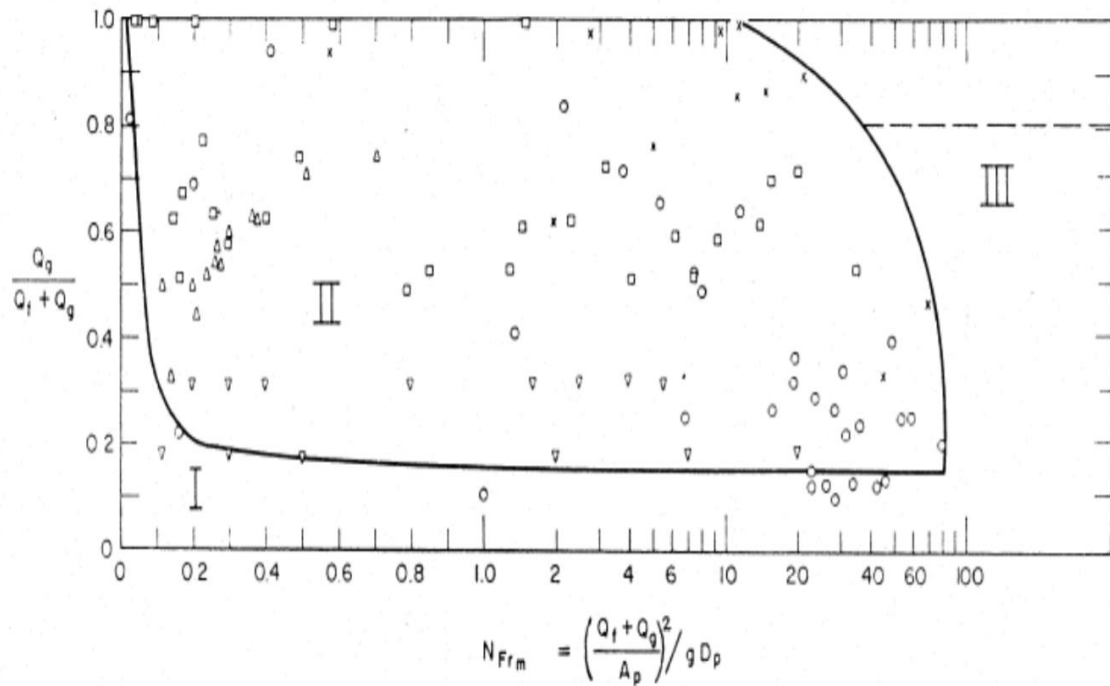


Figure 3.3 – Griffith and Wallis Flow pattern map

Table 3.2 – System Characteristics

Pipe characteristics	
Length of pipe, m	5.48
Diameter of pipe, mm	12.7 – 25.4
Pressure	
Pressure, bar	1.013
Liquid Properties	
Surface tension, kg/s <sup>2</sup>	73 × 10 <sup>-3</sup>
Viscosity, kg/ms	1 × 10 <sup>-3</sup>
Density, kg/m <sup>3</sup> (Water)	1000

- Golan and Stenning's (1969) map

Sequel to noting disagreements between maps of vertical flows, Golan and Stenning developed two new maps shown in Figures 3.4 and 3.5 in 1969. The two maps were for vertical upward and downward flows.

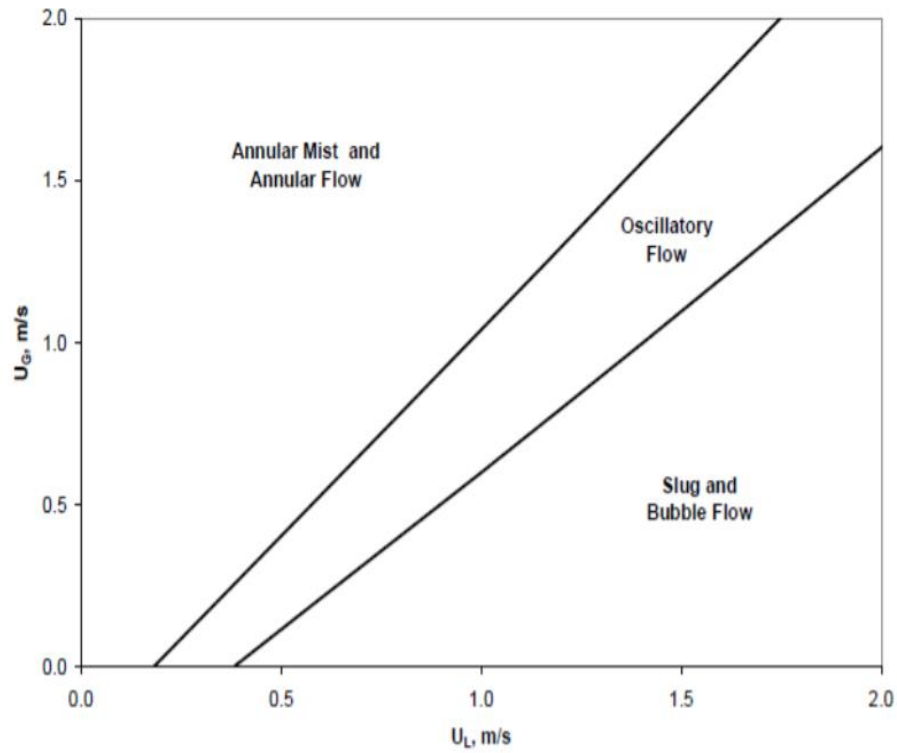


Figure 3.4 – Golan and Stenning's Down-flow pattern map

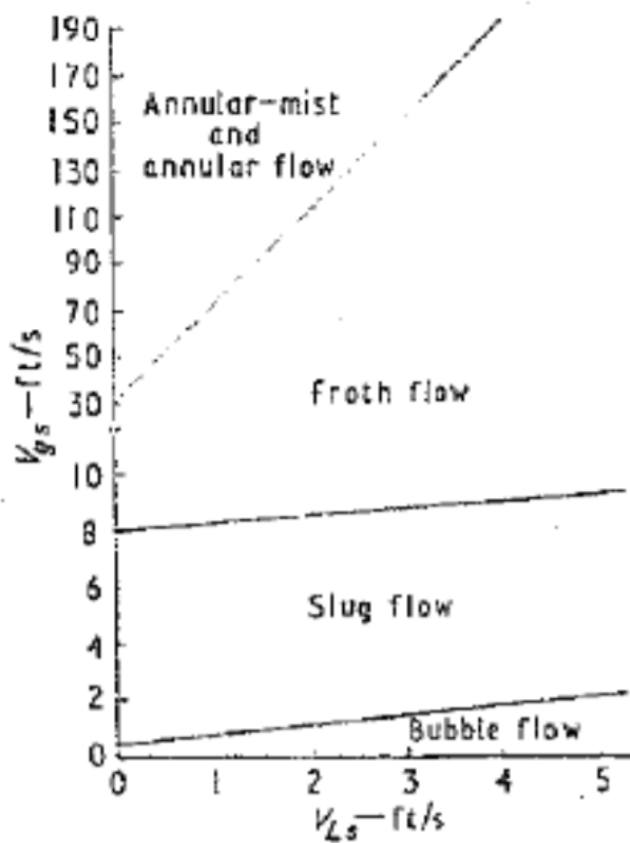


Figure 3.5 - Golan and Stenning's (1969) Up-flow pattern map

Table 1.3 – System Characteristics

Pipe characteristics	
Length of pipe, m	3
Diameter of pipe, mm	38.1
Pressure	
Pressure, bar	3.12
Liquid Properties	
Surface tension, $kg/s^2$	$72 \times 10^{-3}$
Viscosity, $kg/ms$	$1 \times 10^{-3}$
Density, $kg/m^3$ (Water)	1000
Liquid Temperature, °C	20
Range of Flow rates	
Gas, $kg/h$ (Air)	10.77 – 3067.5
Liquid, $kg/h$ (Water)	1000 - 10000

- Mandhane-Gregory-Aziz's (1974) map

Mandhane et al. (1974) developed a flow pattern map for horizontal flow using a large dataset shown in Table 3.4. This dataset entailed 14000 experimental points from research carried out between 1962 and 1973. It is the most reliable map for horizontal flows.

Table 3.4 – System Characteristics

Pipe characteristics	
<b>Diameter of pipe, mm</b>	12.7 – 165.1
Range of Flow rates (estimated)	
<b>Gas, kg/h (Air)</b>	0.0000182 – 730
<b>Liquid, kg/h (Water)</b>	0.054 – 632.5
Range of Densities	
<b>Gas, kg/m<sup>3</sup></b>	0.8 – 50.5
<b>Liquid, kg/m<sup>3</sup></b>	704.8 – 1009.2
Range of Viscosities	
<b>Gas Viscosity, kg/ms</b>	0.00005 – 0.000022
<b>Liquid Viscosity, kg/ms</b>	0.0003 – 0.09
Superficial velocities	
<b>Superficial Gas Viscosity, m/s</b>	0.043 – 170.7
<b>Superficial Liquid Viscosity, m/s</b>	0.0009 – 7.32

- Baker's (1954) map

Baker developed a map (as seen in Figure 3.6) in 1954 using data that had being used by Jenkins in 1947, Gazley in 1949, Alves in 1953 and Kosterin in 1949. Baker introduced two parameters ( $\lambda$ ,  $\psi$ ), accounting for the gas and liquid properties (See equations 3.4 and 3.5 below).

$$x - axis ; \frac{L\lambda\psi}{G} \qquad y - axis ; \frac{G}{\lambda}$$

$$L = \frac{m_L}{s} \qquad (3.3)$$

$$G = \frac{m_G}{s} \qquad (3.4)$$

$$\lambda = \left[ \frac{\rho_G}{\rho_{air}} \frac{\rho_l}{\rho_w} \right]^{0.5} \qquad (3.5)$$

$$\psi = \frac{\sigma_w}{\sigma_L} \left[ \frac{\mu_L}{\mu_W} \left( \frac{\rho_W}{\rho_L} \right)^2 \right]^{1/3} \quad (3.6)$$

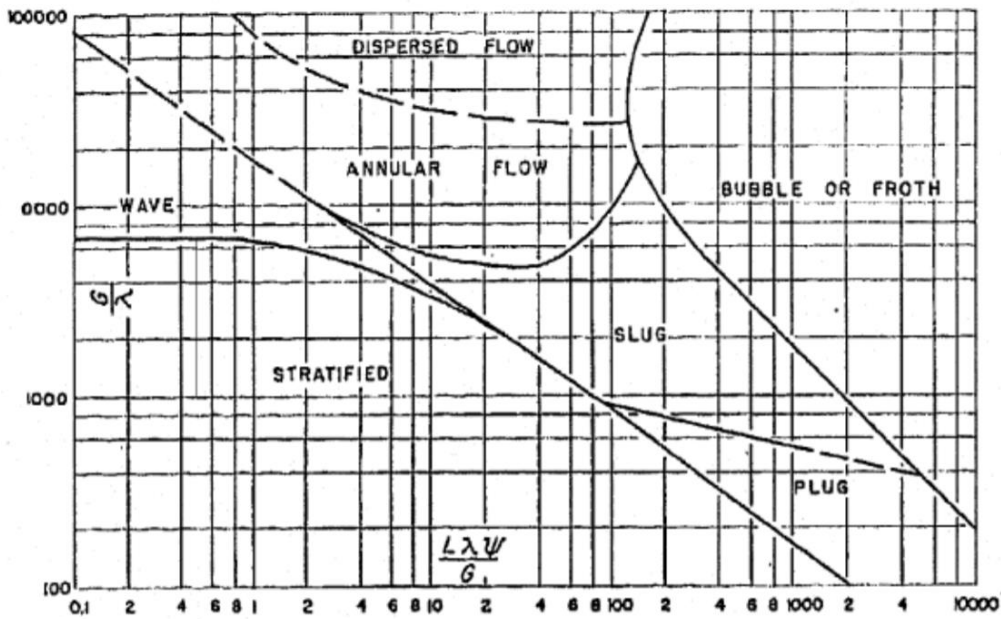


Figure 3.6 – Baker's (1954) original flow pattern map

Scott then modified the original map by Baker by including pipe diameters, thereby improving agreement with the data of Hoogendoorn and Govier (Scott 1964). The modified map is as shown in Figure 3.7;

#

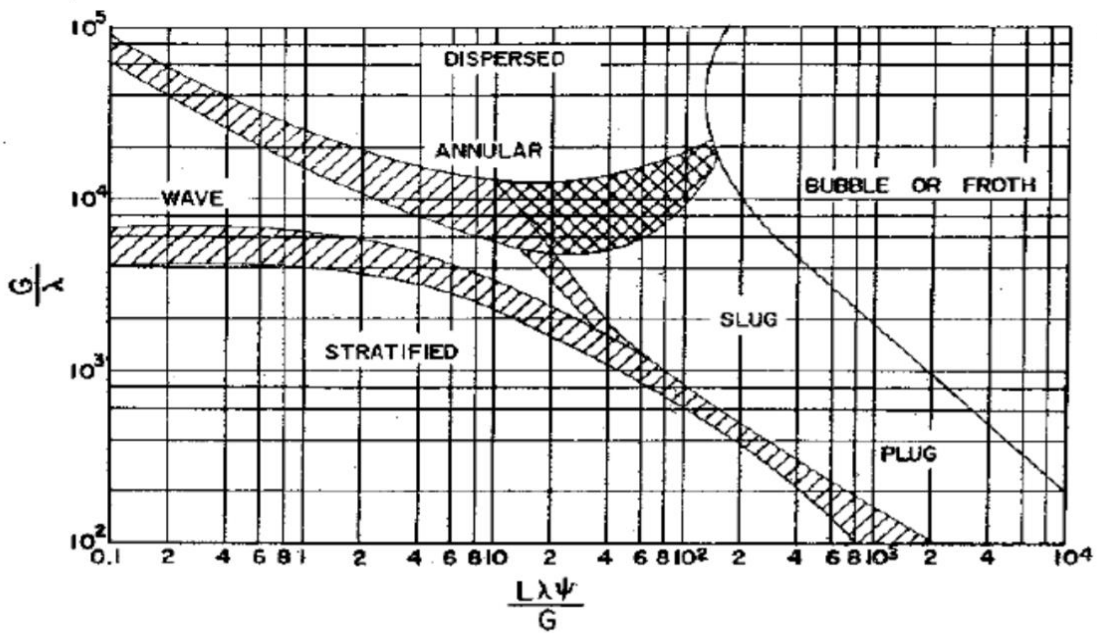


Figure 3.7 - Baker's (1954) modified flow pattern map

Bell et al. (1970) also made modifications later on, changing the axes.

$$x - axis ; G_L \psi \quad y - axis ; \frac{G_V}{\lambda}$$

$$G_L = L = \frac{m_L}{s} \quad (3.7)$$

$$G_V = G = \frac{m_G}{s} \quad (3.8)$$

$$\lambda = [\rho_G \rho_L]^{0.5} \quad (3.9)$$

$$\psi = [\mu_L \rho_L^2]^{1/3} \quad (3.10)$$

Finally, Whalley redrew the map as shown in Figure 3.8 in 1987 using the system characteristics depicted in Table 3.5 and represented the axes units in dimensionless forms.

$$x - axis ; G_L \psi \quad y - axis ; \frac{G_V}{\lambda}$$

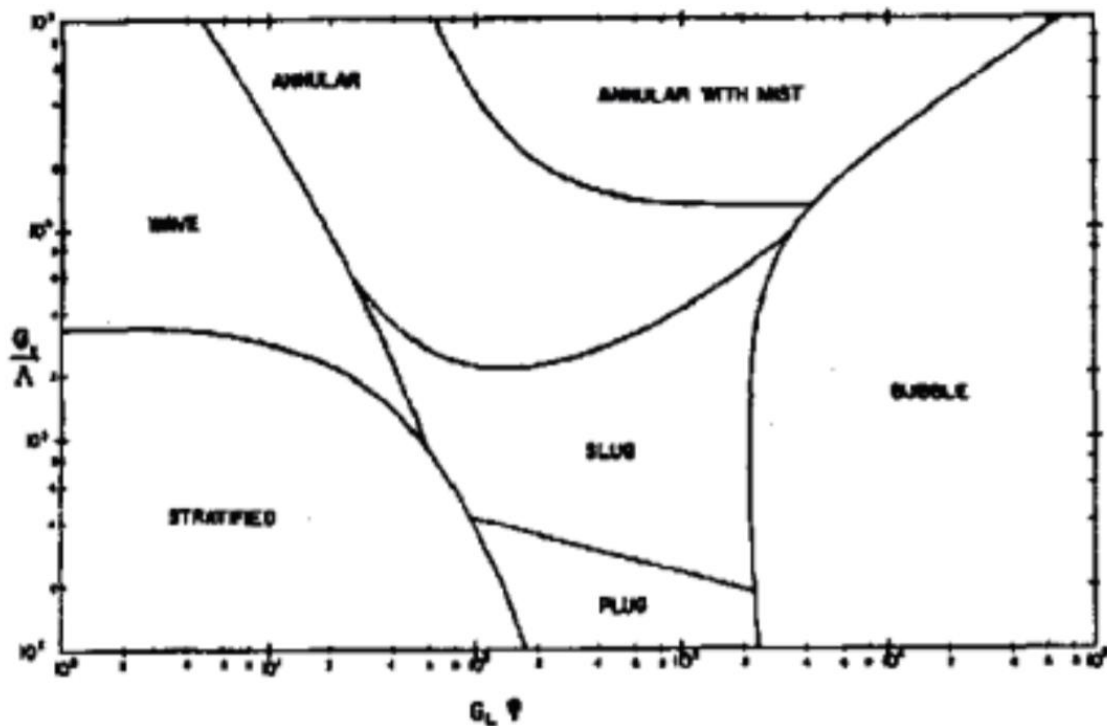


Figure 3.8 – Whalley - Baker's modified flow pattern map

Table 3.2 – System Characteristics

<b>Diameter of pipe, mm</b>	<b>25.4 – 101.60</b>
<b>Pressure, barg</b>	0 -1
<b>Liquid Density, kg/m<sup>3</sup> (Water)</b>	1000
<b>Liquid Viscosity, kg/ms</b>	0.001
<b>Surface Tension, kg/s<sup>2</sup></b>	0.073
<b>Temperature, °C</b>	20

## CHAPTER FOUR

### METHODOLOGY

Literature review indicates the existence of different methodologies for prediction via Machine Learning. The two most popular frameworks were defined by Guo (2017) and Chollet (2017).

#### 4.1. Guo's (2017) Method

##### 1. Data collection

The relevant data for developing the predictive model is appropriately collected. Data is usually represented in tables. It is important that the actual data is collected; else the predictive model will be affected.

##### 2. Data preparation

The data is then prepared for the training step. Preparation would include deleting duplicates, treating rows / columns not having missing values, conversion of data types, rearranging data to inculcate randomization. Such are necessary to ensure the data fed into the algorithm is not biased. An extra test for bias in data is data visualization. Data visualization shows the existing relationships between features. The final step involved in preparation is splitting the data into training, testing and validation.

##### 3. Selection of Model

The appropriate training algorithm is then selected. This would be based on the type of data and expectations of the predictive model. Does the model aim to predict continuous or discrete model? Is a time series data?

##### 4. Model training

The portion of the dataset for training (training data) is then fed into the model. This could be done via programming tools like Python, MATLAB.



## 5. Model Evaluation

A metric is used to measure the predictive efficiency of the developed model. Such a metric is popularly the mean square error. Evaluation is carried out some part of the data that was not fed into the algorithm (test dataset).

## 6. Parameter tuning

A few examples of model hyper parameters include the learning rate of the algorithm, original guesses (initialization), number of neurons, number of layers. The aforementioned could be adjusted to obtain better performance.

## 7. Final Predictions

The model is then used to make predictions on some part of the data that was not fed into the algorithm (validation dataset) (Guo, 2017).

### **4.2. Chollet's (2017) Method**

#### 1. Dataset assembly and problem definition

The aim of the predictive model is clearly defined. Subsequently, the relevant dataset is assembled. Its constituents should be as accurate and precise, as needed.

#### 2. Success definition

A successful predictive model should be defined. What is the degree of accuracy required by the predictive models, such that predicted values are not off by a distance?

#### 3. Evaluation protocol definition

The methodology required for the evaluation of the predictive model is also defined.

#### 4. Data preparation

The dataset is prepared. Like Guo (2017), only relevant and clean data should be fed into the training algorithm.

## 5. Model development

A model is then developed that fits the definition of what a successful predictive model is.

## 6. Improve developed model.

The already developed model is improved upon, to the extent that it over fits the dataset.

## 7. Parameter tuning

Model hyperparameters are then adjusted, until a model that can generalize effectively is developed (Chollet, 2017).

### 4.3. Developed method for Annular Flow.

The overall methodology utilized in predicting annular flow is thus extracted from the concepts of the above steps of Guo (2017) and Chollet (2017). It is described in Figure 4.1.

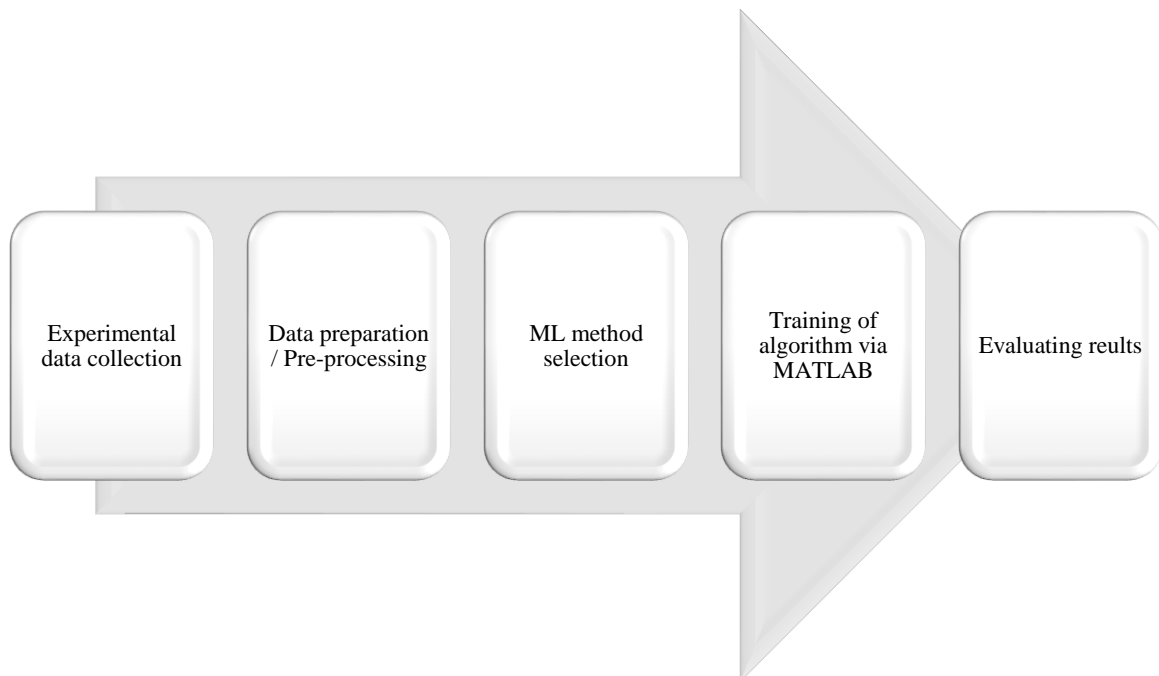


Figure 4.4 – Developed method for Annular Flow prediction

## 1. Data collection

The liquid holdup over a period of 15,000 time points (0.001s to 15s) were recorded for an air – water system. The system's gas superficial velocity was varied (17 different gas superficial velocities ranged from 6.17 ms<sup>-1</sup> to 16.05 ms<sup>-1</sup>), while the liquid superficial velocity (0.02 ms<sup>-1</sup>) was kept constant.

**The experimental procedure from which the data is obtained is described below.**

Compressed air was firstly used to pressurise the flow loop and then delivered to a mixer via two ring pumps. The air mixes with water in the mixer; the water is pumped via a centrifugal pump from a two-phase separator.

The mixer is made up of a 105 mm diameter tube placed at the centre of the 127 mm internal diameter test section. The pipe wall is covered by a water film, the pipe's centre region is filled with air. A calibrated vortex and turbine meter are used as air and water flow meters, respectively.

Annular flow is established downstream of the mixer. It was necessary that the tube be vertical, as inaccuracies in the alignment of a vertical pipe can translate into distortions in the gaseous and liquid distribution profiles of multiphase flows Gill et al. (1963). Therefore, the vertical pipe was ascertained to be vertical. Three identical conductance ring probes (See Figure 4.2) are utilised to measure the cross-sectional film fractions across the length of the riser; placed at distances of 8.1, 8.4 and 8.5 m above the mixer/injection section.

There exists a test bend also of 127 mm internal diameter. Probes were inserted at every 45° around the bend. Cross-sectional film fraction and local liquid film thickness were measured using conductance pin and parallel wire probes. The conductance pin probes were used to measure very thin films outside the bend whilst the parallel wire probes for thick film measurements inside the bend.

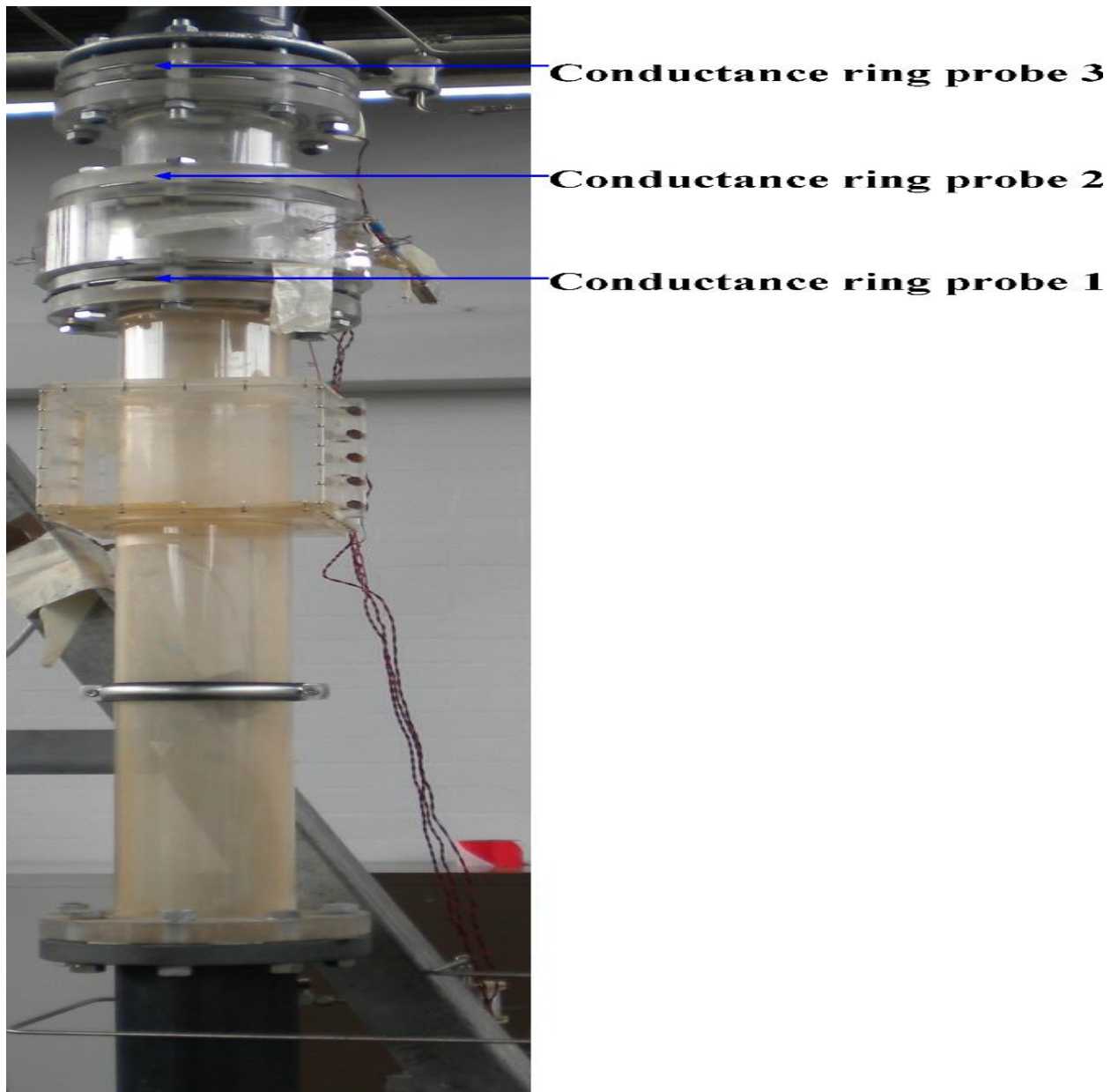


Figure 4.2 – The locations of the measurement of film fraction on the transparent test section of the riser

## 2. Data preparation

The data was split into three excel workbooks, as there were three probes measuring the liquid holdup across the system. There was thus three excel workbooks, titled;  $x = 8.1$  m,  $x = 8.3$  m,  $x = 8.5$  m (“x” represents the probe distance across the pipe). Each workbook contained 17 data sheets, representing the 17 different gas superficial velocities contained in the original data. Furthermore, each sheet contained the various liquid holdups and time points at which they were measured.

### 3. ML method selection

The Artificial Neural Network (ANN) has been chosen as the desired method due to its ability to predict nonlinear data and its renowned efficiency with time series. MATLAB has a Neural Network toolbox for time series.

### 4. Training the ANN using the MATLAB Neural Network Toolbox

The Neural Network Time Series Tool was utilized due its efficiency with nonlinear time series. The “Nonlinear Autoregressive with External (Exogenous) Input” solution was then selected as the preferred choice for each case (See Figure 4.3), due to its renown accuracy. According to MATLAB, “The nonlinear autoregressive neural network with external input model, when supplied with past values of a time series, can learn to predict that time series. The model relates current values of the time series to both the past values of the same time series and an externally determined series to obtain values of the series of interest.”

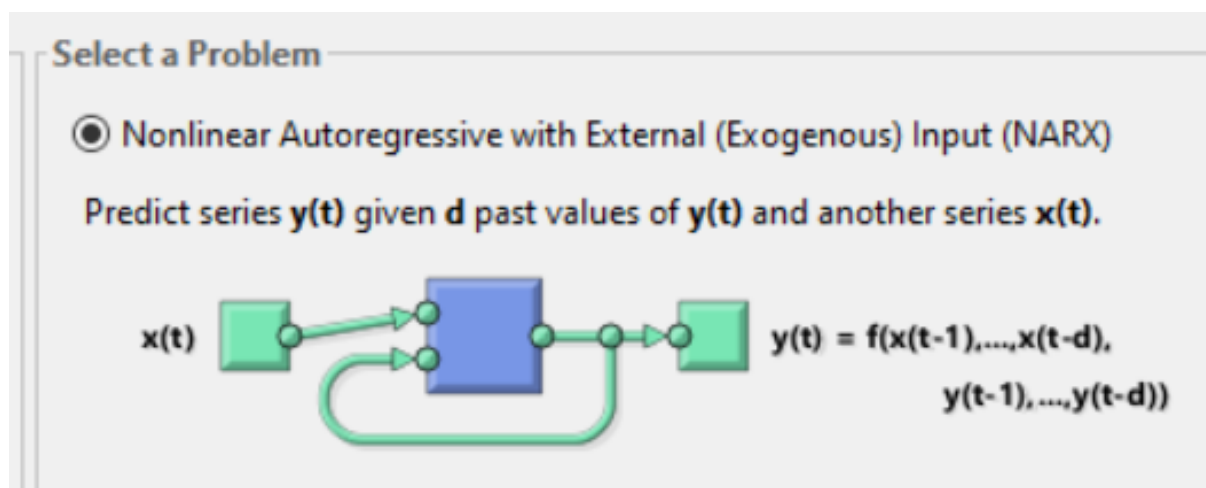


Figure 4.3 – Selection of NARX Solution

Initially prepared data was subsequently uploaded (See Figure 4.3) and divided into; Training data, validation data, & testing data. The default division method of 70%, 15% and 15% was used.

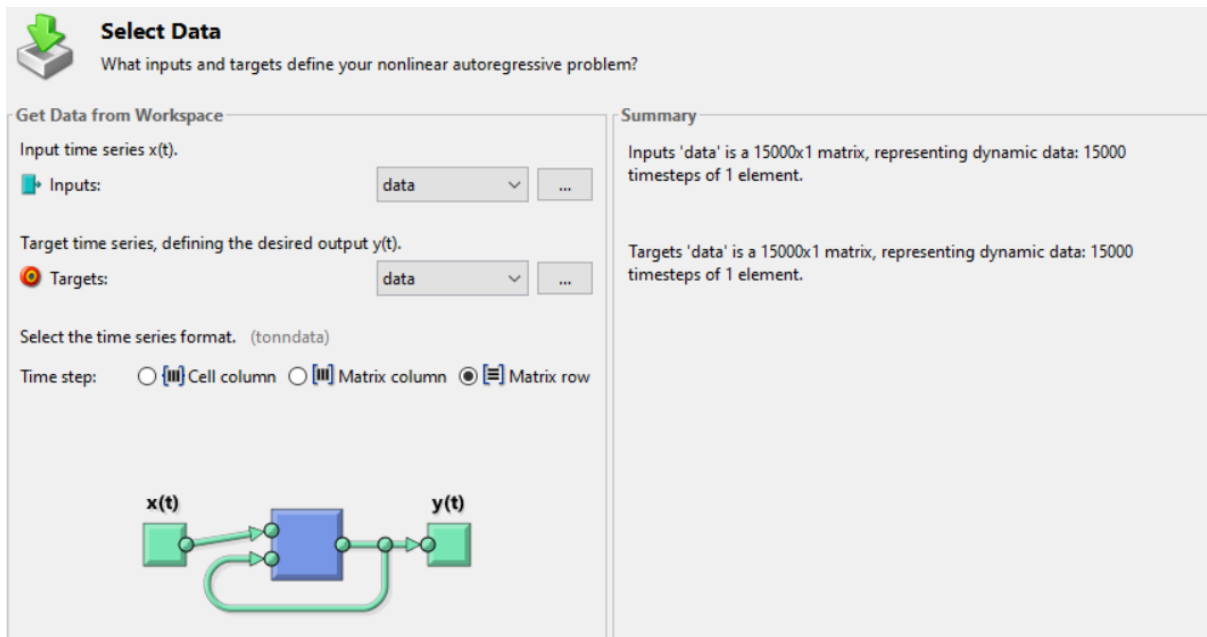


Figure 4.4 – Importing Time Series Data

The next step involved defining the neural network. Parameters needed are the number of hidden neurons, delays and time series data.

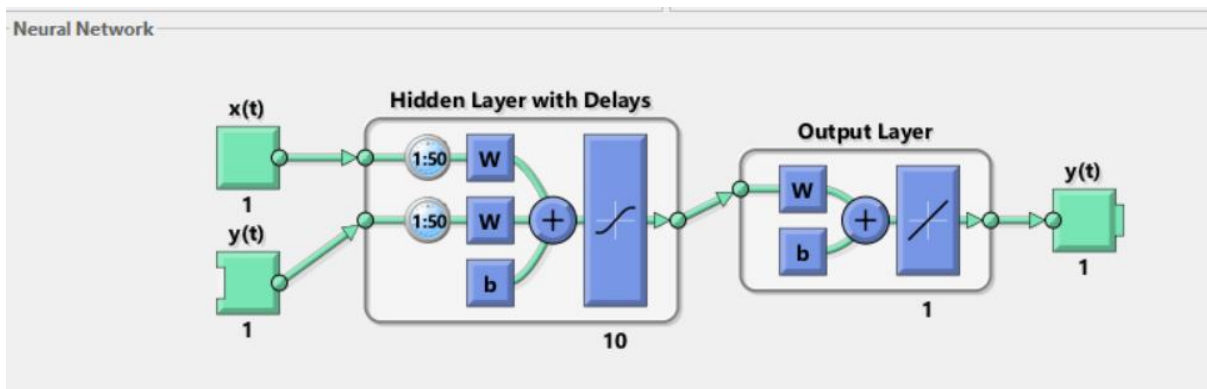


Figure 4.5 – Neural network Architecture (1)

### Validation and Test Data

Set aside some target timesteps for validation and testing.

**Select Percentages**

Randomly divide up the 15000 target timesteps:

Training:	70%	10500 target timesteps
Validation:	15%	2250 target timesteps
Testing:	15%	2250 target timesteps

**Explanation**

**Three Kinds of Target Timesteps:**

- Training:** These are presented to the network during training, and the network is adjusted according to its error.
- Validation:** These are used to measure network generalization, and to halt training when generalization stops improving.
- Testing:** These have no effect on training and so provide an independent measure of network performance during and after training.

Figure 4.6 – Splitting Time series dataset

The appropriate number of hidden neurons and delays is obtained via a trial-and-error method. An efficient neural network is the network which yields high accuracy, efficient training time and a chart of “Autocorrelation of Error 1”, where non-zero lags are within the confidence limit.

Ten (10) hidden layers were finally selected (See Figure 4.7) after trying out different numbers. Any number exceeding ten increases the training time and reduces computing speed. The number of delays was varied, until the best validation performance was obtained.

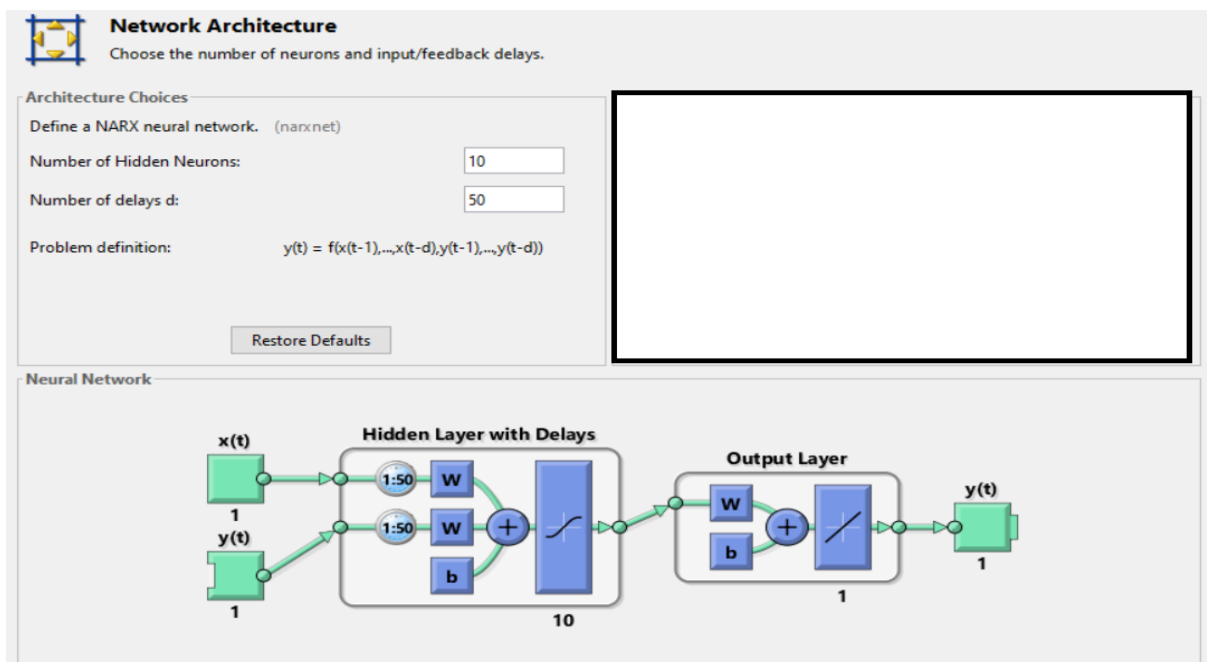


Figure 4.7 - Neural network Architecture (2)

Table 4.13 – Neural Network specifications for each gas superficial velocity

Gas superficial velocity (ms <sup>-1</sup> )	Number of hidden neurons	Number of delays
6.17	10	50
8.56	10	75
9.42	10	80
10.31	10	83
11.05	10	83
11.83	10	83
12.52	10	84
12.98	10	85
13.25	10	85
13.68	10	85
13.97	10	85
14.22	10	85
14.63	10	85
14.96	10	85
15.31	10	85
15.5	10	85
16.05	10	85

As stated earlier, Neural Networks inculcate the concept of nonlinearity via transfer function. The log sigmoid transfer function was utilized as the transfer function in each of the hidden layers and the purelin transfer function was utilized for the output function.

Training algorithms exist to automatically adjust the bias and weights of the neural network. The Levenberg-Marquadt algorithm was used for training the network (See Figure 4.8) Training stops upon the increase in mean square error during validation performance evaluation.

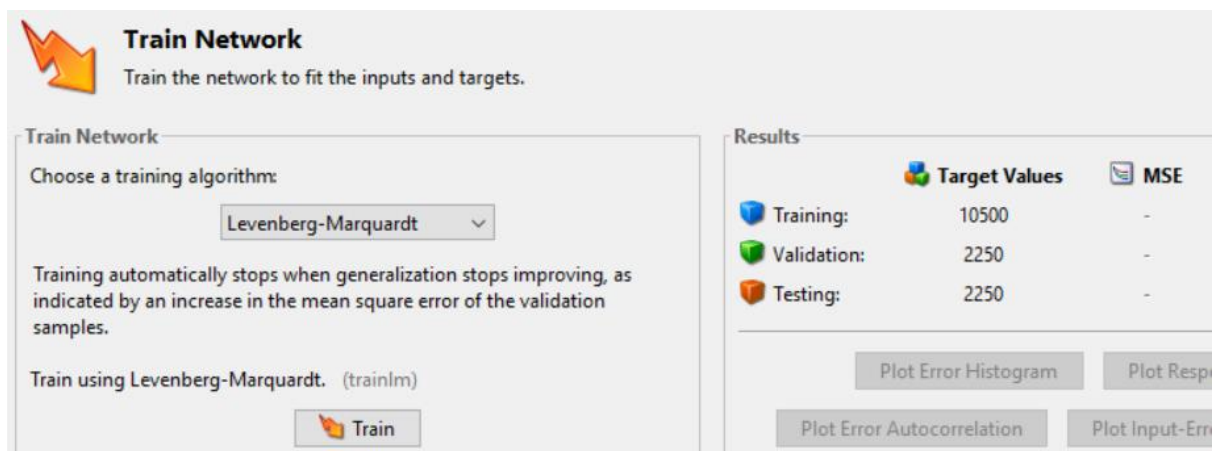


Figure 4.8 – Training Algorithm Selection



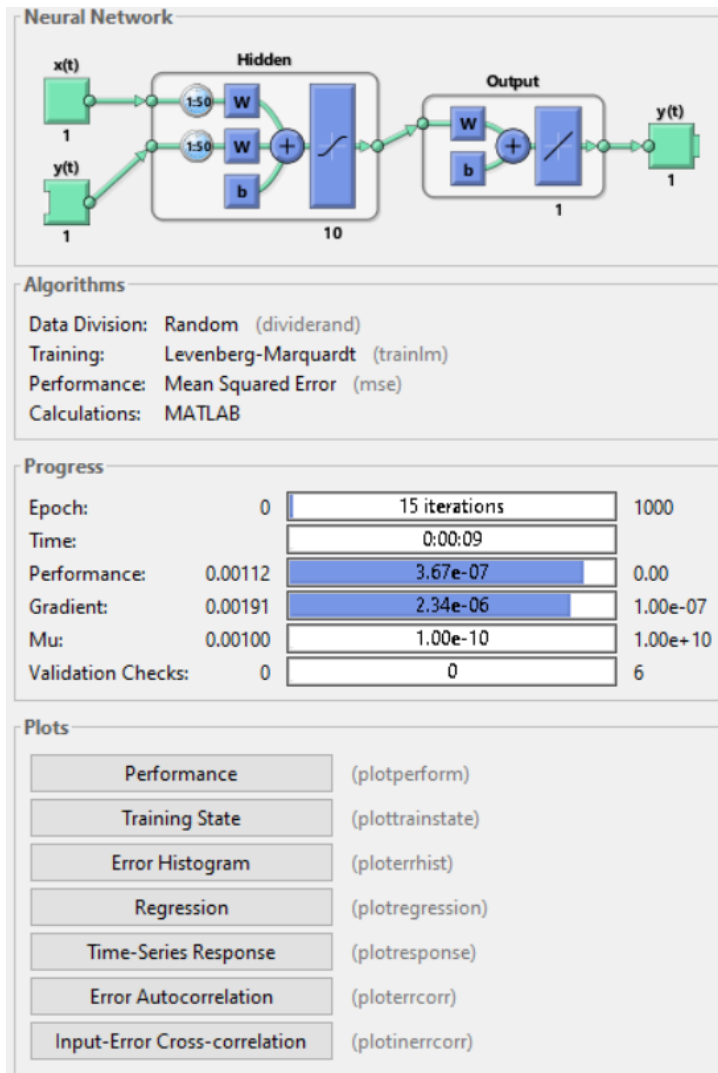


Figure 4.9 – Plots Selection

## 5. Evaluate the model.

As stated earlier, the chart of “Autocorrelation of Error 1” was utilized to evaluate the resulting models. Upon attaining the chart where non-zero lags are all within the confidence limit, the output was copied onto the existing sheets in the workbooks. Experimental values and simulated values were then finally compared, to ascertain the effective prediction ability of the ANN (Ayegba et al., 2017). Also, frequency and structure velocity are then calculated for all cases using customised packages (Abdulkadir et al., 2020); to ascertain the effective prediction ability of the ANN.

## CHAPTER FIVE

### RESULTS & DISCUSSION

This first section involves analysing the time series data. Subsequently, various extracted MATLAB charts and tables are used to analyse the results of the neural network. The time series data analysis would facilitate for richer analysis in the ML section.

A visual inspection of the overall combined charts does not explicitly allude to an evident trend between liquid holdup and time. The curve for the  $6.17 \text{ ms}^{-1}$  liquid holdup is significantly different than that of the other velocities; the liquid holdup is higher for this liquid superficial velocity. This could be explained by the velocity being too low. It could also be insinuated that there exists a threshold velocity between  $6.17 \text{ ms}^{-1}$  and  $8.56 \text{ ms}^{-1}$ , where annular flow becomes apparent. All velocities before this superficial velocity do not really yield the annular flow pattern.

This is further buttressed by the liquid holdup data for  $8.56 \text{ ms}^{-1}$  and other velocities higher than it, having a similar range of liquid holdup as seen in the charts.

In Figures 5.1 to 5.15, the time intervals in the combined charts are split to further aid the recognition of a trend; an explicit trend is not obtained.

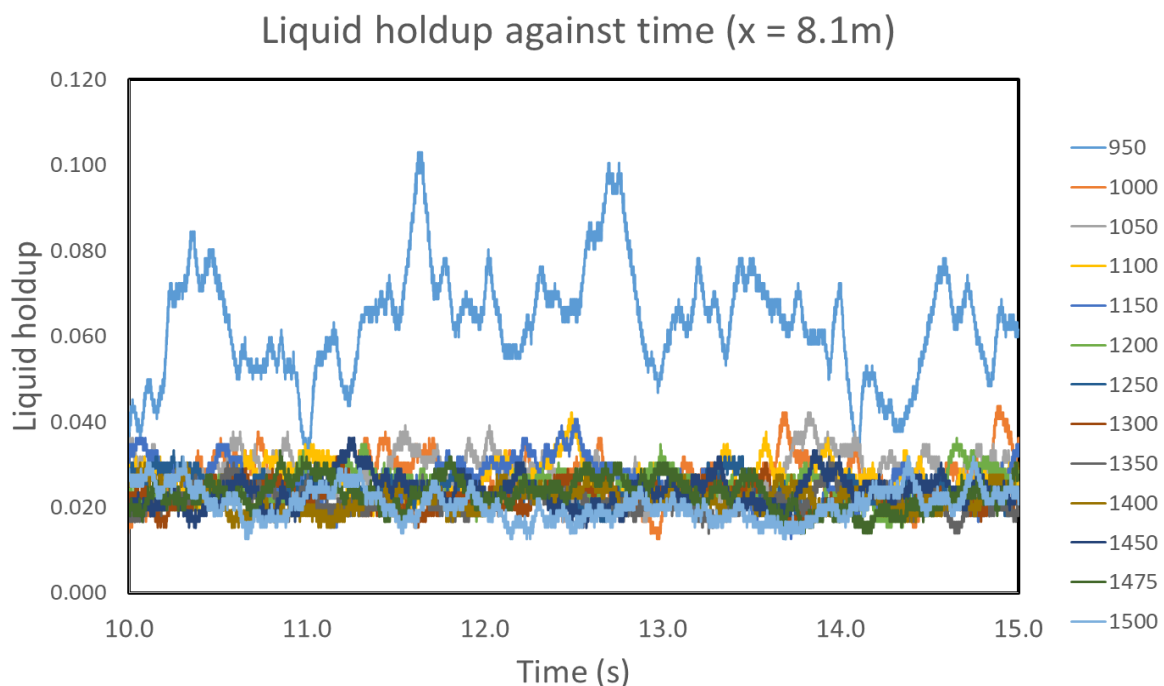


Figure 5.1 - Time series data for liquid holdup (as measured by the first probe,  $x = 8.1 \text{ m}$ )

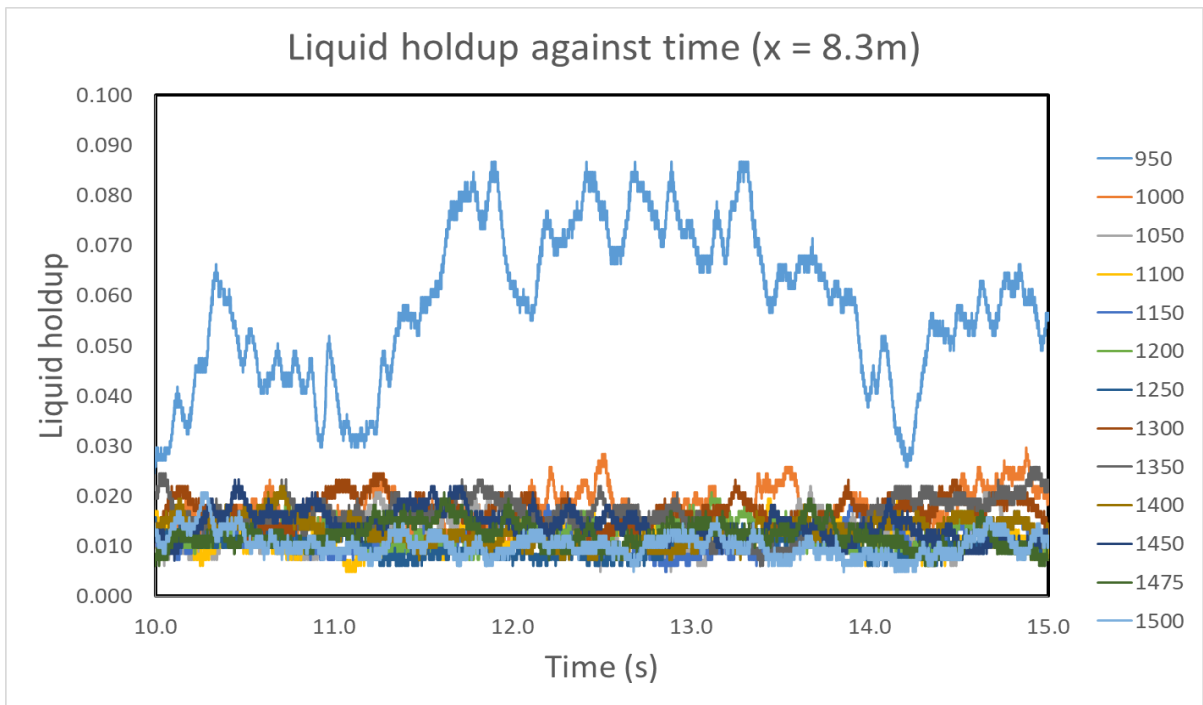


Figure 5.2 - Time series data for liquid holdup (as measured by the second probe, x = 8.3 m)

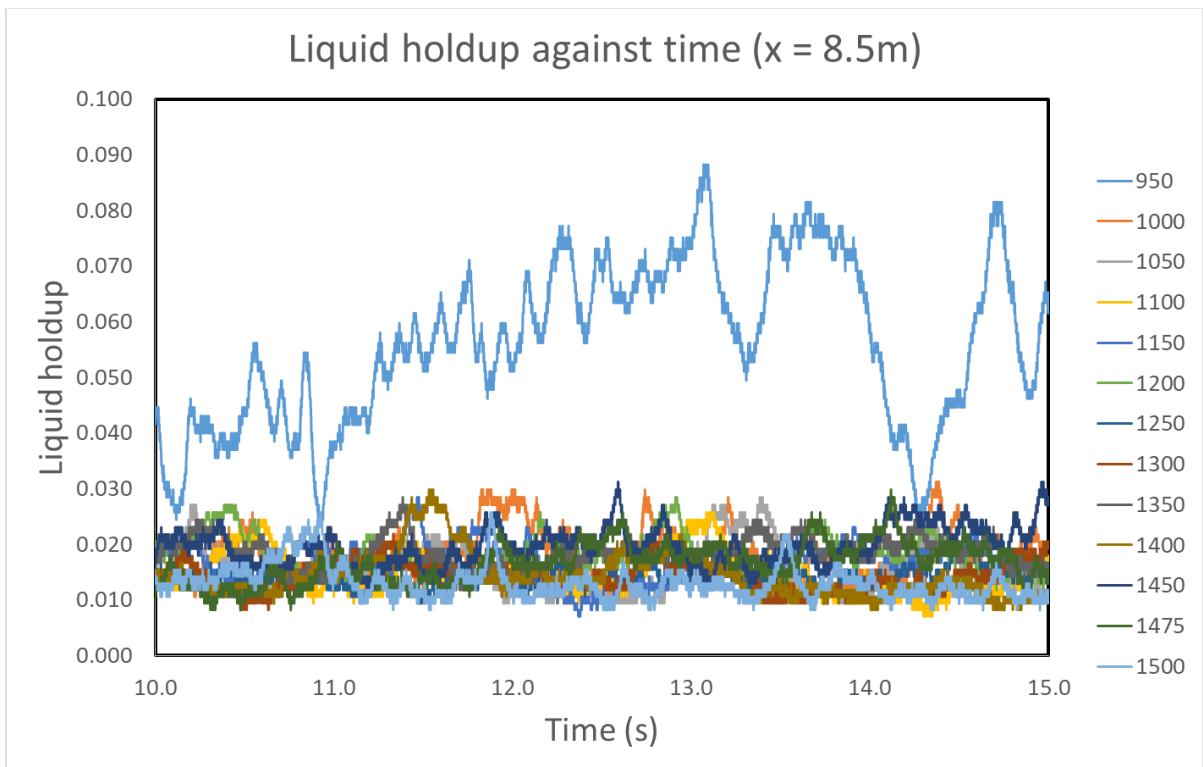


Figure 5.3 - Time series data for liquid holdup (as measured by the third probe, x = 8.5 m)

- **Probe = 8.1m, Time interval = 0 – 5 seconds**

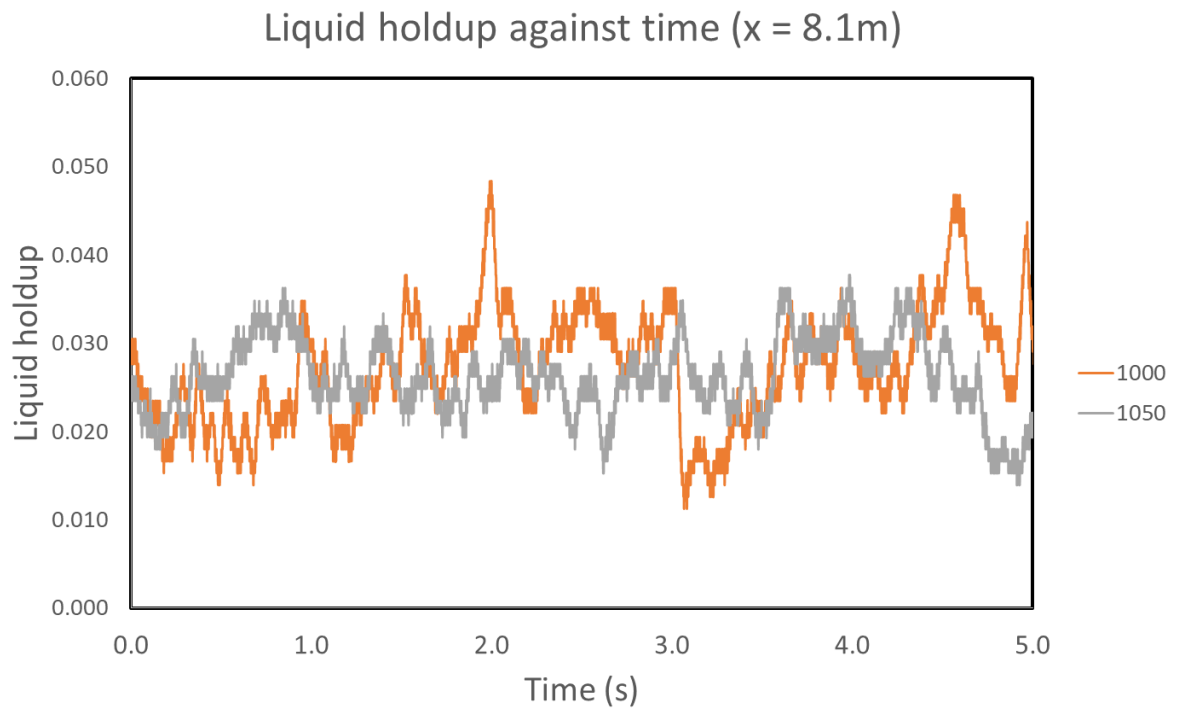


Figure 5.4 -  $U_g = 8.56 \text{ m/s}, 9.42 \text{ m/s}$

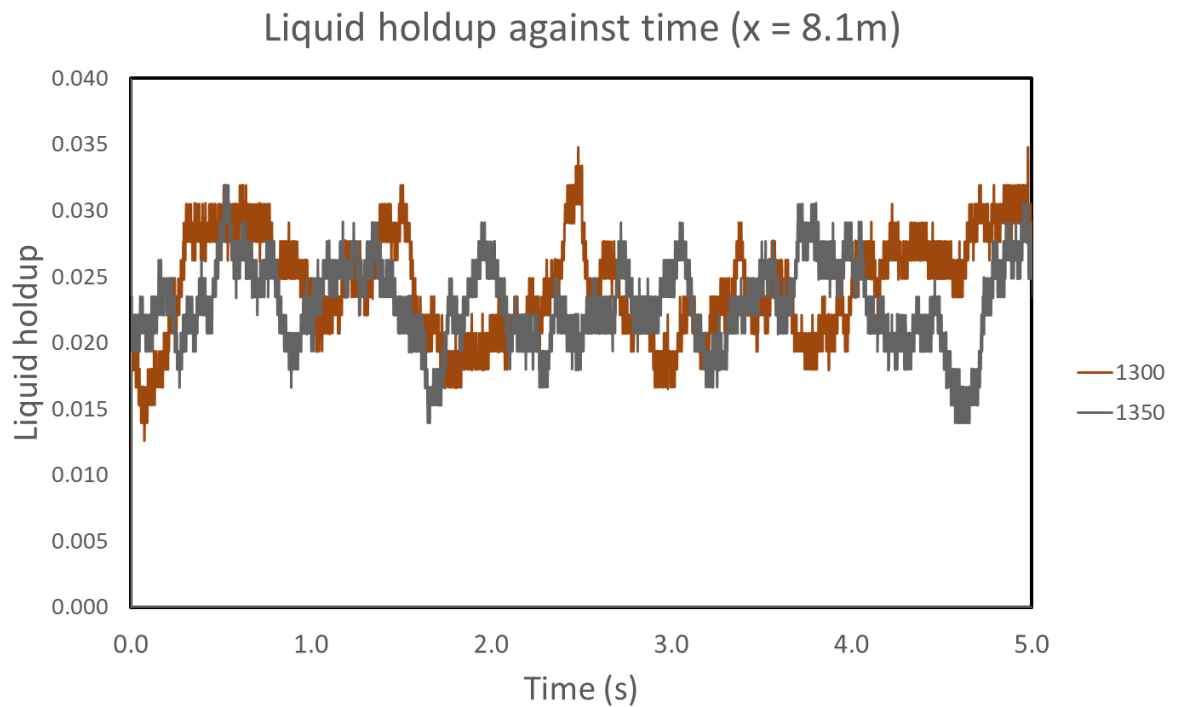


Figure 5.5 -  $U_g = 13.25 \text{ m/s}, 13.97 \text{ m/s}$

- **Probe = 8.1m, Time interval = 5 – 10 seconds**

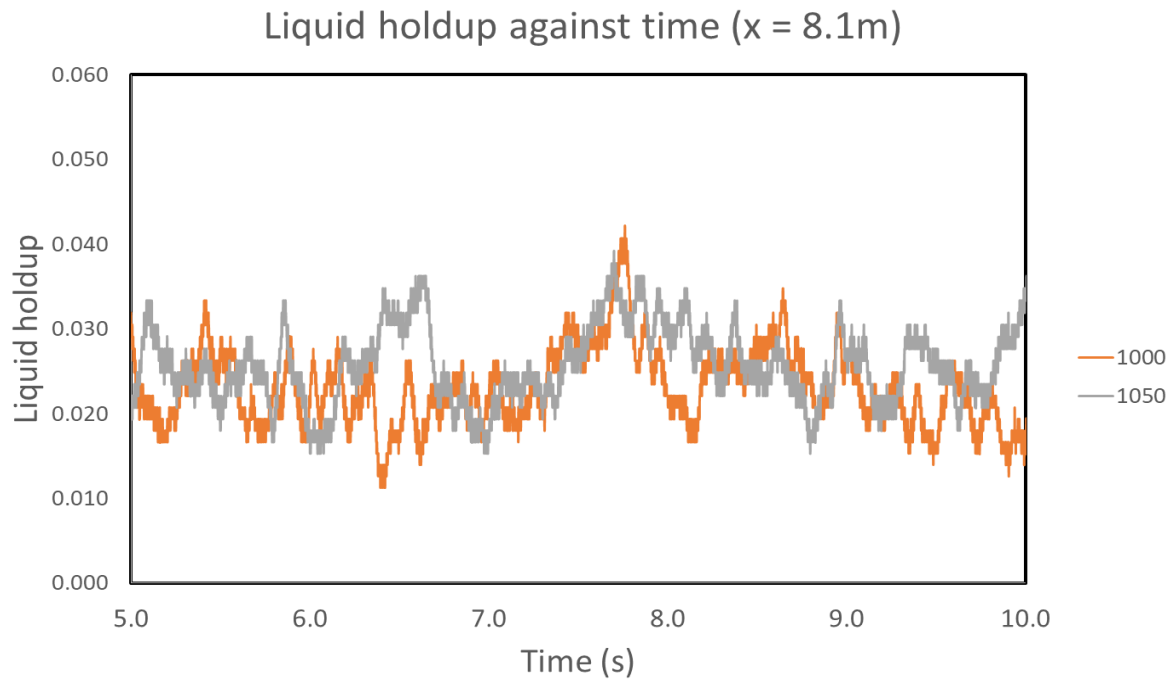


Figure 5.6 -  $U_g = 8.56 \text{ m/s}, 9.42 \text{ m/s}$

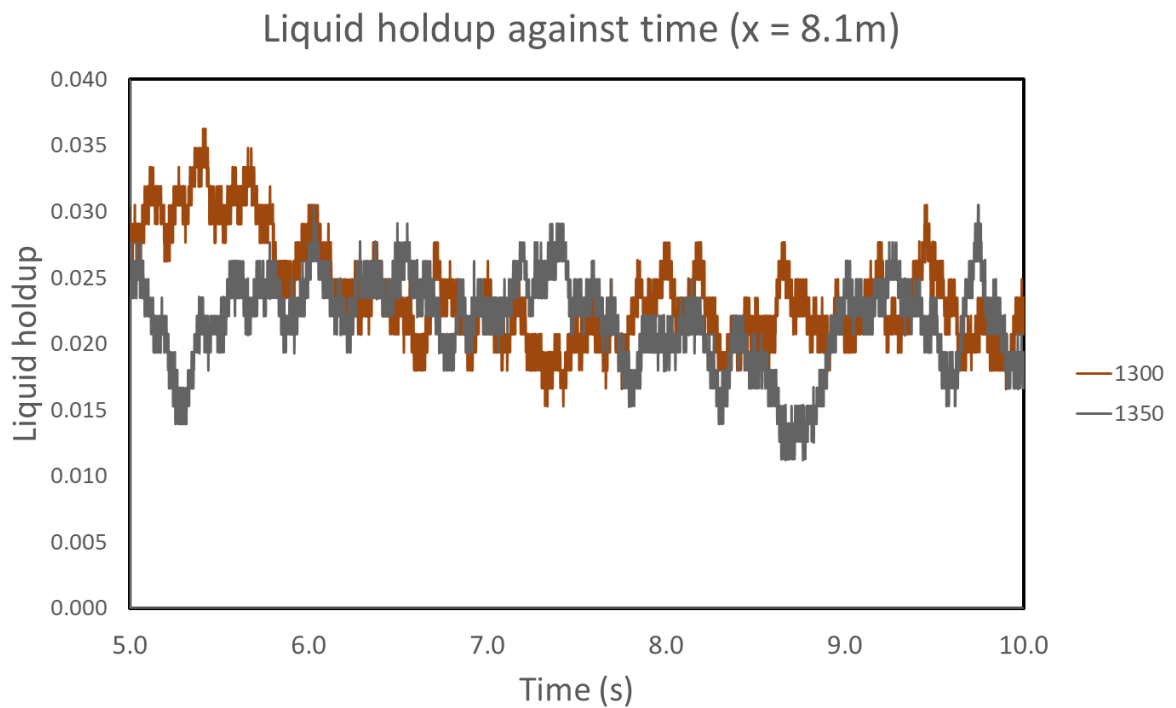


Figure 5.7 -  $U_g = 13.25 \text{ m/s}, 13.97 \text{ m/s}$

- **Probe = 8.1m, Time interval = 10 – 15 seconds**

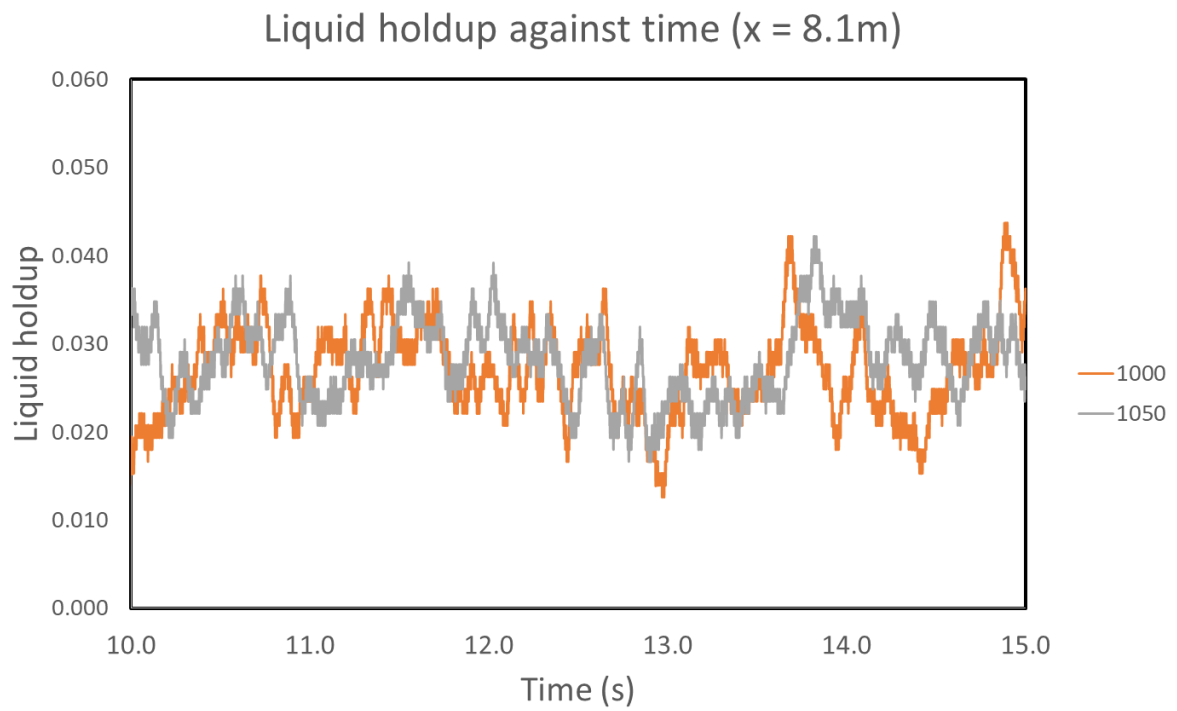


Figure 5.8 -  $U_g = 8.56 \text{ m/s}, 9.42 \text{ m/s}$

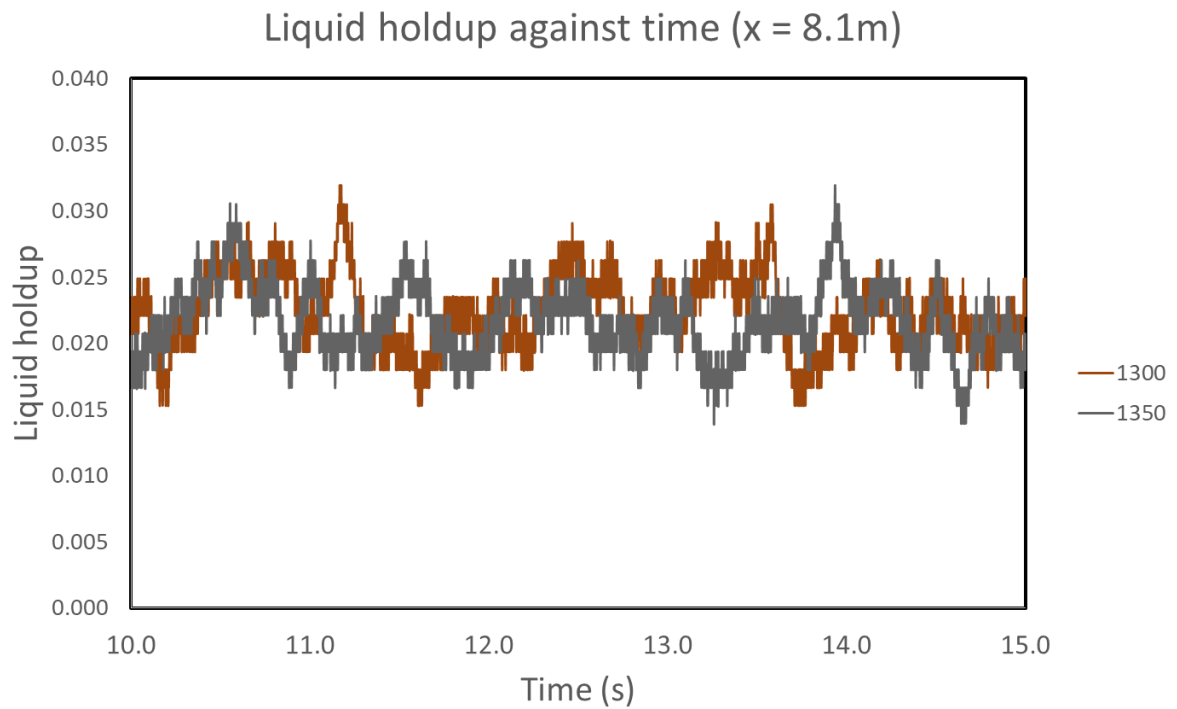


Figure 5.9 -  $U_g = 13.25 \text{ m/s}, 13.97 \text{ m/s}$

- **Probe = 8.3m, Time interval = 0 – 5 seconds**

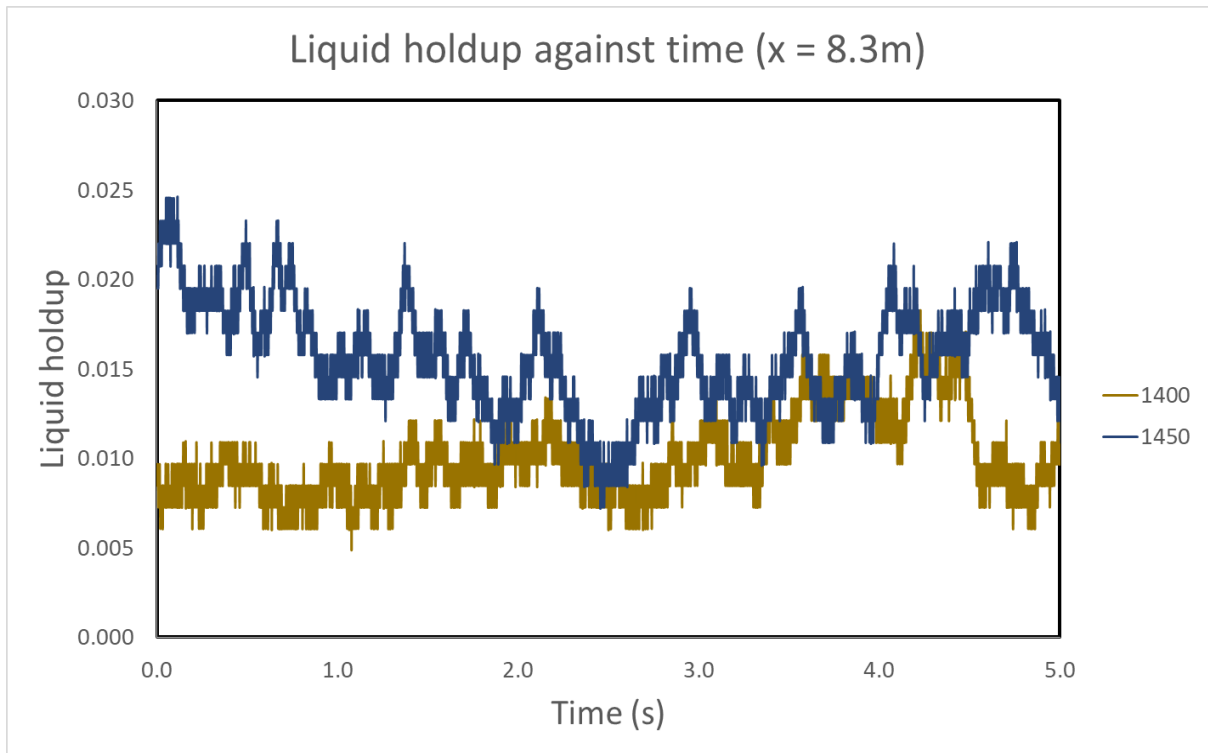


Figure 5.10 -  $U_g = 14.63 \text{ m/s}, 15.31 \text{ m/s}$

- **Probe = 8.3 m, Time interval = 5 – 10 seconds**

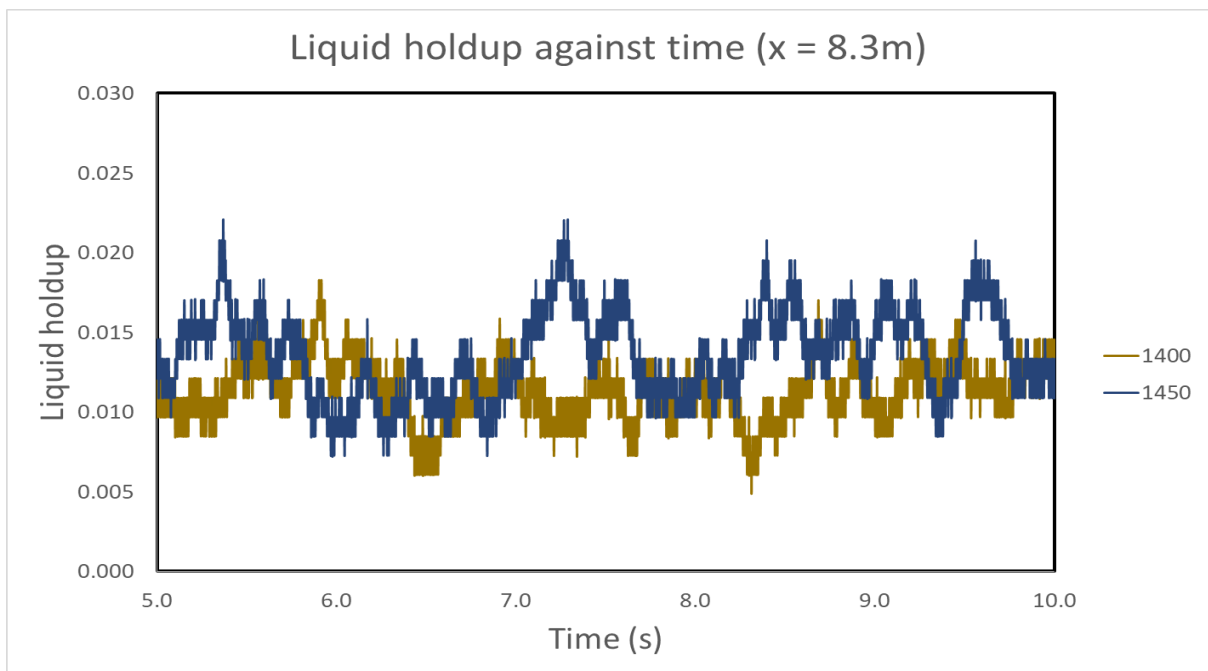


Figure 5.11 -  $U_g = 14.63 \text{ m/s}, 15.31 \text{ m/s}$

- **Probe = 8.3 m, Time interval = 5 – 10 seconds**

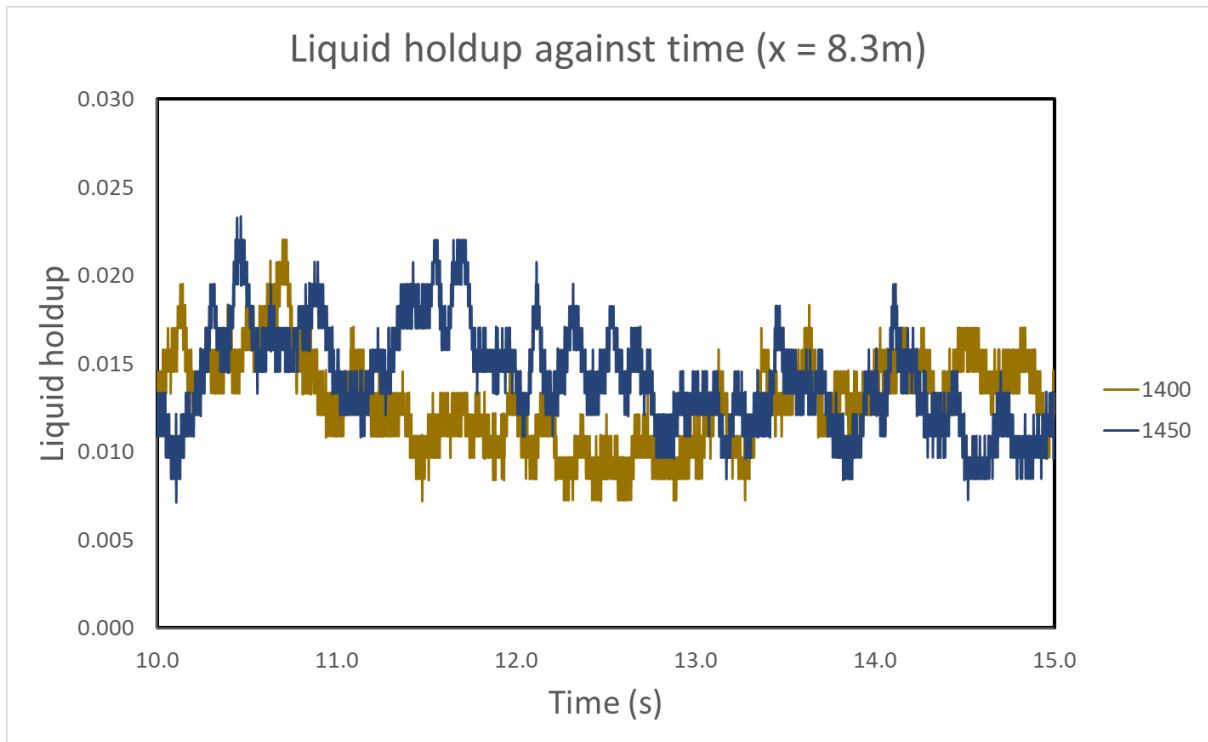


Figure 5.12 -  $U_g = 14.63 \text{ m/s}, 15.31 \text{ m/s}$

- **Probe = 8.5m, Time interval = 0 – 5 seconds**

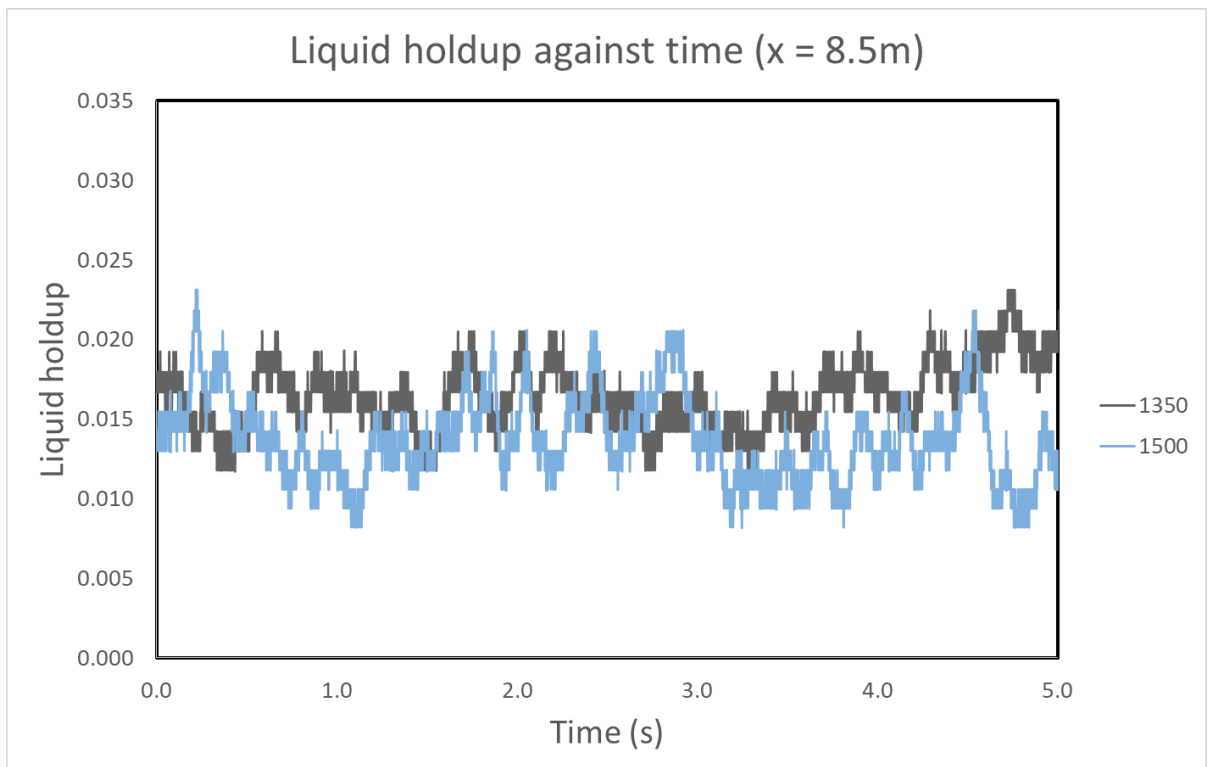


Figure 5.13 -  $U_g = 13.97 \text{ m/s}, 16.05 \text{ m/s}$



- **Probe = 8.5 m, Time interval = 5 – 10 seconds**

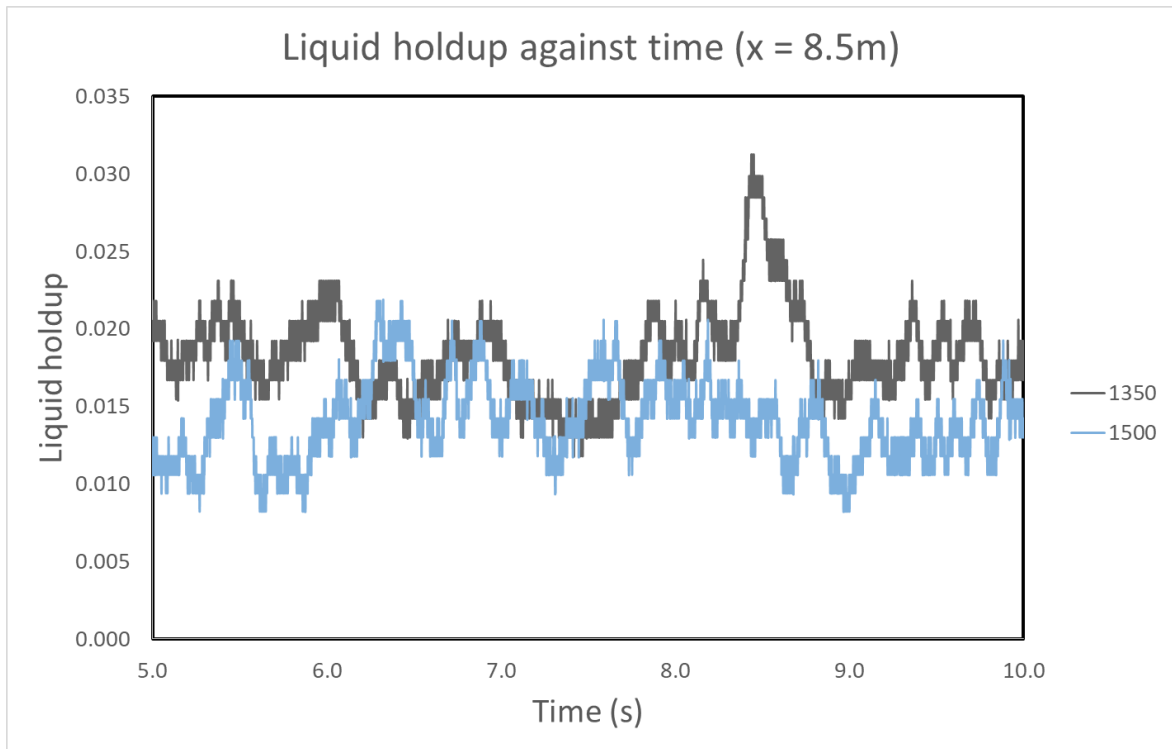


Figure 5.14 -  $U_g = 13.97 \text{ m/s}, 16.05 \text{ m/s}$

- **Probe = 8.5m, Time interval = 10 – 15 seconds**

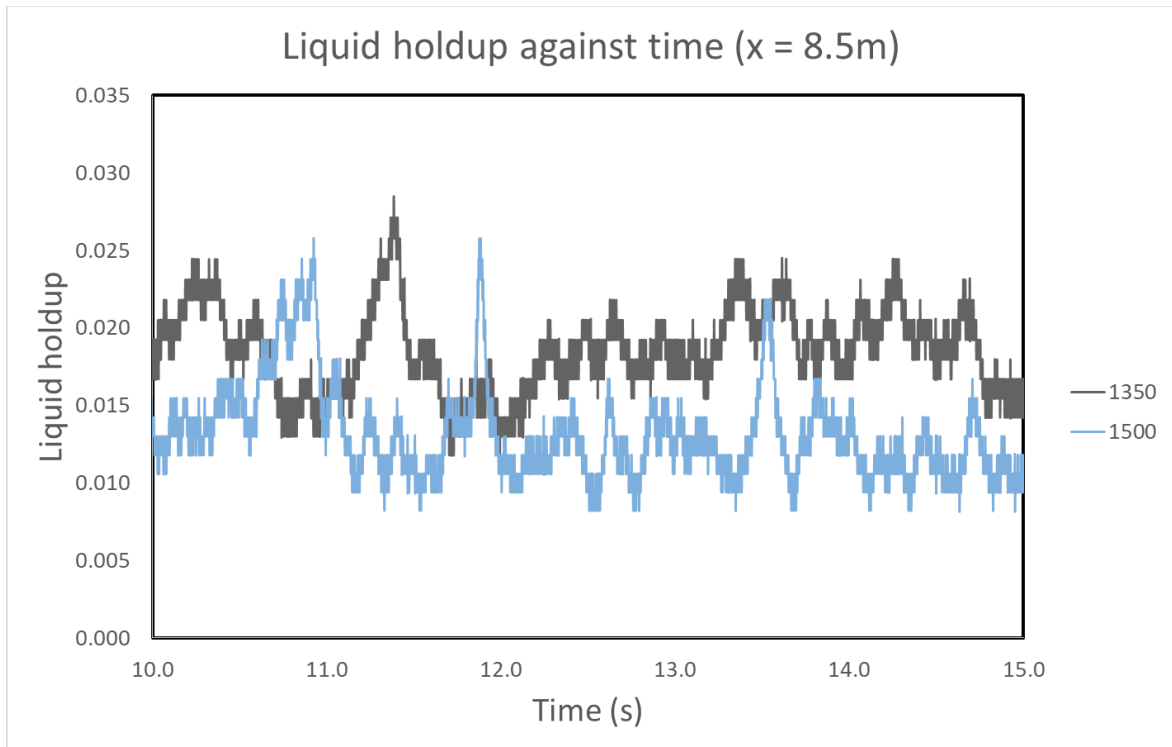


Figure 5.15 -  $U_g = 13.97 \text{ m/s}, 16.05 \text{ m/s}$

Sections 5.1 to 5.3 involve comparing the actual experimental results and the predicted results obtained using MATLAB. They are carried out under five segments; Individual basis, Comparison basis, Average liquid holdup basis (Collective basis), Structure velocity basis, frequency basis.

### 5.1. Individual basis

Figure 5.16 represents the time series simulations for different segments of the datasets; training, test and validations. Using an individual case for a gas superficial velocity of  $6.17 \text{ ms}^{-1}$ , it is observed in the figure that the validation and testing curves are aligned with the training curve; alluding to the high prediction efficiency of the utilized neural network's design. The neural network has thus been able to learn effectively and obtain a trend. It then applies this pattern learnt to the training and validation data; also proving efficient. Furthermore, the error chart also shows the minimal differences between outputs and targets for the datasets.

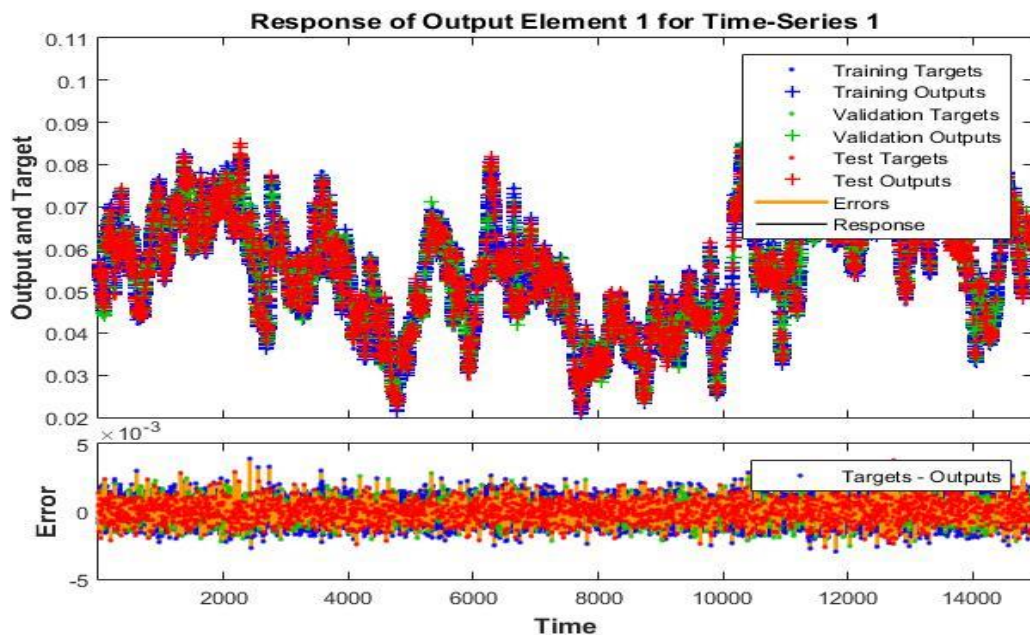


Figure 5.16 – Time series ( $x = 8.1 \text{ m}$ , Gas superficial velocity =  $6.17 \text{ ms}^{-1}$ )

Figure 5.17 represents the autocorrelation of Error 1 for the gas superficial velocity of  $6.17 \text{ ms}^{-1}$ . At zero lag, the  $|A_{\text{error}}|$  is not highly related to itself. Also, other lags being within the confidence limit region further proves the efficiency of the neural network's design.

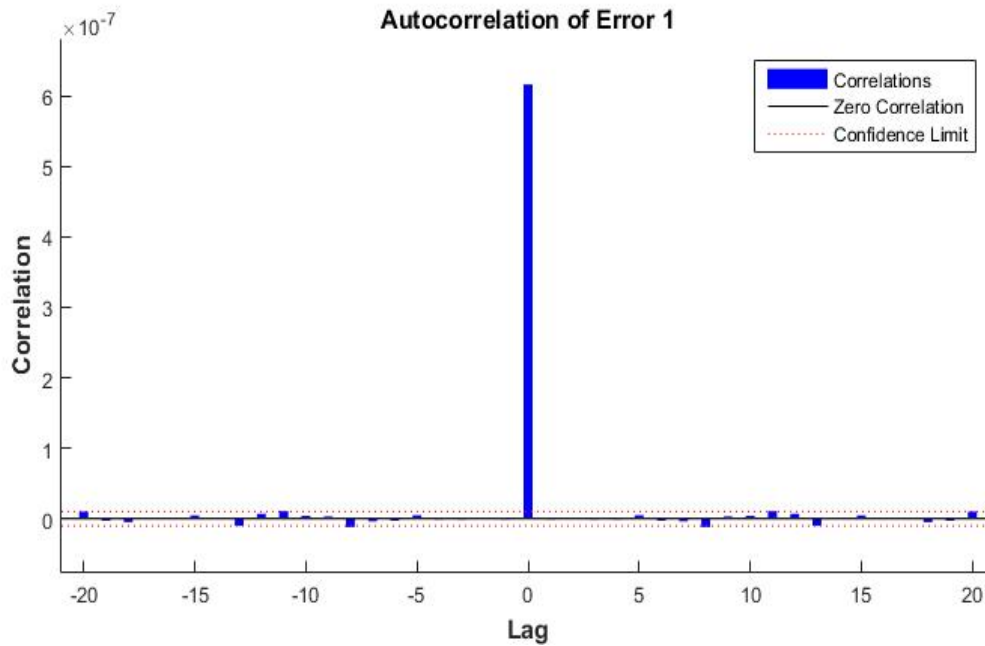


Figure 5.17 – Autocorrelation of Error 1 ( $x = 8.1 \text{ m}$ , Gas superficial velocity =  $6.17\text{ms}^{-1}$ )

The mean square error (MSE) shown in Figure 5.18 also shows a decreasing MSE with every iteration. After 57 iterations (At an epoch of 57), the best validation performance was obtained. In clearer terms, the appropriate biases and weights were adjusted 57 times, until the best validation performance was obtained.

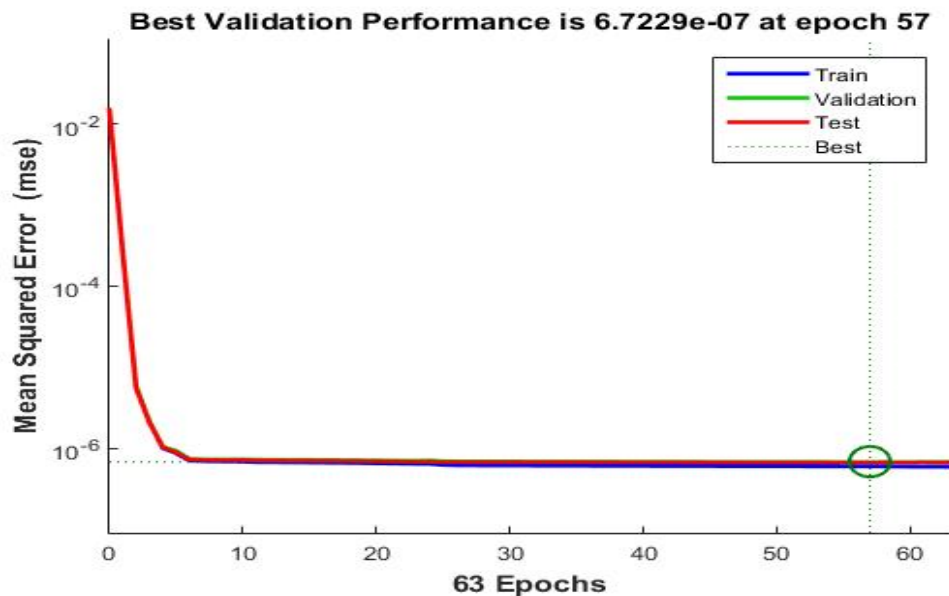


Figure 5.18 – Best Validation performance ( $x = 8.1 \text{ m}$ , Gas superficial velocity =  $6.17\text{ms}^{-1}$ )

It can be concluded that the gas superficial velocities are expected to yield similar discussion points. The main difference between the data of gas superficial velocity of  $6.17 \text{ ms}^{-1}$  and other gas superficial velocities is time taken due to its higher epoch number and higher MSE, insinuating a reduced neural network efficiency.

## 5.2. Comparison basis

From Tables 5.1 to 5.3, it can be noted that the case of a gas superficial velocity of  $6.17 \text{ ms}^{-1}$ , yields the highest MSE; insinuating a higher difference between the output and targets. Also, this minimum MSE was obtained after 57 iterations: the most across all probes. The neural network required more time, in comparison to other superficial velocities, to achieve a minimum MSE. There was no distinct pattern for minimum epochs, showing that the neural network's efficiency is independent for the case of other gas superficial velocities.

The times series for the gas superficial velocity of  $14.63 \text{ ms}^{-1}$  yields the minimum MSE for the different probes. It is important to note that all MSE values are close to zero, thus the overall neural network's efficiency is high.

Table 5.1 – MSE and Epoch for each superficial velocity, at the first probe ( $x = 8.1 \text{ m}$ )

Gas superficial velocity ( $\text{ms}^{-1}$ )	Mean Squared Error (MSE)	Epoch
6.17	$6.7229 \times 10^{-7}$	57
8.56	$3.747 \times 10^{-7}$	26
9.42	$4.1078 \times 10^{-7}$	14
10.31	$3.8068 \times 10^{-7}$	22
11.05	$3.7499 \times 10^{-7}$	30
11.83	$3.6064 \times 10^{-7}$	27
12.52	$3.7167 \times 10^{-7}$	20
12.98	$3.6374 \times 10^{-7}$	15
13.25	$3.7376 \times 10^{-7}$	12
13.68	$3.8181 \times 10^{-7}$	16
13.97	$3.7973 \times 10^{-7}$	17
14.22	$5.2943 \times 10^{-7}$	7
14.63	$3.4083 \times 10^{-7}$	19
14.96	$3.6723 \times 10^{-7}$	20
15.31	$3.7685 \times 10^{-7}$	13
15.5	$3.6061 \times 10^{-7}$	16
16.05	$3.8909 \times 10^{-7}$	11

Table 5.2 - MSE and Epoch for each superficial velocity, at the second probe (x = 8.3 m)

Gas superficial velocity (ms <sup>-1</sup> )	Mean Squared Error (MSE)	Epoch
6.17	$4.696 \times 10^{-7}$	99
8.56	$2.9612 \times 10^{-7}$	22
9.42	$2.8256 \times 10^{-7}$	12
10.31	$2.7758 \times 10^{-7}$	15
11.05	$2.6701 \times 10^{-7}$	9
11.83	$2.7007 \times 10^{-7}$	14
12.52	$2.3788 \times 10^{-7}$	16
12.98	$2.4616 \times 10^{-7}$	29
13.25	$2.5672 \times 10^{-7}$	22
13.68	$2.8256 \times 10^{-7}$	14
13.97	$2.6749 \times 10^{-7}$	13
14.22	$2.4687 \times 10^{-7}$	16
14.63	$2.4018 \times 10^{-7}$	12
14.96	$2.8662 \times 10^{-7}$	13
15.31	$2.6376 \times 10^{-7}$	15
15.5	$2.6659 \times 10^{-7}$	12
16.05	$2.8732 \times 10^{-7}$	10

Table 5.3 - MSE and Epoch for each superficial velocity, at the first probe (x = 8.5 m)

Gas superficial velocity (ms <sup>-1</sup> )	Mean Squared Error (MSE)	Epoch
6.17	$5.878 \times 10^{-7}$	35
8.56	$3.0622 \times 10^{-7}$	20
9.42	$2.8015 \times 10^{-7}$	21
10.31	$2.7758 \times 10^{-7}$	21
11.05	$2.6169 \times 10^{-7}$	18
11.83	$2.8533 \times 10^{-7}$	12
12.52	$2.573 \times 10^{-7}$	15

Gas superficial velocity (ms <sup>-1</sup> )	Mean Squared Error (MSE)	Epoch
<b>12.98</b>	$2.5581 \times 10^{-7}$	14
<b>13.25</b>	$2.533 \times 10^{-7}$	15
<b>13.68</b>	$2.7909 \times 10^{-7}$	17
<b>13.97</b>	$2.8289 \times 10^{-7}$	12
<b>14.22</b>	$2.4057 \times 10^{-7}$	13
<b>14.63</b>	$2.4538 \times 10^{-7}$	17
<b>14.96</b>	$2.8331 \times 10^{-7}$	14
<b>15.31</b>	$3.0547 \times 10^{-7}$	15
<b>15.5</b>	$2.7345 \times 10^{-7}$	18
<b>16.05</b>	$2.8391 \times 10^{-7}$	21

### 5.3. Average liquid holdup value basis

In the calculation of the average liquid holdup values for both cases of experimental and simulated shown in Tables 5.4 to 5.6, close similarities were noticed at most times. The highlighted values in the tables indicate the gas superficial velocities for which little differences were noted; the neural network setup is thus highly effective.

Noteworthy is the neural network achieving a 100% predictive accuracy for the measurements of the first probe ( $x = 8.1\text{m}$ ).

Table 5.4 – Average liquid holdup at the first probe ( $x = 8.1\text{ m}$ ) for each gas superficial velocity

Gas superficial velocity (ms <sup>-1</sup> )	Average liquid holdup (Experimental)	Average liquid holdup (Simulated)
<b>6.17</b>	0.0554	0.0554
<b>8.56</b>	0.0257	0.0257
<b>9.42</b>	0.0266	0.0266
<b>10.31</b>	0.0266	0.0266
<b>11.05</b>	0.0264	0.0265
<b>11.83</b>	0.0242	0.0242
<b>12.52</b>	0.0240	0.0240
<b>12.98</b>	0.0253	0.0253

Gas superficial velocity (ms <sup>-1</sup> )	Average liquid holdup (Experimental)	Average liquid holdup (Simulated)
13.25	0.0234	0.0234
13.68	0.0245	0.0245
13.97	0.0220	0.0220
14.22	0.0203	0.0204
14.63	0.0222	0.0222
14.96	0.0246	0.0246
15.31	0.0230	0.0230
15.5	0.0227	0.0227
16.05	0.0205	0.0205

Table 5.5 - Average liquid holdup at the second probe ( $x = 8.3$  m) for each gas superficial velocity

Gas superficial velocity (ms <sup>-1</sup> )	Average liquid holdup value (Experimental)	Average liquid holdup value (Simulated)
6.17	0.0507	0.0508
8.56	0.0157	0.0157
9.42	0.0116	0.0117
10.31	0.0118	0.0118
11.05	0.0116	0.0116
11.83	0.0119	0.0119
12.52	0.0113	0.0113
12.98	0.0128	0.0128
13.25	0.0153	0.0153
13.68	0.0158	0.0158
13.97	0.0175	0.0175
14.22	0.0110	0.0110
14.63	0.0114	0.0114
14.96	0.0165	0.0165
15.31	0.0144	0.0144
15.50	0.0124	0.0125
16.05	0.0107	0.0107

Table 5.6 - Average liquid holdup at the third probe ( $x = 8.5$  m) for each gas superficial velocity

Gas superficial velocity ( $\text{ms}^{-1}$ )	Average liquid holdup value (Experimental)	Average liquid holdup value (Simulated)
6.17	0.0499	0.0499
8.56	0.0174	0.0174
9.42	0.0146	0.0146
10.31	0.0152	0.0152
11.05	0.0169	0.0170
11.83	0.0173	0.0173
12.52	0.0156	0.0156
12.98	0.0162	0.0162
13.25	0.0154	0.0155
13.68	0.0159	0.0159
13.97	0.0177	0.0177
14.22	0.0148	0.0148
14.63	0.0135	0.0135
14.96	0.0183	0.0184
15.31	0.0197	0.0197
15.5	0.0159	0.0159
16.05	0.0136	0.0136

Finally, a graph of liquid holdup for all three probes against gas superficial velocity depicted in Figure 5.19 shows an average downward sloping trend; liquid holdup decreases with increasing gas superficial velocity.



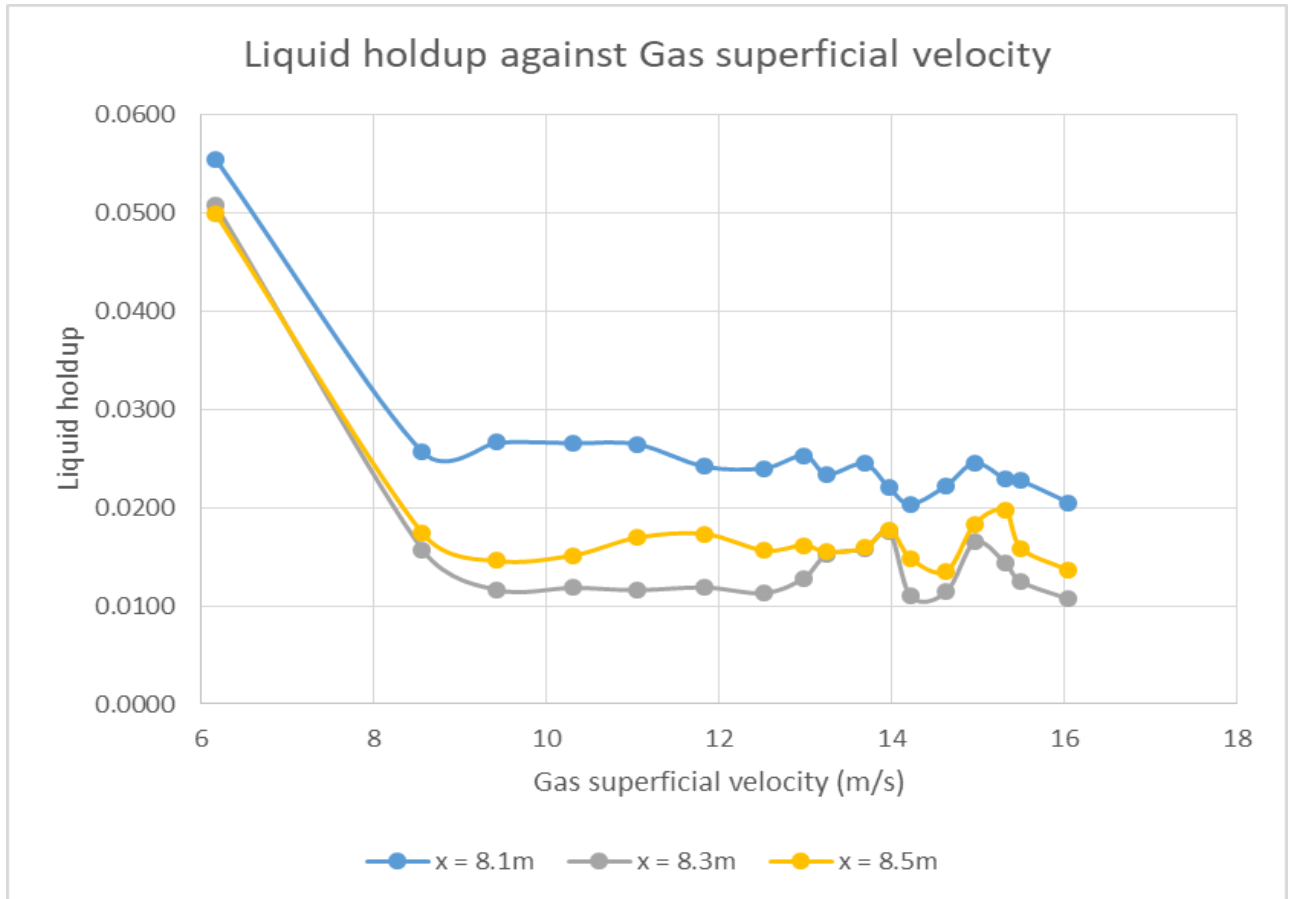


Figure 5.19 – Liquid holdup against Gas superficial velocity

## 5.4. Frequency basis

### Crossplot of Experimental and Simulated Frequencies

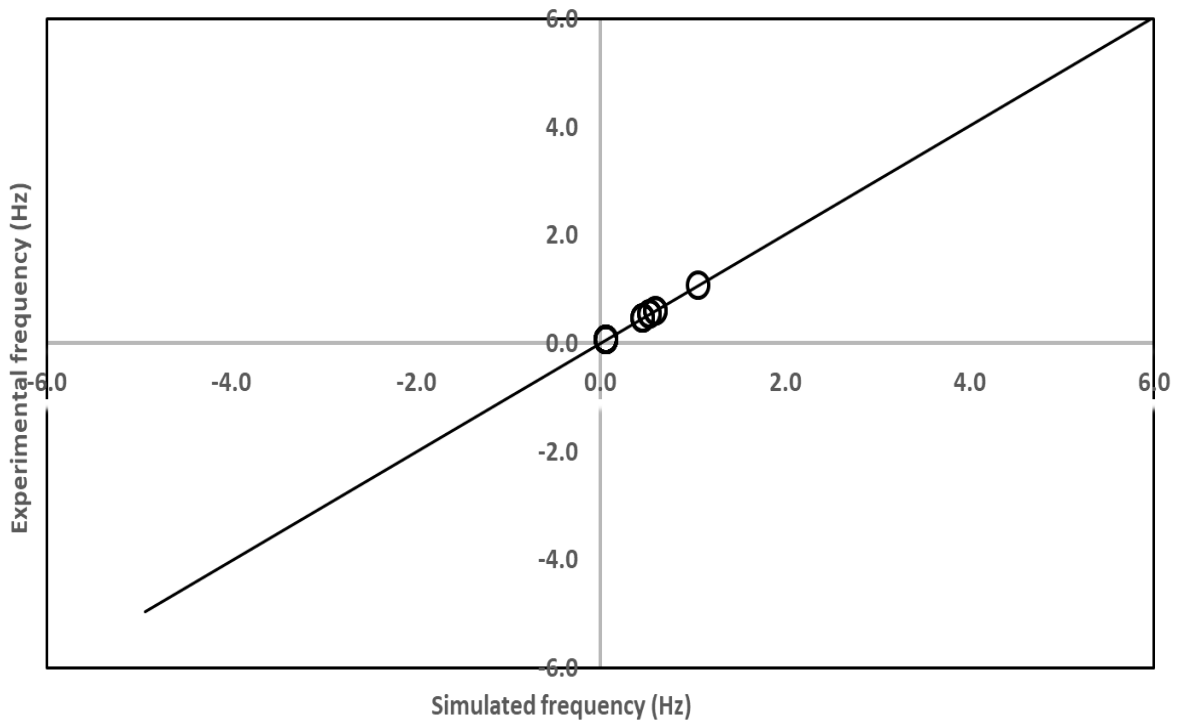


Figure 5.20 – Crossplot of Experimental and Simulated frequencies

Figure 5.20 shows that the cross plot shows 100% agreement between the neural network and experimental values for frequency calculations. This further shows the efficiency of the neural network.

## 5.5. Structure velocity basis

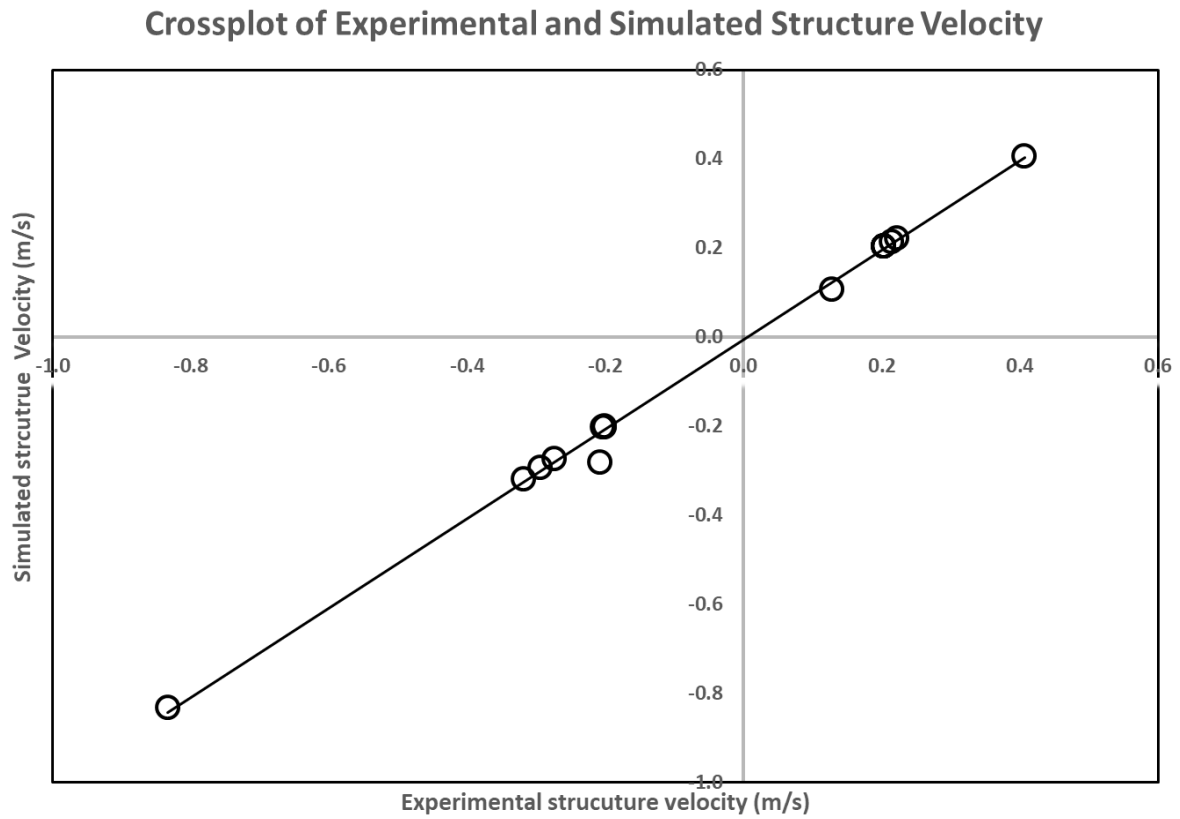


Figure 5.21 - Crossplot of Experimental and Simulated Structure velocity

A slightly decreased level of agreement is noted for structure velocities as shown in Figure 5.21, although there still exists a high level of agreement. This represents the final check of the neural network's efficiency.

## CHAPTER SIX

### CONCLUSION & RECOMMENDATIONS

#### 6.1. Summary and Conclusions

Lack of substantial literature exists for the prediction of liquid holdup and flow behaviour during annular flow. A neural network of a specific design was able to accurately predict liquid holdup during annular flow, in this research work. Furthermore, the utilized approach could be modified as appropriate and used to solve other Flow Assurance problems.

In this research, experimental annular flow data containing liquid holdup against time was fed into a neural network. Data represented the liquid holdup measurements at three different probes, each located at different points across the air–water system. Also, liquid holdup was measured for 17 different systems each having different gas superficial velocities, whilst the liquid velocity was maintained in all cases. The neural network was trained via the Levenberg-Marquadt algorithm in all cases.

It was noted that neural network architectures made up of a maximum of 10 hidden neurons and a minimum of 50 delays accurately predicted liquid holdup values for all systems, regardless of the probe location and liquid and gas superficial velocities. Furthermore, prediction was carried out efficiently; reasonable time and memory was utilized in training, testing and validating the neural network.

The neural network's >90% predictive accuracy was validated by finding the average liquid holdup in experimental and simulated cases; no differences in results were noted. Structural velocity and frequency were also used to validate the neural network's efficiency.

#### 6.2. Recommendations

Future and more detailed research should attempt to focus on establishing relationships between liquid holdup and time. The different time series charts in this research work portray seasonality and trend; an equation should thus be able to provide accurate liquid holdup results. Different neural network architectures where their independent variables could be inputted (surface tension, gas superficial velocity liquid superficial velocity) should also be tested. This would provide a better understanding on the modalities of neural networks. Such different neural network setups need not be on only annular flow. Including other flow patterns would

help identify if results obtained in this research work are peculiar to only annular flow or could be extended to other flow patterns.

In this research, only gas superficial velocity was varied; it would be advantageous to test the neural network architectures on data where liquid superficial velocity is varied. The validation performance would hint at where extra efforts need be directed. The training algorithm utilized could also be changed and its effect on the neural network accuracy noted.

Finally, experimental data of different liquid-gas systems should be tested against neural networks; findings could establish a direction for the utilization of machine learning for flow assurance in the oil & gas sector.

Implementing neural networks in different manners as stated above, would provide extra literature further enriching the few existing literature present.

## REFERENCES

1. P.O. Ayegba, M. Abdulkadir, V. Hernandez-Perez, I.S. Lowndes, B.J. Azzopardi (2017) 'Applications of artificial neural network (ANN) method for performance prediction of the effect of a vertical 90° bend on an air–silicone oil flow', *Journal of the Taiwan Institute of Chemical Engineers*, 74(17), pp. 59 - 64.
2. Abdulkadir, M. (2020) *Supervisor Meetings*.
3. Ali and Tawfiq, F. (2019) *Algorithm*, Available at: <https://whatis.techtarget.com/definition/algorithm> (Accessed: 14th August 2020).
4. Alpaydin, E. (2010) *Introduction to Machine Learning*, 2nd edn., United States of America: MIT Press.
5. Baker, O. (1954) *Simultaneous Flow of Oil and Gas*, *Oil and Gas Journal*, 53, pp.185-195.
6. Chauhan, N.S (2020) *Decision Tree Algorithm, Explained*, Available at: <https://www.kdnuggets.com/2020/01/decision-tree-algorithm-explained.html> (Accessed: 5th August 2020).
7. Chollet, F. (2017) *Deep Learning with Python*, United States of America: Manning Publications.
8. G. F. Hewitt and D. N. Roberts. (1969) *Studies of Two-Phase Flow Patterns by Simultaneous Flash and XRay Photography*, AERE-M2159
9. Geocities *Liquid holdup*, Available at: <http://www.geocities.ws/abouelsaoud/productionstorage/liquidholdup.pdf> (Accessed: 30th November 2017).
10. Golan, L.P. and Stenning, A.H. (1969) *Two-Phase Vertical Flow Maps*, *Proc. Inst. Mech. Eng.* Vol. 184 (3C), pp. 110-116.
11. Guo, Y. (2017) *The 7 Steps of Machine Learning*, Available at: <https://towardsdatascience.com/the-7-steps-of-machine-learning-2877d7e5548e> (Accessed: 14th October 2020).
12. Gupta, D. (2018) *Mathematics for Machine Learning: Linear Regression & Least Square Regression*, Available at: <https://towardsdatascience.com/mathematics-for-machine-learning-linear-regression-least-square-regression-de09cf53757c> (Accessed: 18th September 2020).

13. Hagan, T., Demuth, H., Beale, M. and Jesús, O. (2014) *Neural Network Design*, 2nd edn., Online: Martin Hagan.
14. Izaugarat, E. (2018) *Understanding Neural Networks: What, How and Why?*, Available at: <https://towardsdatascience.com/understanding-neural-networks-what-how-and-why-18ec703ebd31> (Accessed: 22nd October 2020).
15. Jacobs, T. (2020) 'Firm That Transforms Surface Properties With Lasers Wins Top Prize at ATCE Startup Village', *Journal of Petroleum Technology*, (), pp. [Online]. Available at: <https://pubs.spe.org/en/jpt/jpt-article-detail/?art=7737> (Accessed: 14th October 2020).
16. Luhaniwal, V. (2019) *Analyzing different types of activation functions in neural networks — which one to prefer?*, Available at: <https://towardsdatascience.com/analyzing-different-types-of-activation-functions-in-neural-networks-which-one-to-prefer-e11649256209> (Accessed: 22nd October 2020).
17. Mandhane, J.M., Gregory, G.A., and Aziz, K. (1974) *A flow pattern map for gas-liquid flow in horizontal pipes*. *International Journal of Multiphase Flow* 1, 537-553.
18. Marsland, S. (2015) *MACHINE LEARNING An Algorithmic Perspective*, 2nd edn., United States of America: CRC Press.
19. Mayo, M. (2017) *Neural Network Foundations, Explained: Updating Weights with Gradient Descent & Backpropagation*, Available at: <https://www.kdnuggets.com/2017/10/neural-network-foundations-explained-gradient-descent.html> (Accessed: 11th September 2020).
20. Michaelides, E., Crowe, C. and Schwarzkopf, J. (2017) *Multiphase Flow Handbook*, 2nd edn., United States of America: Taylor & Francis Group.
21. Nilsson, N. J. (2005). *Introduction to Machine Learning*. Stanford, CA.
22. Oil & Gas IQ Editor (2018) *What is flow assurance?*, Available at: <https://www.oilandgasiq.com/oil-and-gas-production-and-operations/news/what-is-flow-assurance> (Accessed: 1st September 2020).
23. Paran, M. and Palermo, T. (2020) *Deep Offshore Flow Assurance*, Available at: <https://www.ep.total.com/en/areas/deep-offshore/flow-assurance-sensitive-issue-any-oil-development-project> (Accessed: 2nd October 2020).
24. Petroleum Economist (2006) *The billion-dollar blockage*, Available at: <http://dev.petroleum-economist.com/articles/upstream/technology/2006/the-billion-dollar-blockage> (Accessed: 15th September 2020).

25. Sun, B. (2016) *Multiphase Flow in Oil and Gas Well Drilling*, Singapore: Wiley & Sons (Asia) Pte Ltd Pacific, John.
26. Taitel, Y. and Dukler, A. E. (1976) *A Model Of Predicting Flow Regime Transitions In Horizontal And Near Horizontal Gas-Liquid Flow*. *AIChE J.*, 22:47–55
27. Tay, K. (2017) *Terminology Explained: What is multiphase flow?*, Available at: <https://blogs.dnvgl.com/software/2017/06/terminology-explained-multiphase-flow/> (Accessed: 30th June 2017).
28. Theobald, O. (2017) *Machine Learning For Absolute Beginners*, 2nd edn., : Oliver Theobald.
29. Wasserman, L. (2004) *All of Statistics: A Concise Course in Statistical Inference*, United States of America: Springer Texts in Classics.
30. Whalley, P. B. (1987) *Boiling, condensation, and gas-liquid flow*. Oxford Oxfordshire. New York: Clarendon Press; Oxford University Press
31. Yale University (2018) *Multiple Linear Regression*, Available at: <http://www.stat.yale.edu/Courses/1997-98/101/linmult.htm> (Accessed: 5th August 2020).
32. Yiu, T. (2019) *Understanding Random Forest*, Available at: <https://towardsdatascience.com/understanding-random-forest-58381e0602d2> (Accessed: 9th August 2020)