

**IZMIR KATIP CELEBI UNIVERSITY ★ GRADUATE SCHOOL OF NATURAL AND  
APPLIED SCIENCES**

**FUZZY LOGIC MODELLING OF SEDIMENT TRANSPORT IN ANNULUS**

**M.Sc. THESIS**

**Tevfik Denizhan MÜFTÜOĞLU**

**Department of Civil Engineering**

**Thesis Advisor: Assoc. Prof. Mehmet SORGUN**

**JUNE 2016**

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**İZMİR KATİP ÇELEBİ ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ**

**İKİ BORU ARASINDAKİ SEDİMENT TAŞINIMININ  
BULANIK MANTIKLA MODELLENMESİ**

**YÜKSEK LİSANS TEZİ**

**Tevfik Denizhan MÜFTÜOĞLU  
(Y140104006)**

**İnşaat Mühendisliği Bölümü**

**Tez Danışmanı: Doç. Dr. Mehmet SORGUN**

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**Tevfik Denizhan MÜFTÜOĞLU**, a **M.Sc.** student of **IZMIR KATIP CELEBI UNIVERSITY Graduate School of Natural and Applied Sciences**, Y140104006, successfully defended the **thesis** entitled “**FUZZY LOGIC MODELLING OF SEDIMENT TRANSPORT IN ANNULUS**”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

**Thesis Advisor : Assoc. Prof. Mehmet SORGUN** .....

Izmir Katip Celebi University

**Jury Members : Assoc. Prof. Ayşegül ALAYBEYOĞLU YILMAZ** .....

Izmir Katip Celebi University

**Asst. Prof. Ahmet Ali KUMANLIOĞLU** .....

Celal Bayar University

**Date of Submission : 06 June 2016**  
**Date of Defense : 22 June 2016**

*To my family,*

## **FOREWORD**

In the following thesis, I have tried to give a new perspective for modelling of sediment transport in an annulus. The introduced model is Fuzzy Logic based and with its point of view, it aims to bring a different approach compared to the other theoretical and experimental approaches.

It has been a remarkable experience working on this kind of subject for my thesis. This master thesis was prepared at İzmir Katip Çelebi University under the supervision of Assoc. Prof. Mehmet Sorgun. I would like to give my heartfelt gratitude to him for his guidance, motivation and invaluable advice throughout my education.

I would like to also give my sincere thanks to my family, my relatives and persons who always encourage me by being at my side no matter what.

I believe that I presented an useful study which brings one of the precursor touches that incorporates a different reasoning process in contradistinction to former approaches.

June 2016

Tevfik Denizhan MÜFTÜOĞLU  
(Civil Engineer)

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## ABBREVIATIONS AND NOMENCLATURE

<b><i>A</i></b>	: Area [ $L^2$ ]
<b><i>AAE</i></b>	: Average Absolute Error (psi/ft)
<b><i>AAPE</i></b>	: Average Absolute Percent Error
<b><i>ANN</i></b>	: Artificial Neural Network
<b><i>A<sub>r</sub></i></b>	: Cuttings Bed Thickness
<b><i>A<sub>bed</sub></i></b>	: Area which is Occupied by Stationary Cuttings in the Annulus Cross-Section
<b><i>A<sub>wellbore</sub></i></b>	: Area of Wellbore, the Total Flow Area.
<b><i>c</i></b>	: Cuttings
<b><i>D, d</i></b>	: Diameter [ $L$ ]
<b><i>D<sub>0</sub></i></b>	: Diameter of Outer Pipe [ $L$ ]
<b><i>D<sub>i</sub></i></b>	: Diameter of Inner Pipe [ $L$ ]
<b><i>d<sub>c</sub></i></b>	: Diameter of Cuttings [ $L$ ]
<b><i>CFD</i></b>	: Computational Fluid Dynamics
<b><i>FL</i></b>	: Fuzzy Logic
<b><i>ft</i></b>	: Feet
<b><i>g</i></b>	: Gravitational Constant [ $L/t^2$ ]
<b><i>hr</i></b>	: Hour
<b><i>L</i></b>	: Length
<b><i>m</i></b>	: Mass
<b><i>M. B.</i></b>	: Moving Bed
<b><i>Q</i></b>	: Flow Rate [ $L^3/t$ ]
<b><i>RMSE</i></b>	: Root Mean Square Error (psi/ft)
<b><i>ROP</i></b>	: Rate of Penetration [ $L/t$ ]
<b><i>RPM</i></b>	: Revolutions per Minute, Pipe Rotation Speed
<b><i>t</i></b>	: Time
<b><i>V</i></b>	: Velocity [ $L/t$ ]
<b><math>\rho</math></b>	: Density [ $m/L^3$ ]
<b><math>\rho_c</math></b>	: Density of Cuttings [ $m/L^3$ ]
<b><math>\theta</math></b>	: Inclination
<b><math>\Omega</math></b>	: Rotation [ $1/t$ ]
<b><math>\mu</math></b>	: Viscosity [ $m/(Lt)$ ]



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## **FUZZY LOGIC MODELLING OF SEDIMENT TRANSPORT IN ANNULUS**

### **SUMMARY**

The understanding of sediment transport with fluid in pipes is one of the important issues in hydraulics engineering. If the fluid velocity is lower than a critical value, a stationary cuttings bed develops, which may cause excessive head loss. In this study, a Fuzzy Logic (FL) model is developed to estimate stationary cuttings bed thickness inside the annulus. Experimental data is collected from literature in order to train proposed models. Results showed that the cuttings bed thickness could be estimated using the developed model with a reasonable accuracy when compared with the experimental results. Also, the thickness of the stationary bed can be estimated within an error range of  $\pm 6.8$  %, more accurately than the widely used models available in the literature.

**Keywords:** cuttings bed thickness, fuzzy logic, liquid-solid flow, sediment transport

## İKİ BORU ARASINDAKİ SEDİMENT TAŞINIMININ BULANIK MANTIKLA MODELLENMESİ

### ÖZET

Boru içerisindeki akışkanlarla sediment taşınımının anlaşılması hidrolik mühendisliğindeki en önemli konulardan birisidir. Eğer akışkan hızı kritik bir değerden daha küçükse, çok büyük miktarda hidrolik yük kaybına sebep olabilecek yerleşik bir kesinti yatağı oluşmaktadır. Bu çalışmada, iki boru arasında oluşan yerleşik kesinti yatağı kalınlığını tahmin etmek için bir bulanık mantık modeli geliştirilmiştir. Önerilen modeli meydana getirmek için literatürden deneysel veriler alınmıştır. Geliştirilen model kullanılarak elde edilen sonuçlar deneysel sonuçlarla karşılaştırıldığında, modelin kesinti yatağı kalınlığını uygun doğrulukla tahmin edilebildiği ortaya çıkmıştır. Ayrıca, yerleşik yatak kalınlığı  $\pm 6.8$  %'lik bir hata aralığı içerisinde, literatürde yer alan ve yoğun olarak kullanılan diğer modellerden daha yüksek doğrulukla tahmin edilebilmektedir.

**Anahtar Kelimeler:** yatak kesinti kalınlığı, bulanık mantık, sıvı-katı akım, sediment taşınımı

## **1. INTRODUCTION**

### **1.1 General Description**

Accurate prediction of cuttings bed thickness in sediment transport has great importance in hydraulic engineering. The interest of hydraulic conveying of solid materials has increased due to its economic sake. Solid particles such as coal, gravel, clay, sand, agricultural products and plastics have been generally transported through wellbores and pipes by using fluids.

The hydraulic transportation of sediments in pressurized flows can be defined as transporting maximum amount of solid particles by consuming minimum energy between two specific points [1]. The transportation of solid particles in pipes and annuli is carried through fluids. Many parameters affect the transportation of solid materials in fluids, such as the velocity of the fluid and rheological properties, properties of the solid particles (diameter and specific gravity of a particle), pipe diameter and solid particle concentration. In drilling operations, sediment transportation has crucial importance and it has to be considered as a major factor while designing the transportation system in order to avoid any problems on operational processes.

Forming of stationary cuttings bed is one of the most important issues in the transportation of solid particles. There is a sufficient velocity for transporting sediments and this velocity is called as critical flow velocity. If the velocity of flow is lower than critical velocity, some sediments will not get transported and cuttings bed formation occurs. Cuttings bed formation causes head loss and pipe stuck. Many researchers, in order to calculate critical flow velocity, proposed empirical equations, which were developed by using experimental results [2-6]. The developed equation gives different results from each other and one has to realize that validation of these equations had been obtained at their own specific experimental conditions.

According to previous studies, one of the most important factors that affect solid particle thickness is shear tension [7,8]. The relation between shear tension on solid particle and pressure loss can be revealed from the force balance. Therefore, the main factor influences the thickness of the solid material is pressure losses [9]. In literature, numerous mechanistic models have been presented in order to calculate the pressure losses and thickness of solid materials that create cuttings bed thickness. Those models are divided into two, which are two-layer and three-layer models [10-14]. In two-layer models, it is considered that the system consists steady sediment bed layer and fluid flow layer, but in three-layer models, another layer which is created by hanging sediment particles must be added.

In recent years, many studies in engineering have been presented in the area of computational fluid dynamics (CFD) due to huge developments in technology. Additional to that, numerous studies have been used intelligence models in fluid mechanics. However, a Fuzzy Logic based model for the determination of cuttings bed thickness for sediment transport in an annulus has not been conducted.

## **1.2 Significance and Aim of the Study**

Fuzzy logic is one of the intelligence techniques that used in scientific investigations. Although there are numerous methods for estimating cuttings bed thickness, the Fuzzy Logic approach is a new perspective to estimate cuttings bed thickness in an annulus. It is clearly seen that the fuzzy model gives a different thinking approach which provides sensitive results. Also, this approach eliminates the solid pattern of theories, time and money consumptions. The outputs of the model present broad ranged possibilities on solutions of a problem than rough sketch results. It is believed that this approach provides efficient support for thinking about the varieties of solution for the one who deals the specific problem in drilling industry. The results of the model should be compared with experimental data in order to evaluate how accurate the fuzzy approach is. Comparison of experimental and computational results for estimating cuttings bed thickness in an annulus shows that the Fuzzy Logic model gives sufficiently accurate results. The results of proposed model provide also vital knowledge within very low error range for the companies which drill a well for transporting natural resources from ground to surface and the results prevent companies substantially from improper drilling.

## **1.3 Literature Review**

### **1.3.1 Sediment transport in annuli and pipes**

Cuttings bed describes a ratio between two specific areas in an annulus or pipe, which are the area of the cuttings and the area of the flow. Cuttings bed may cause insufficient hole cleaning. The insufficiency on hole cleaning brings critical problems for drilling processes such as torque and drag increase which occur at the out of the predicted limits and density issues for any kind of work [15,16]. The generated cuttings must be removed by drilling fluid from the wellbore in order to eliminate the mentioned problems above.

Fluids have cuttings lifting ability and this ability is called as carrying capacity. Some of the main factors that influence this ability are properties of fluids and cuttings, velocities, penetration rates, rotation speed of drill pipes, the geometry of holes, the inclination of holes and eccentricities between pipes and holes [17]. All those parameters affect - and are in conjunction with - each other. As soon as liquid flows, hydrodynamic forces are exerted on the solid particles at the cuttings bed.

Studies on sediment transport are mainly classified in three approaches which are theoretical, experimental and numerical approaches.

With a large scale study, some factors that affect cuttings transport performance, such as pipe rotation effect, eccentricity, hole inclination angle and flow regime, have been investigated experimentally. With this study, it was investigated distinctively than previous ones where unrealistically high fluid velocities and short test sections used at without concerning steady-state conditions. [17]. Another experimental study was conducted with a large scale flow loop in order to compare some of the important effects which are dependent on fluid rheology. Yield point of fluids, plastic viscosity, the ratio between the yield point of fluids and plastic viscosity, consistency index and these kinds of parameters were investigated [18]. It was pointed out that for highly inclined wellbores, the turbulent flow improved cuttings transport. At low inclinations fluid rheology becomes insignificant when the effects of it were repressed [18]. The variables which influence cuttings bed thickness were investigated with a multifactor experimentally study. Those variables were stated as annular velocity and density of the fluid, rotation and inclination angle of drillpipe [19]. The rotation of drillpipe was investigated with an experimental

work, and it was expressed that the effect caused by rotation of the drillpipe improved bed erosion. With this experimental work, the relation between pipe rotation and bed thickness irregularities were observed [20]. To increase the drilling fluid capacity for the transportation of cuttings in wells, a laboratory experiment based new approach was proposed. In this approach, it was underlined that the gravitational force increasing the settling level of the cuttings. Due to the mentioned effect of gravitational force, this approach was a new solution for increasing the cuttings transport capacity by counteracting to gravitational force [21].

To describe the bed development mechanism and transportation of cuttings in wells, both theoretical and mechanistic models that have two and three layers were developed [13,16,22,23,25]. To see the performances of these models, they were tested with experimental data obtained from the designed flow loops. Furthermore, to avoid the formation of bed, experimentally, theoretically and numerically attempts have been made. These attempts contained investigations for the determination of critical velocity which prohibits bed formation. A model for the cuttings transportation has been presented based on the attempts mentioned above. This model was developed for the prediction of critical velocity which prevents bed formation by keeping all particles dynamically in horizontal wells as well as deviated wells [12].

As it mentioned above, two and three layer models were developed to describe the bed development mechanism and transportation of cuttings in wells. Similar to one of these models which were developed by Nguyen and Rahman [13], a three layer model was developed. In this model, a simulator that works on bed development and cuttings transport issue was presented. The results that come from this developed simulator were investigated and checked against to the existing models that were already developed by other researchers. At the same study, the lowest pressure gradient was investigated and to determine it, some charts have been developed. These charts were like pathfinder, they used as an operational pilot for the drilling purposes [24]. For the determination of critical fluid velocity, numerical simulation and experimental investigation were used in particularly flow types [26].

A study which was suitable for both highly inclined and horizontal wellbores has been presented. In this study, the critical fluid velocity estimation for preventing stationary bed development have been investigated by using empirical correlations. It



was obtained by flow loop experiments that, 6.0 ft/s was a base fluid velocity. It was underlined that below this velocity a stationary bed formation occurs. It was also obtained that, the no-bed condition was valid if only the fluid velocity were not lower than 8 ft/s. With this study, it was declared as the thickness of developed stationary bed and fluid velocity could be projected with a proper certainty [5]. The rheological character of non-Newtonian fluids become quite different when the fluid flows in an eccentric annulus instead of a concentric annulus. Determination of the annular performance of non-Newtonian fluids is more difficult, especially if the fluid flows in eccentric annulus because of the inner pipe rotation. When the inner pipe rotates, inertia effects and shear thinning lead to changes in frictional pressure loss. At the same time, two tendency appears on frictional pressure loss inside the annulus. Shear thinning is trying to reduce frictional pressure loss, the inertia effects and secondary flows are trying to increase the frictional pressure loss [27]. It was stated that, for frictional pressure loss, a 50% cut occurs because of the eccentricity when compared with concentric annuli [28].

An experimental study revealed that hole cleaning efficiency was increasing when the rotation of drill pipe increases. It was also stated that turbulent flow was a factor for the increase in hole cleaning efficiency [29]. Some experimental investigations were performed for the determination of parameters which alters the transportation of cuttings. The most important factors affected cuttings transport were reported. Also, about hole cleaning, it was obtained that the impact came from the density of the drilling fluids and size of cuttings was moderate [30]. The major factors that alter on the drilling fluids were researched for the capacity of fluid that carries cuttings. It was stated that increasing the hole inclination causes a reduction on the carrying capacity of drilling fluid drastically while the other parameters standing constantly [31].

The rotation effect has different importance in different flow regions. While it is more efficient in the transition region, it is unnoticeable in the turbulent region, particularly in fluids which have low viscosity [32]. According to the field studies, it was stated that rotation of the drill sting mostly causes increased equivalent circulation density [33]. It was stated that some variables significantly affect the efficiency of cuttings transport. These variables were noted as rotation of the drill pipe, rheological parameters of drilling fluids and temperature [34]. Simulation of

two-phase solid-liquid flows in a wellbore annulus has been developed. It was reported quasi-spiral flow was the main pattern for transporting the horizontal annulus [35].

A study which contains a review of cuttings transport in directional wellbores was presented. Also, a through review based on available studies and approaches which interest with hole cleaning problems were presented [36]. It was presented that for the amount of erosion of the cuttings bed in an annulus, pipe orientation is very important and have a substantial effect [37]. The barite particles were investigated and settling of them in the shear flow of Newtonian fluids in a pipe was analyzed [38]. The near-wall turbulence effect in pipelines was investigated to understand the small size particulates selective removal [39].

To predict slug liquid holdup predictions, there are many correlations and mechanistic models in the literature. The mechanistic models and correlations which were available in the literature were investigated and a summary has been presented [40]. Characteristics of sand transport in pipelines for multiphase flows were investigated. According to the investigations, it was stated that the transportation of sand particles was more efficient in terrain slugs, against +5 degree inclined pipes which have stratified wavy flow [41].

An approach was proposed for modelling of non-Newtonian fluid flow behavior in an eccentric annulus. That approach was neural network and evolutionary programming. The neural network model easily outperformed the simulation model when the fluid velocity was high. For non-Newtonian fluids, it was achieved that the eccentricity effect on pressure loss was not as notable as Newtonian fluids. [42].

Correlations for cuttings bed thickness and simple empirical frictional pressure losses were developed. Those developed correlations for cuttings bed thickness and simple empirical frictional losses included rotation of pipe for two-phase solid-liquid flow in wellbores. The pipe rotation effect on transportation of cuttings in wells was experimentally investigated [43].

### **1.3.2 Fuzzy logic and ANN (Artificial Neural Network) applications in other branches**

Fuzzy Logic is a member of the many-valued logic family. The main focus on Fuzzy Logic is different than other fixed and exact reasoning. Fuzzy Logic brings a new approach which is the approximate reasoning. Traditional variables have 0 and 1 values which can be named as false and true. As opposed to traditional, Fuzzy Logic can have variables which have truth-values between 0 and 1.

The computational models, which are neural networks or artificial neural networks, in short ANN, are developed based on biological neural structure. ANN is composed of artificial neurons that are connecting each other. According to the information that a user designs, an ANN structure adapts its own structure to that defined information.

Even though the approaches used by them are different, it can be said that both Fuzzy Logic and Artificial Neural Networks have same working principle fundamentally. Both of them try to exploit the scope of using tolerance towards uncertainty and imprecision. A few of the recent studies related to Fuzzy Logic and Artificial Neural Network other than hydraulics, on different branches are presented below.

Iijima et al. [44] presented an application with Fuzzy Logic system that works on a control system. In their paper, a feed-water control system was introduced in a thermal reactor. The introduced Fuzzy Logic control system controls the steam drum water level more efficiently by enabling operators, against a traditional system.

Gowan [45] introduced an application using Fuzzy Logic for optical character recognition.

Thuillard [46] developed a learning procedure which contains a neuro-fuzzy approach. The developed learning procedure in order to describe a set of data authorizes evaluating numbers and forming the membership functions and also forming the rules of the fuzzy. The mentioned learning procedure was based on the modified the Kohonen's algorithm. The learning algorithm was stated as hierarchical. New fuzzy rules of inference engine and membership functions were developed by taking into account the previous result classification. When learning process completed, by using Boolean Logic rules of inference engine were reduced. The presented method has limiting feature. It restrains the learning process for input

space data which is in the domains. In this way, the limiting feature prevents confusion and provides efficiency on computing time.

Lie and Sharaf [47] introduced a paper which contains a power system stabilizer based on Fuzzy Logic approach. The newly introduced power system stabilizer allows a parallel usage with the traditional analog system with switch criteria.

Ranaweera et al. [48] introduced a study on load forecasting for the short term, with the Fuzzy Logic. In this study, in order to create proposed model, an investigation on a Fuzzy Logic model was presented with its results. The reason of Fuzzy Logic use in this study is incorporating historical data which are weather and load data. In the study, a learning algorithm was used and fuzzy rules were acquired from historical data. It was stated that, with Fuzzy Logic the similar accuracy achieved. Also, it became easier to have forecasts with Fuzzy Logic instead of complicated statistics and also it became easier to have forecasts than neural network methods.

Phillips et al. [49] used Fuzzy Logic approach to develop a fuzzy system for controlling a helicopter's various maneuvers. Due to the difficulty of flying a helicopter, a complex controller was necessary. To fly the helicopter, the Fuzzy Logic system had very detailed rules and associated membership functions which had to give sensitive outputs. An effective control, the rules were very important to write. In order to discover the rules to write, a genetic algorithm was used.

Chen and Xie [50] developed a pen-based drawing system using a Fuzzy Logic concept.

Shabani et al. [51] presented a new approach in order to estimate the power system state which was based on Fuzzy Logic. With a hybrid estimator incorporating Fuzzy Logic concept, crucial improvements were obtained in state estimates. Results were supported by using illustrations to point the advantage of the presented approach.

Kaya et al. [52] presented a study by using Fuzzy Logic which works on digital holographic optimization setup. The Fuzzy Logic approach was the foundation of the prediction system. With this study, it was aimed to optimize digital holographic setup with both Fuzzy Logic prediction approach and experimental method.

Chithra et al. [53] presented a study which included artificial neural networks (ANN) and regression analysis. These methods and approaches were used in order to predict high performance concrete's compressive strength. The data for constructing models

were obtained from laboratory experiments. It was stated that the ANN model gave more accurate results.

Mallela and Upadhyay [54] studied on buckling load prediction. They investigated the buckling load for laminated composite stiffened panels. The paper which was presented aimed to predict the mentioned buckling load by using artificial neural networks (ANN).

Ahmadloo and Azizi [55] presented a study that investigates thermal prediction conductivity of miscellaneous nanofluids by ANN.

Najafi et al. [56] introduced a paper which investigates prediction of vehicle crash rates. A Fuzzy Logic system has been developed in order to investigate the mentioned prediction. The developed system was based on some parameters such as surface friction, speed limit and traffic level. They used Mamdani and Sugeno fuzzy controllers in the model. Their model was suitable for highway agencies. The highway agencies can use the developed model in order to take necessary actions based on crash risk. The model is also a good source for warning drivers for any slippery locations.

Medjber et al. [57] studied on wind energy conversion system by monitoring the maximum power for the system. The proposed study aimed to control the transfer of power between wind energy conversion system by using ANN and Fuzzy Logic.

Macedo et al. [58] proposed a methodology to indicate the order of priority, based on the characteristics of each system. The proposed methodology based on applying Fuzzy Logic for calculating the priority factor for criteria. Technical, economic and environmental criteria could be assessed and quantified with the Fuzzy Logic approach which was working inside the methodology.

Zareiforush et al. [59] presented a study to control the performance of rice whitening machines. The presented study has Fuzzy Logic techniques for an automatic control system which is based on machine vision.

## 2. PROPOSED MODEL

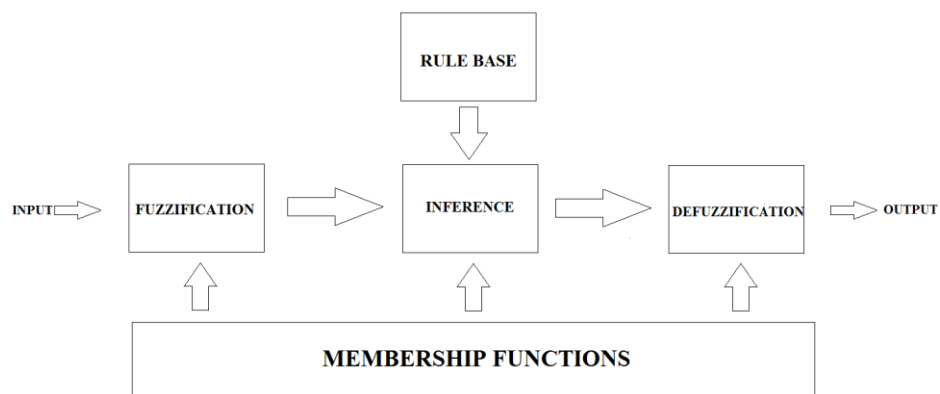
Fuzzy Logic is a member of many-valued logic oppositely Boolean Logic. While Boolean logic, which can be defined as classical logic, is taking only 0 and 1 as truth variables, Fuzzy Logic is taking all real numbers between 0 and 1 as truth variables. Fuzzy Logic has a different perspective for handling the partial truth concept. In short, Fuzzy Logic has the truth values ranged between 0 (completely false) and 1 (completely correct) [60].

### 2.1 The Components of a Fuzzy System

A fuzzy system has mainly four components which are fuzzification component, rule base component, inference engine component and defuzzification component.

- Fuzzification component takes the input values as real numbers and transforms them into fuzzy sets. The membership functions work on the variables which are transformed into fuzzy sets by fuzzification component.
- The rule base is another component that has the rules such as if and then structure. If and then structure is set by users on the determined subject.
- Inference engine component processes the inputs with if and then structure.
- Defuzzification component takes the obtained fuzzy sets by inference component and transforms them into real values.

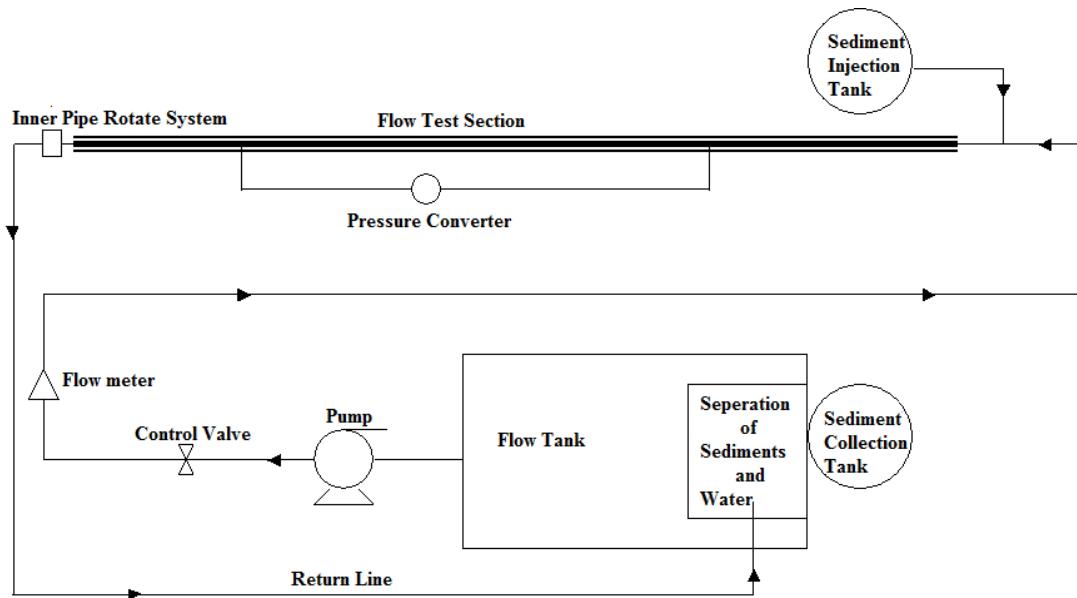
All components of the Fuzzy System were presented in Figure 2.1.



**Figure 2.1** : Main structure of Fuzzy Logic system [61]

## 2.2 Background of the Proposed Fuzzy Model

The experimental data were obtained from the paper which was presented by Sorgun, M. [43]. In order to see the cuttings bed development, he carried out two-phase solid-liquid flow experiments with 101 data, in a cuttings transport flow. An annular test section which can be regulatable for any inclination between vertical and horizontal was used in the study. For all flow tests, the pipe of the flow loop was fully eccentric. With the help of other equipment, many parameters have been applied on flow loop such as flow rate, cuttings injection, the rate of penetration, revolutions per minute etc. In Figure 2.2, the schematic drawing of flow loop system is as follows;

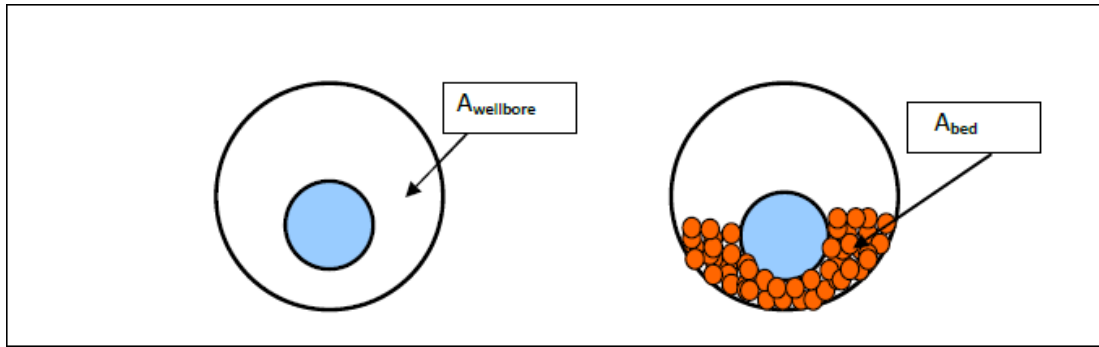


**Figure 2.2 :** Schematic drawing of flow loop system [62]

The ratio between the specific areas, which are the stationary cuttings area ( $A_{bed}$ ) and the total flow area ( $A_{wellbore}$ ), gives the cuttings bed thickness ( $A_r$ ).

$$A_r = A_{bed} / A_{wellbore} \quad (1)$$

The presence of cuttings bed thickness in horizontal eccentric annulus is shown in Figure 2.3.



**Figure 2.3 :** Horizontal eccentric annulus with and without cuttings [62]

Parameters directly or indirectly affect the stationary cuttings bed development in a wellbore as follows.

$$A_r = f(V, ROP, \theta, \mu, \rho, \Omega, D_0, D_i, d_c, \rho_c, g) \quad (2)$$

### 2.3 Fuzzy Mechanism

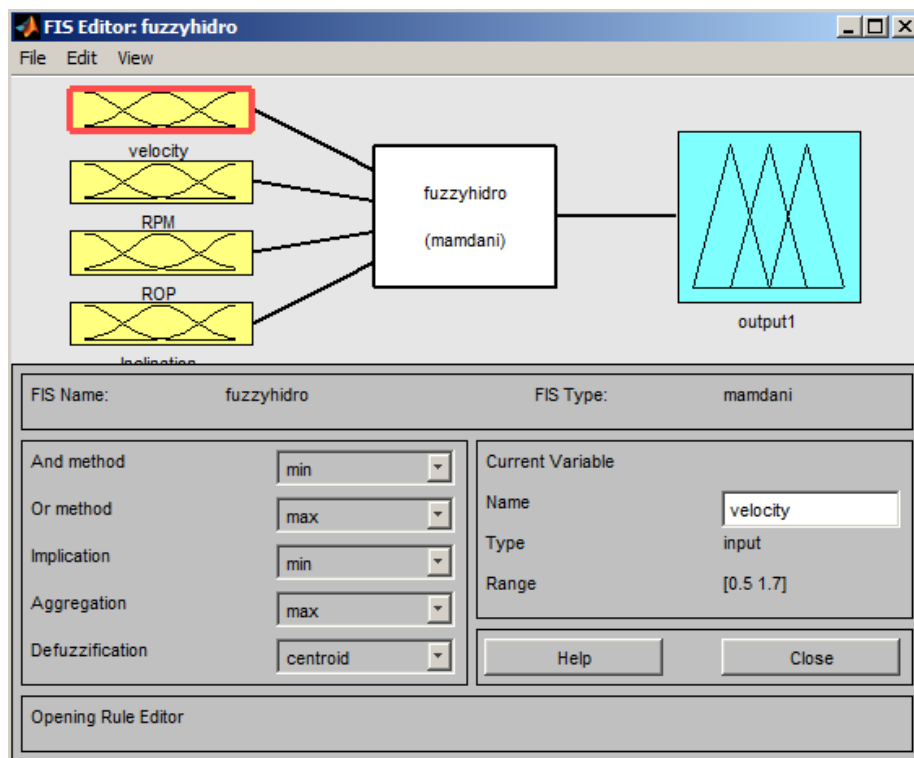
In order to have a proper fuzzy mechanism, it is essentially required to have all parameters that affect the cuttings bed formation. With the guidance of the experimental study, the results were gathered precisely. This precision is necessary in order to define the membership functions into fuzzy mechanism due to needs of accurate results. Few of the experimental results are introduced in Table 2.3 for more visualization.

**Table 2.3 :** Experimental result examples for cuttings bed thickness

Vf(m/s)	ROP(m/s)	RPM(rev/min)	Inclination(degree)	$A_{bed}/A_{wellbore}$
1.115302	0.00254	0	75	0.32490754
1.115302	0.00381	0	75	0.31444743
1.281411	0.00254	0	60	0.23161355
1.281411	0.00381	0	60	0.28947146
1.281411	0.00127	0	75	0.22755178
1.42379	0.00254	0	75	0.20801642
1.589899	0.00127	0	60	0.13048324



As mentioned, several membership functions were defined in the fuzzy model for training inputs for the prediction of the cuttings bed thickness. Those input membership functions are related to Velocity, RPM, ROP and Inclination values. RPM is an abbreviation for revolutions per minute and it represents the measurement of the inner pipe rotation around an axis. ROP stands for rates of penetration and it represents a measurement for the speed where the drill bit breaks the rock. The units for those inputs can be found in page vii, abbreviations and nomenclature section. Besides input membership functions, the rule pattern was introduced inside the interface of the model mechanism. Another section, namely output membership function, was defined in order to have the results which come from the process between inputs and rule patterns. The main structure of Fuzzy Logic that contains input and output membership functions and rule patterns is illustrated in Figure 2.4.



**Figure 2.4 :** Base of the Fuzzy Logic system with its input membership functions, rule patterns and output membership functions

The membership functions for both inputs and outputs were set their boundaries according to the experimental data. There are several membership functions for each input and there are linguistic terms corresponding to each membership function. These linguistic terms were assigned by evaluating the experimental data and they were compared each other to bring sensitive results. The membership functions were analyzed according to their lowest and highest points, ranges, and capabilities. The most capable membership functions were applied to the Fuzzy Logic system in order to satisfy the user's expectation with a high accuracy. When the experimental and Fuzzy Logic results are compared, it can be seen that the triangular membership functions are the best type of membership functions which provide efficiently accurate results. However, triangular and trapezoidal membership functions were used in both inputs and outputs.. In order to create membership functions, the experimental results are grouped with linguistic terms. Some of them are presented in Table 2.4, Table 2.5 and Table 2.6, for the velocity, rop, rpm, inclination inputs respectively.

**Table 2.4 :** Linguistic terms and grouping the experimental data for stuck bed

V	ROP	RPM	INCLINATION	$A_r$	V	ROP	RPM	INCLINATION	$A_r$
m/s	m/s	rev/min	degree						
1.115302	0.00381	0	60	0.314447431	Lowest	High	Low	Low	Stuck

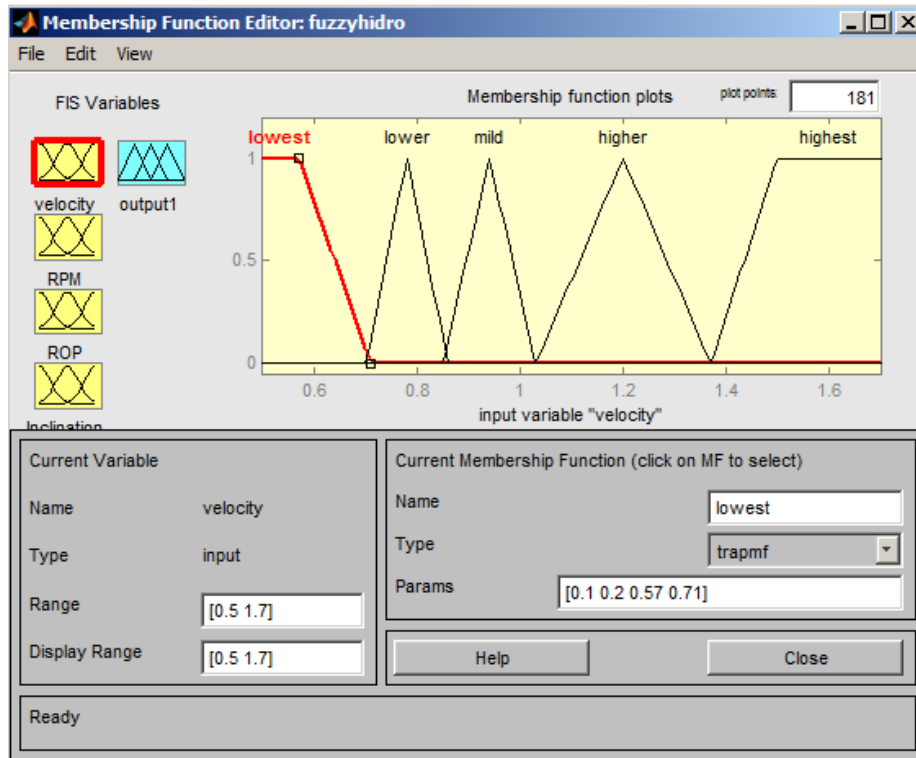
**Table 2.5 :** Linguistic terms and grouping the experimental data for moderate bed

V	ROP	RPM	INCLINATION	$A_r$	V	ROP	RPM	INCLINATION	$A_r$
m/s	m/s	rev/min	degree						
1.281411	0.00381	0	90	0,261562225	Lower	High	Low	High	Moderate

**Table 2.6 :** Linguistic terms and grouping the experimental data for moving bed

V	ROP	RPM	INCLINATION	$A_r$	V	ROP	RPM	INCLINATION	$A_r$
m/s	m/s	rev/min	Degree						
1.42379	0.00254	0	75	0.208016415	Mild	Mild	Low	Mild	Movingbed

Membership functions for the velocity inputs were assigned according to the velocity data are shown in Figure 2.5.

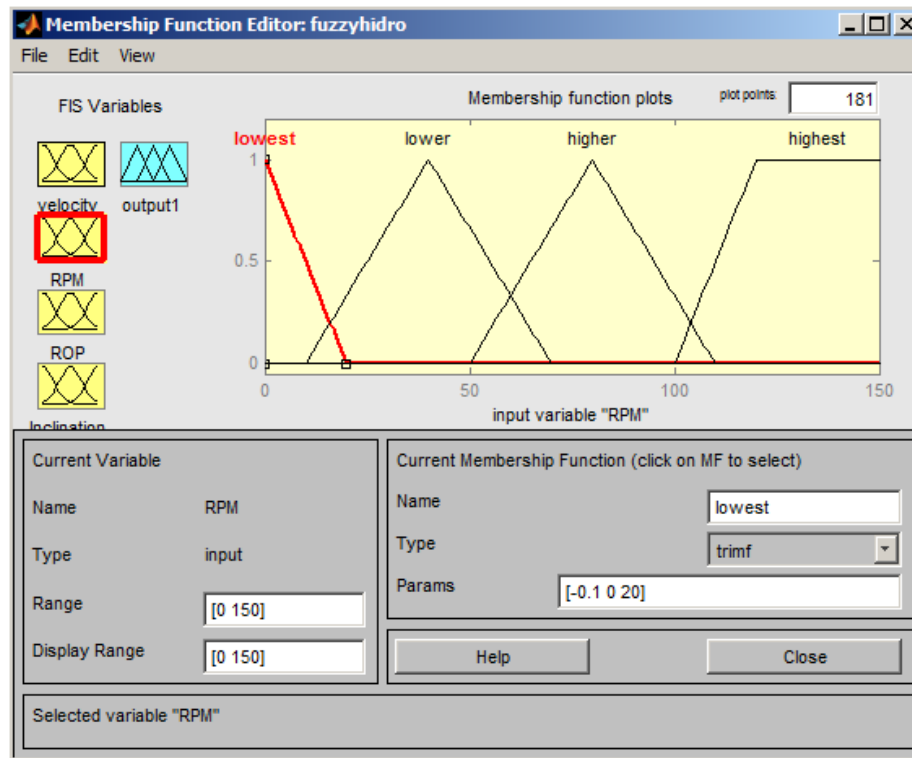


**Figure 2.5** : Defining the velocity membership functions as inputs in the Fuzzy Logic system

Velocity inputs for membership functions were defined as,

- General range for all membership functions : 0.5 – 1.7
- Parameters of “lowest” membership function : 0.1 ; 0.2 ; 0.57 ; 0.71
- Parameters of “lower” membership function : 0.7 ; 0.78 ; 0.86
- Parameters of “mild” membership function : 0.85 ; 0.94 ; 1.03
- Parameters of “higher” membership function : 1.03 ; 1.2 ; 1.37
- Parameters of “highest” membership function : 1.37 ; 1.5 ; 1.82 ; 2.78

RPM values, obtained from the experiments, were assigned according to their minimum and maximum points as membership functions, likewise, velocity values. And the membership functions are illustrated in Figure 2.6.

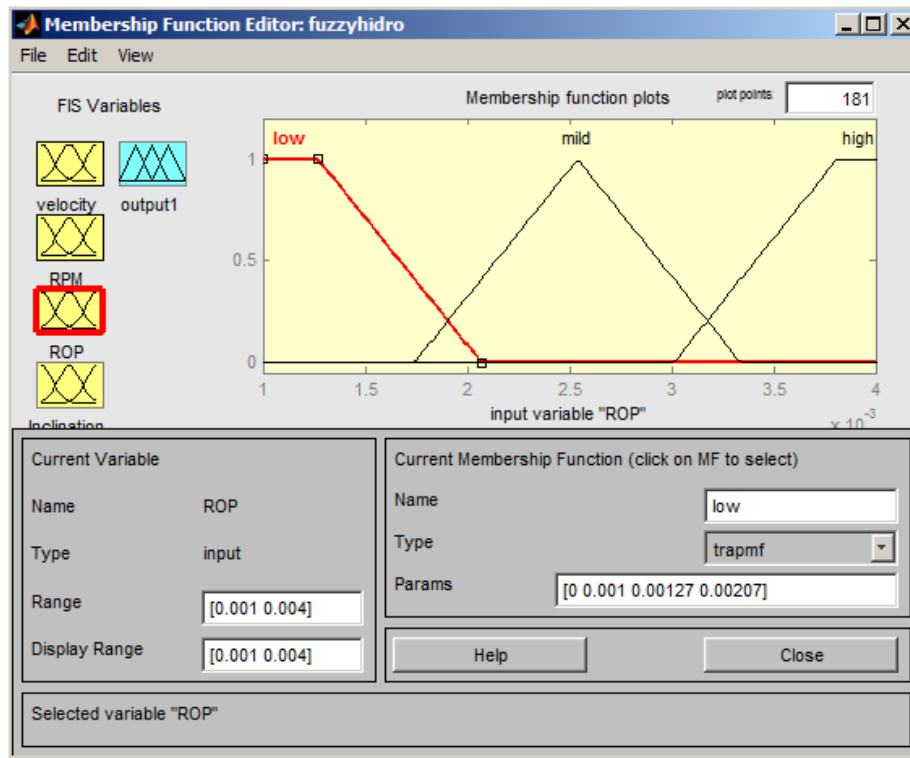


**Figure 2.6** : Defining the RPM membership functions as inputs in the Fuzzy Logic system

RPM inputs for membership functions were defined as,

- General range for all membership functions : 0 – 150
- Parameters of “lowest” membership function : -0.1 ; 0 ; 20
- Parameters of “lower” membership function : 10 ; 40 ; 70
- Parameters of “higher” membership function : 50 ; 80 ; 100
- Parameters of “highest” membership function : 100 ; 120 ; 200 ; 250

ROP values were also assigned by membership functions according to the points that have with the linguistic terms as same as previous inputs. Membership functions of ROP were presented in Figure 2.7.

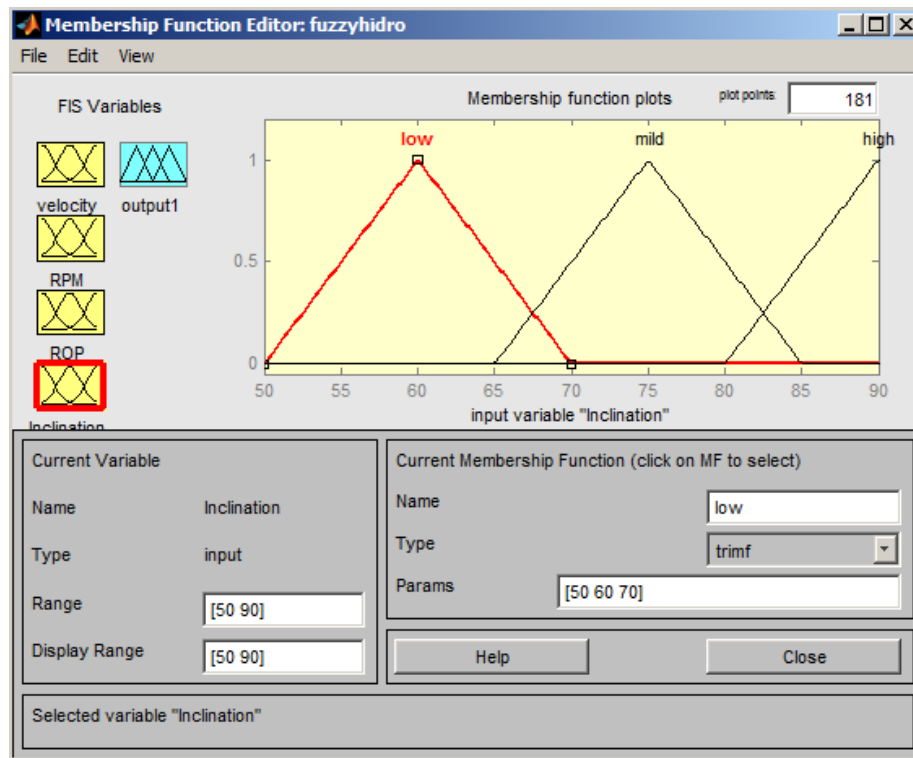


**Figure 2.7 :** Defining the ROP membership functions as inputs in the Fuzzy Logic system

ROP inputs for membership functions were defined as,

- General range for all membership functions : 0.001 – 0.004
- Parameters of “low” membership function : 0 ; 0.001 ; 0.00127 ; 0.00207
- Parameters of “mild” membership function : 0.00174 ; 0.00254 ; 0.00334
- Parameters of “high” membership function : 0.00301 ; 0.00381 ; 0.005 ; 0.006

The last input for the model mechanism was inclination values, and they were assigned as membership functions with their minimum and maximum points and with their linguistic terms, as it was done for the three previous inputs which are Velocity, RPM and ROP values. The membership functions of inclination values are shown in Figure 2.8.

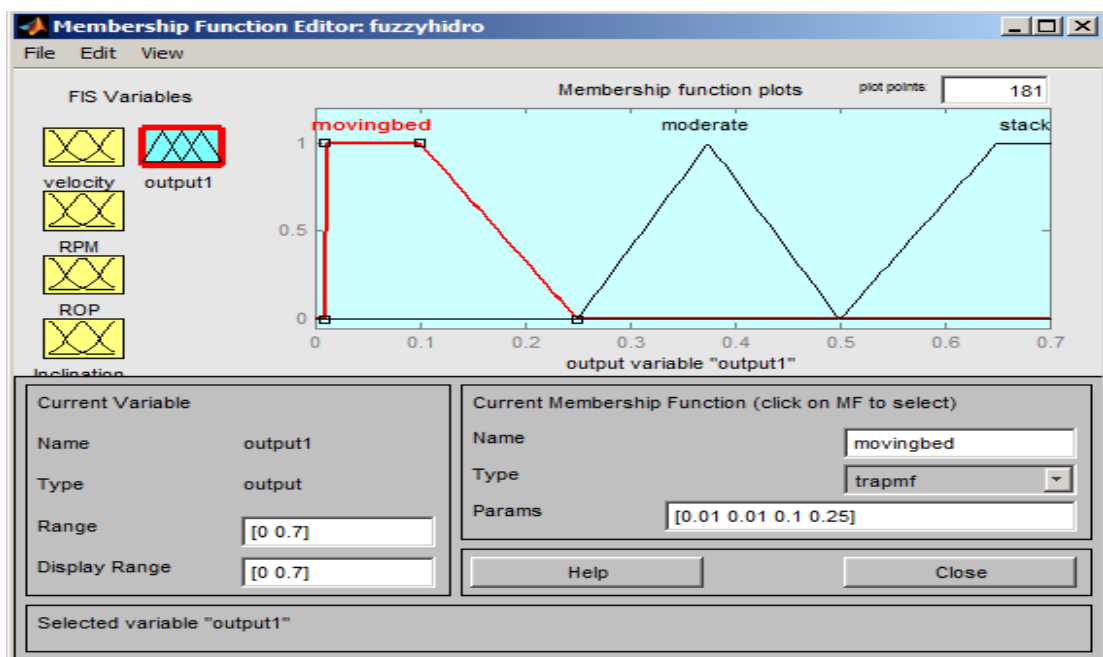


**Figure 2.8 :** Defining the inclination membership functions as inputs in the Fuzzy Logic system

Inclination inputs for membership functions were defined as,

- General range for all membership functions : 50-90
- Parameters of “low” membership function : 50 ; 60 ; 70
- Parameters of “mild” membership function : 65 ; 75 ; 85
- Parameters of “high” membership function : 80 ; 90 ; 100

The output section defines the minimum and maximum points of membership functions with its linguistic terms that classify the results which predict the cuttings bed thickness. Membership functions for the output section were defined as same method as input section. According to the experimental results, the linguistic terms were applied on each membership function and the condition in the wellbore was classified with different geometric shaped membership functions. For accurate results, the nearest points of each limit were used instead of exact values. Due to this reason, sometimes the membership functions don't take exact 0 (zeroes) and 1 (ones), but closest alternatives. It is clearly seen that this thesis focused on the sediment transport and for all experiments cuttings amount presented, instead of the no-cuttings situation. Movingbed, moderate, and stuck linguistic terms represent the instantaneous situation in the wellbore according to the cuttings amount. The membership functions of output section are illustrated in Figure 2.9.

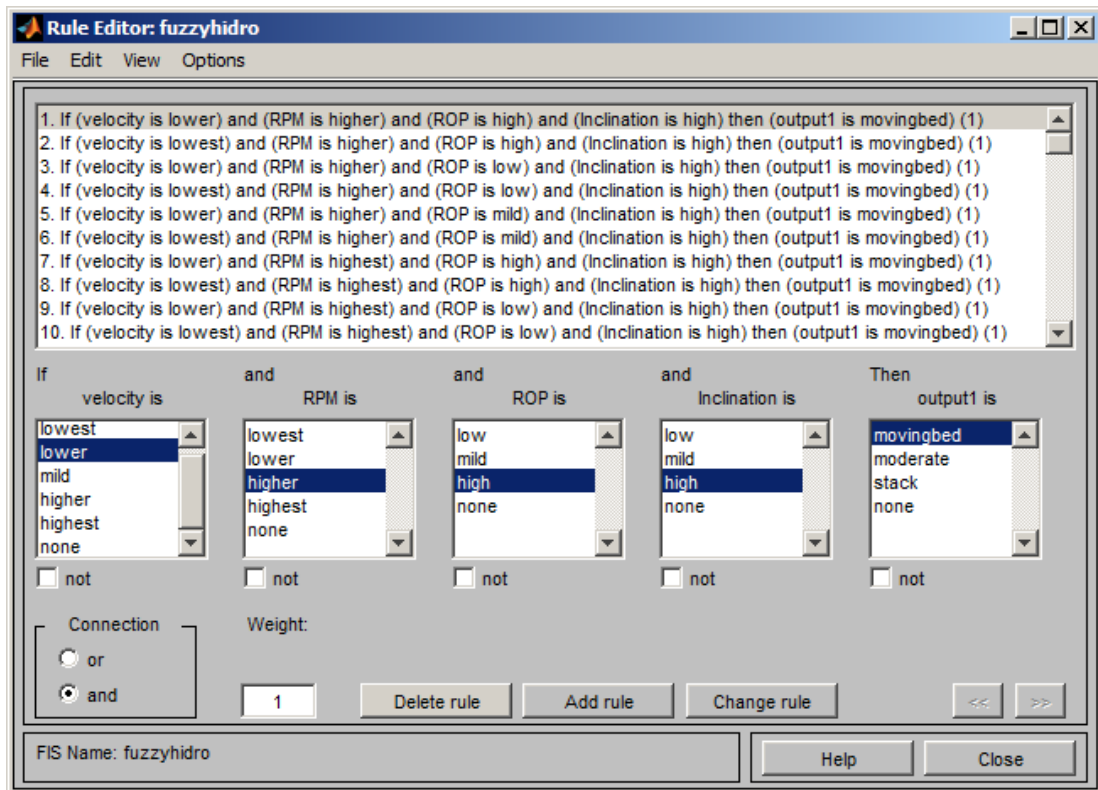


**Figure 2.9 :** Defining output membership functions in the Fuzzy Logic system

Membership functions of output were defined as,

- General range for all membership functions : 0 – 0.7
- Parameters of “movingbed” membership function : 0.01 ; 0.01 ; 0.1 ; 0.25
- Parameters of “moderate” membership function : 0.25 ; 0.375 ; 0.5
- Parameters of “stuck” membership function : 0.5 ; 0.65 ; 0.7 ; 0.8

After assigning the inputs and outputs into the model mechanism, a rule pattern was introduced in this section. This rule pattern combines the possibilities that can have between each other to give outputs as results that we are looking for. This section based on Mamdani method which is very useful. The crisp values, inputs is given by the user according to the data. The membership values are obtained by the user. With these 2-step process, the fuzzification has done. After fuzzification, the fuzzificated values connect with defuzzification component with the help of mamdani method. The Mamdani method processes the fuzzificated data with operators which are if, not (optional), then operators. Also, the and-or connection operators with a weight factor take part in the rule base. Rule pattern and inference engine of Fuzzy Logic system are shown in Figure 2.10.

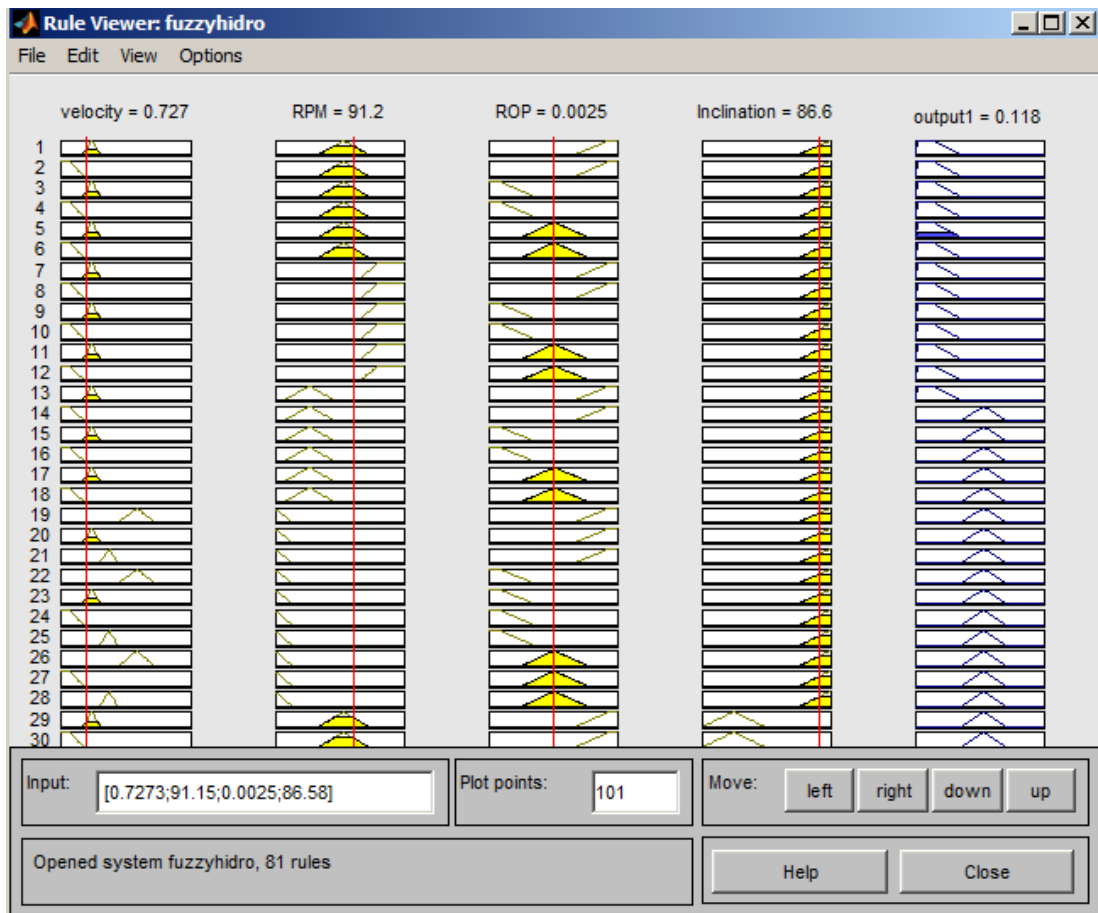


**Figure 2.10 :** Rule pattern and inference engine of Fuzzy Logic system

All these rules are written according to the investigation of experimental data. For all inputs and outputs, the linguistic terms have been defined and they are gathered by groups. After the management of groups, the rule base is created. The rule viewer section which processes the connections between inputs and outputs according to the rule pattern gives more visualization of the whole system. In this way, which input



values are affecting the output are more visible. The draggable verticle line on each membership functions of inputs and the box which enable entering inputs as numerical values change dynamically the output values and colors both input and output membership functions. It contributes to identifying the results momentarily. The rule viewer is presented in Figure 2.11.



**Figure 2.11 :** The graphic visual of the rule engine

### 3. RESULTS AND DISCUSSION

Verification of Fuzzy Logic (FL) model was performed by comparing with the experiment data. The cuttings bed thickness inside the annulus was measured for various hole inclinations from horizontal to 60 degrees, the rate of penetrations from 15 to 45 ft/hr (0.00127 to 0.00381 m/s), flow velocities from 0.68 m/s to 2 m/s, and pipe rotations from 0 to 120 rpm.

At Table 3, the results of FL model demonstrates the performance comparison based on different error metrics. At Table 3, RMSE stands for Root Mean Square Error; AAE means Average Absolute Error and AAPE is used for Average Absolute Percent Error. As seen from Table 3, the results of the fuzzy system are quite similar to the experiment data.

**Table 3 :** Error values of introduced Fuzzy Logic system

RMSE	AAE	AAPE
0.284	0.023	6.8

- RMSE (Root Mean Square Error) =  $\sqrt{\frac{1}{n} \sum_{i=1}^n (f_i - y_i)^2}$  (3)

n represents the number of the sample which is available in the data set.

$f_i$  represents the prediction,  $y_i$  represents the true value.

- AAE (Average Absolute Error) can be called as MAE which is Mean Absolute Error.

$$AAE = MAE = \frac{1}{n} \sum_{i=1}^n |f_i - y_i| = \frac{1}{n} \sum_{i=1}^n |e_i| \quad (4)$$

n represents the number of the sample which is available in the data set.

$f_i$  represents the prediction,  $y_i$  represents the true value.

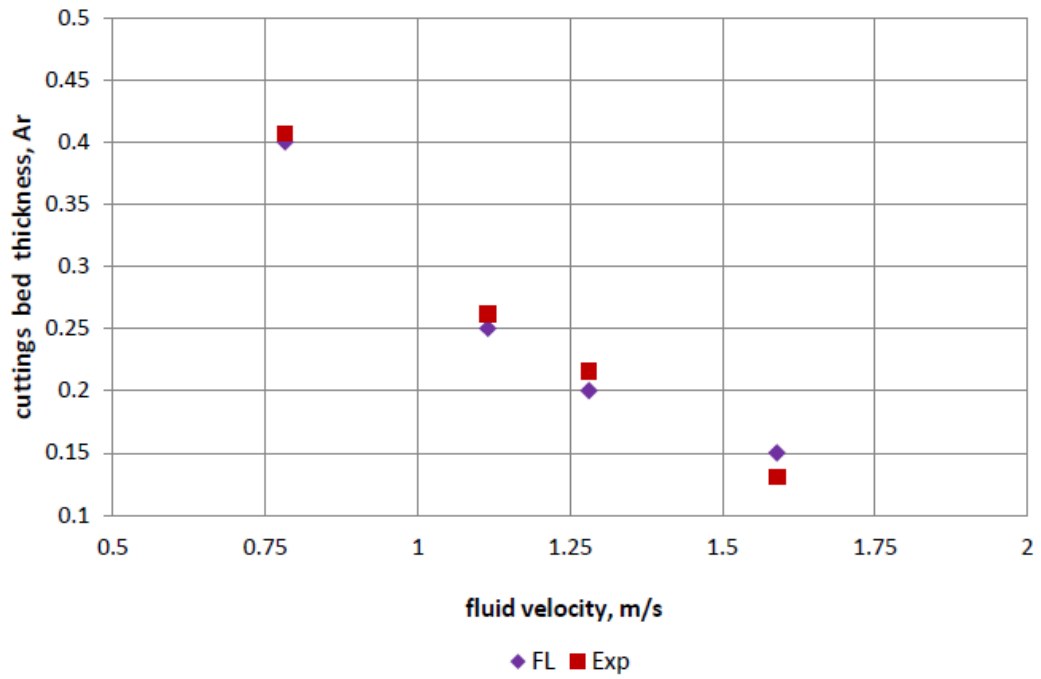
- AAPE (Average Absolute Percentage Error) can be called as MAPE which is Mean Absolute Percentage Error.

$$AAPE = MAPE = \frac{1}{n} \sum_{t=1}^n \left| \frac{A_t - F_t}{A_t} \right| \quad (5)$$

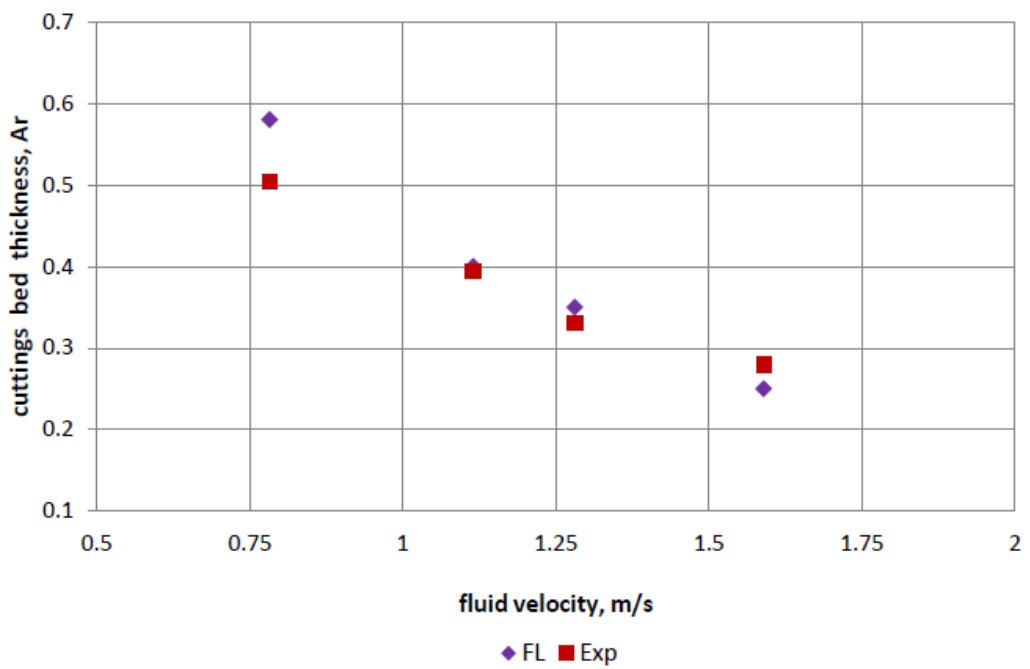
n represents the number of the sample which is available in the data set.

$F_t$  represents the forecast value,  $A_t$  represents the actual value.

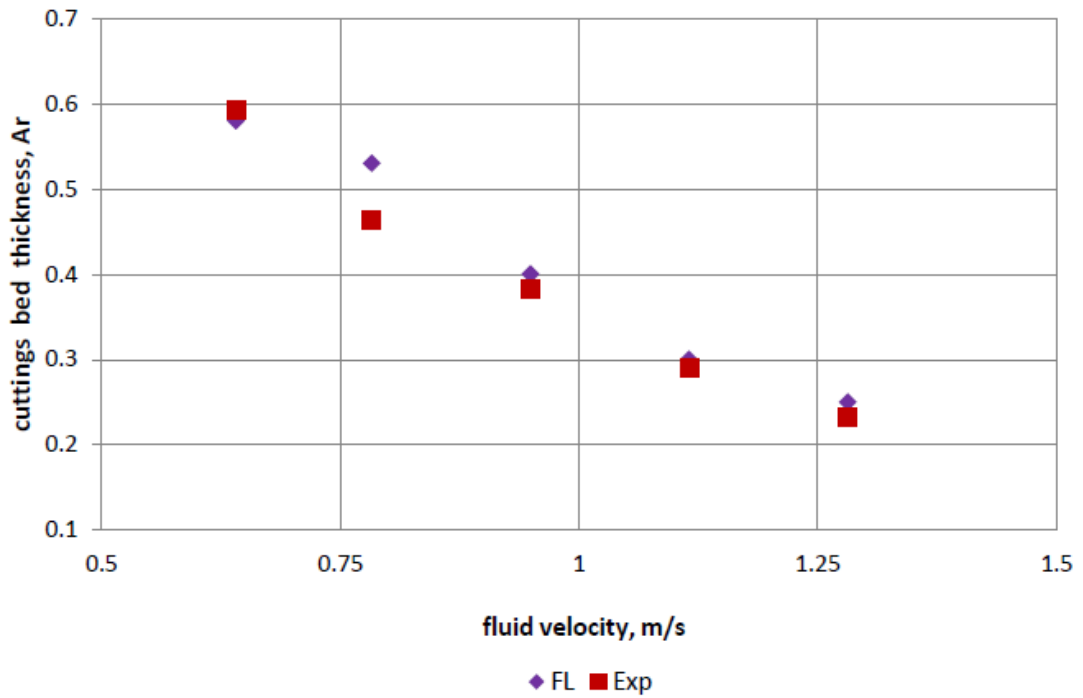
Predicted cuttings bed thickness obtained from FL model are illustrated in Figures 3.1, 3.2, 3.3, 3.4.



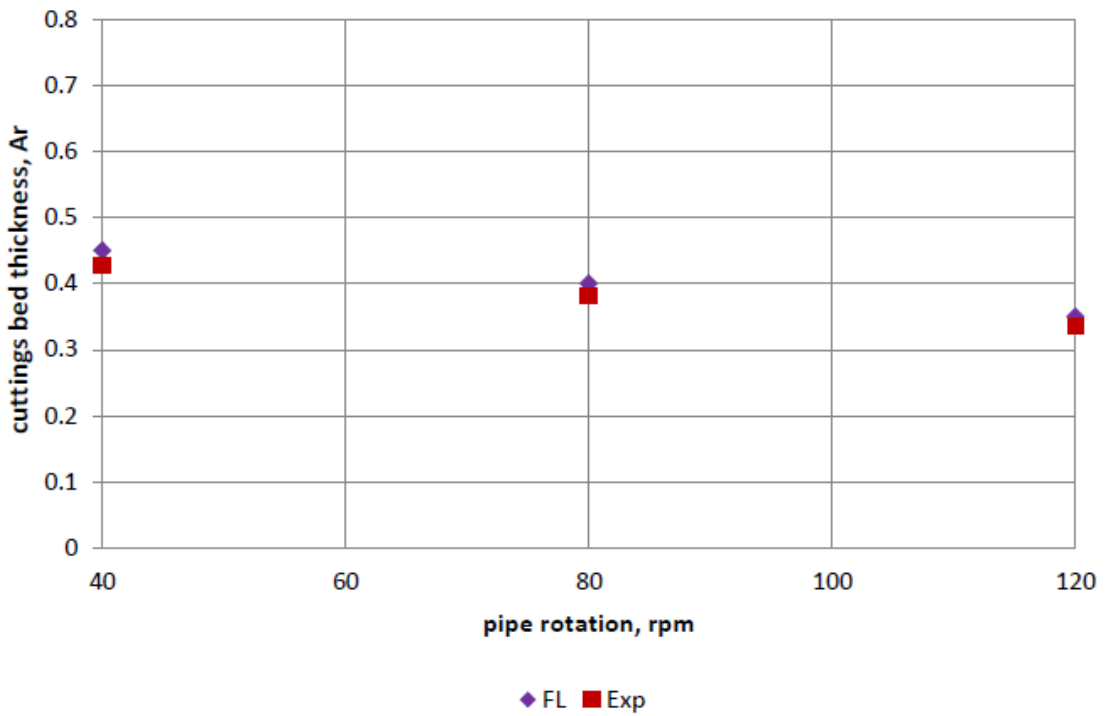
**Figure 3.1 :** Measured and predicted cuttings bed thickness for hole inclination 60 degrees



**Figure 3.2 :** Measured and predicted cuttings bed thickness for hole inclination 75 degrees



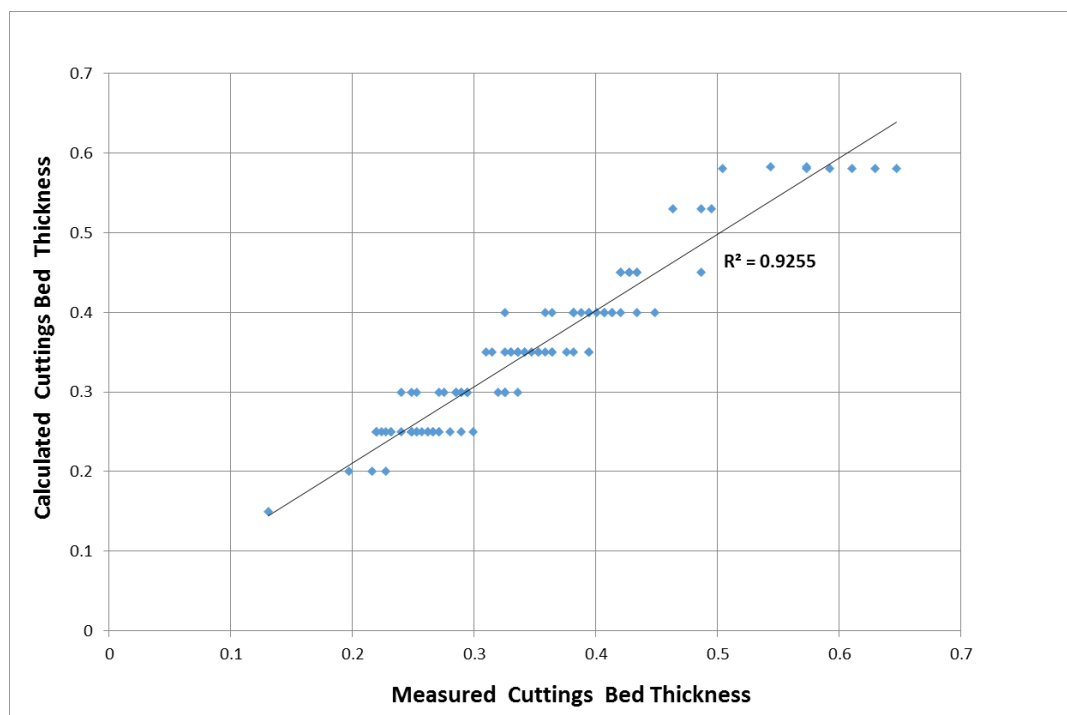
**Figure 3.3** : Measured and predicted cuttings bed thickness for the horizontal wellbore



**Figure 3.4** : Measured and predicted cuttings bed thickness for horizontal wellbore and fluid velocity = 0.64 m/s

After the analysis, it can be seen that pipe rotation speed and fluid velocity decrease cuttings bed thickness inside the annulus for all inclination values. Moreover, it is clear that the model can predict cuttings bed thickness successfully for a given fluid velocity, rate of penetration, hole inclination, pipe rotation speed.

The comparisons between experimental results and fuzzy approach results in the form of  $A_r$ , ( $A_{bed}/ A_{wellbore}$ ), are shown in Figure 3.5. The comparison has 0.93  $R^2$  value (coefficient of determination). Therefore, it can be concluded that the value of the variable among experimental and computational data is sufficiently proportional.



**Figure 3.5 :** Comparison between experimental results and fuzzy approach results

Small -trace- differences in those numerical values with respect to experimental results prove that our simulation based on the Fuzzy Logic system works within acceptable limits. In order to have a position between acceptable limits, membership functions should be very detailed. From this point of view, it means that there should be membership functions very frequently, as much as possible, to have sensitive results in order to shorten the gaps of X (variable) value, which is linked to membership degree. In connection with sensitive numerical results, the first decision point before numerical ones is linguistic terms. Some linguistic terms that have been defined by the user such as low, mild, high are the basic pattern to identify which

classification would be working for the results. After getting the results made by linguistics, numerical results come by with proper synchronization for cuttings bed thickness.

#### **4. CONCLUSIONS**

In this study, cuttings bed thickness inside wellbore is predicted using FL (Fuzzy Logic) model. The cuttings bed thickness estimations are compared with experimental data by Sorgun (2010). Results show that FL model can accurately estimate cuttings bed thickness for two-phase flow inside the wellbore. Also, by using this model, the thickness of the stationary bed can be detected within an error range of 6.81%. It has seen that Fuzzy Logic method for expanding a limited number of experimental data is reasonable and in acceptable error range.

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## CURRICULUM VITAE



**Name Surname:** TEVFIK DENİZHAN MÜFTÜOĞLU

**Place and Date of Birth:** MUĞLA / TURKEY – 02/07/1992

**Adress:** İZMİR / TURKEY

**E-Mail:** td.muftuoglu@gmail.com

### EDUCATION:

#### B.Sc.:

- CELAL BAYAR UNIVERSITY – ENGINEERING FACULTY – CIVIL ENGINEERING DEPARTMENT (MANISA / TURKEY) (2010-2014)
- POLITECHNIKA KRAKOWSKA IM. TADEUSZA KOSCIUSZKI – ENGINEERING FACULTY – CIVIL ENGINEERING DEPARTMENT (KRAKOW/ POLAND) (ERASMUS STUDENT EXCHANGE PROGRAM) (2014)

### PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS1:

- **Müftüoğlu, T. D.**, Sorgun, M., Ülker, E. (2015): A Fuzzy Model to Estimate Cuttings Bed Thickness in Horizontal and Inclined Wellbores. *International Conference on Advances in Applied and Computational Mechanics – ACM 2015*, August 5-7, 2015 İzmir, Turkey.

### OTHER PRESENTATIONS:

- Alaybeyoğlu, A., Özdemir, A., Balbal, K. F., **Müftüoğlu, T. D.** (2016): Fuzzy Logic Based Door Lock-Release Control System For Metro Systems. *International Conference on Research in Education and Science – ICRES 2016*, May 19-22, 2016 Bodrum/Muğla, Turkey.

**TECHNICAL SKILLS:**

- MatLAB
- AutoCAD
- Sap2000
- IdeCAD
- ANSYS
- VISUM
- VISSIM
- Artificial Neural Network
- Genetic Algorithms
- Fuzzy Logic

**CERTIFICATES:**

- Certificate of Appreciation, International Conference on Advances in Applied and Computational Mechanics (ACM 2015, J.N. REDDY)
- IdeCAD Static, Certificate of Achievement (CBÜSEM, Licence No: 2013.0087)
- IdeCAD Static Certificate (IdeCAD Central Office, Licence No: 220113/0192)

**LANGUAGE SKILLS:**

- Turkish (Native)
- English (Fluent)
- Russian (Intermediate)
- Polish (Pre-Intermediate)
- German (Beginner)