Analysis of crude oil fouling deposit in tube and heat exchangers

Abstract

The aim of this research was to investigate the fouling phenomenon in crude oil refining, and to investigate the best time for cleaning as a step to mitigate or prevent fouling. This study also focuses on the phenomenon of fouling in detail, including an investigation of what leads to fouling, how it can be prevented, make recommendations on how best oil and gas companies can increase their production efficiency by mitigating the effects of fouling. Many previous studies, as would be expected, have focused on identifying the factors that lead to fouling with the aim of coming up with fouling management strategies, especially in the context of industrial practice. Some of these strategies that have been suggested so far include cleaning of the heat exchangers, and sometimes, the use of antifoulants. Part of what this research sought to achieve was to determine the ideal cleaning time. The study established that greater heat duty is saved when cleaning is done early than when it is done later. Assertive cleaning results to significant advancement in hydraulic and thermal achievement. The findings of this study also implied that there is need to do the cleaning as early as possible, since this increased the effectiveness. From most of the outputs on different heat exchangers, this study established that cleaning should be done before the 50th day. These results were consistent both in the shell and tube sides.

TABLE OF CONTENTS

1 Chapter 1; Introduction

Fouling, according to Coletti (2014), is a challenging, longstanding, and one of the most costly problems that affect an array of heat transfer applications, and as such, it is imperative to come up with techniques and methodologies that can help in addressing these problems. According to Yeap, Wilson, Polley, and Pugh (2004), environmental policies around the world are becoming more and more stringent, and the refining margins have also tightened, which has led to an inevitable consequence of the need to have a competitive edge in an already very competitive oil industry. The fouling problem has become a key contributor to high costs of production and thus, relatively low efficiency.

According to Yeap, Wilson, Polley, and Pugh (2004), refinery efficiency is critical, and studies have established that its importance does not only affect the profit margins, but can also affect the share price of major oil companies across the world. The question, therefore, becomes, how can energy efficiency be achieved, and what is the most impeding factor. Baweja and Bartaria (2013) arguesthat fouling, which can also be explained as the deposition of unwanted material on heat transfer surfaces, is one of the primary causes of inefficiencies in the refinery processes. This would certainly impact the refinery economics, the health and safety, the operability, and the environmental impact.

The fact that fouling is not only costly and complex, but also a disruptive process, according to Baweja and Bartaria (2013), necessitates the need to come up with lasting solutions using an array of available technologies, since the need for energy efficiency goes beyond just improving the profit margins for oil and gas companies. Energy efficiency is an important environmental goal, and this makes it even more urgent to come up with technologies that could be used to address this fundamental problem in oil refineries.

Expectedly, previous researches have focused on identifying the factors that lead to fouling with the aim of coming up with fouling management strategies, especially in the context of industrial practice. Some of these strategies included the constant cleaning of the heat exchangers, and sometimes, the use of antifoulants (Coletti , 2014). These methods or strategies have, however, not been as effective as the benchmarks would state, and as such, there is room for improvement, which can be done only through further research and incorporation of better technology to address this problem. The need for improvement is particularly in the context of the designs and the condition monitoring of the heat exchangers being used in the oil refineries.

The need to predict, capture, manage, simulate and most importantly, mitigate fouling cannot be overemphasized. Previous experiments have come up with correlations that try to describe the thermal resistance that is given by fouling as a function of the various process conditions and time. These have been captured in mathematical models and equations, by Mostafa (2007) insists on the need to come up with models that consider the deposition of fouling on the tube side, as well as on the shell side.

The need for easier and effective cleaning in the oil refinery process is a key step in the right direction when dealing with the problem of fouling, and according to Basu and Chahar (2013), this can be achieved by allocating liquids or simply fluids with the highest fouling propensity, especially on the tube side in an effort to allow easier, as well as more effective cleaning. The main challenge has always been the fact that not only the shell side is prone to fouling, the shell side too, and this is especially in the refinery applications. This kind of fouling on the shell side, according to Yeap, Wilson, Polley, and Pugh (2004), does not only occur, but in some cases, it could become one of the most dormant resistors to heat transfer. The shell side should, therefore, not be ignored, unless the company is prepared to run a risk of gross errors, especially in the analysis of plant data.   This study examines oil fouling deposit in tube and heat exchangers.

1.1 Background and significance of the study

The oil companies, in many parts of the world, have to face high market competition and significant environment protected policies, which, as Baweja and Bartaria (2013) explains, limit their freedom of operations and dents their profit margins. Hence, the companies have to put their attention at improving the efficiency of energy usage and crude oil production in general (Colleti,F & Hewitt,G 2015). However, crude oil fouling deposit is still a long-standing problem, which suggests that some or most of the techniques put in place already have not been every effective. The crude oil fouling deposit will limit the flow of crude oil in the tube. In extreme situations, the deposit could even lead to pipe plug, which would be a huge impediment on the whole production process. These problems decrease the production efficiency and cost huge amounts of money to clean the furnace and exchangers.

It cost at most 50% of total fouling related cost (Van Nostrand and et 1981). To keep the production, the oil companies have to raise the fuel to maintain the temperature of furnace and exchangers. Van Nostrand and et (1981) estimate there are 1.3bn US$ per year for process side fouling cost in United States. In addition, the equipment cleaning also cost huge sums of money. The full cleaning is an expensive choice, but part cleaning need to consider the cleaning efficiency and cost problem. Hence estimation the fouling level is important part of decrease cost. In other words, the primary problem here is fouling, and one of the surest ways of bringing the mentioned costs down is by coming up with a solution that could address the fouling problem in oil refineries.

As stated earlier in this chapter, the crude oil fouling is a long-standing problem, and so far, it has been a major problem when people and researchers try to predict and analyse the fouling production. A number of mathematical equations and models have already been proposed, but these have not effectively addressed this problem as Mostafa (2007) explains. First of all, it is hard to analyse the ingredient of fouling deposit. Colleti and Hewitt (2015) pointed out that it is still not certain about the chemical structure of fouling and the aspects or factors that lead to the fouling. According to Basu and Chahar (2013), there are five main categories in fouling: Crystallization fouling, particulate fouling, Chemical reaction fouling, Corrosion fouling and Biological fouling. The effect factors and fouling ingredient indeterminacy cause the hardness of fouling deposit production to rise. This is main reason why the fouling problem remains unsolved so far.

While this fouling prediction is common research topic, there are many researches that have focused on fouling evaluation and reduction. Bell–Delaware and the Flow Stream model developed and widely used in the calculation of the thermal and hydraulic performance of the shell side in clean conditions, but they ignore the fouling build up (Diaz-Bejarano,E et 2018). Collite and Macchietto design a dynamic, distributed model which considers the shell side fouling. It could be shown that this model is able to predict fouling in both deposition and cleaning with excellent accuracy. The TEMA table has 25% over deign cause rules of thumb, which accelerates bench scale measurements (KumarMohanty,D et 2014). KumarMohanty,D (2014) claim all these models have limitations. While some models have excellent accuracy in prediction of heat exchanger fouling, it is impossible predict in different contexts because of complex chemical and physical phenomena. However, the regression model based on past experience, or full experience, could be an important alternative in this case, since it provides an effective way to predict non-linear relationship.

The research could help company to avoid economic losses from pipe plug, which, as pointed out, costs most oil companies large sums of money. It could give company a good way to evaluate the fouling situation and take action in right time, thus improve the industry production efficiency. It also can help other researchers to better understand how fouling generation happens, and as such, pave way to suggesting more elaborate solutions to this problem. This result can further enhance industrial efficiency and reduce cost of fouling.

1.2 Aim and objectives

The aim of this research was to investigate the fouling phenomenon in crude oil refining, and to investigate the best time for cleaning as a step to mitigate or prevent fouling. In this case, the research focused on trying to establish what leads to fouling, and in doing so, make recommendations on how best oil and gas companies can increase their production efficiency. In order to achieve this aim, the research sought to achieve the following objectives;

i) To investigate the fouling phenomenon, its causes and the effects it has on the production efficiency

ii) To carry out an analysis that investigates the evolution of the fouling resistance, and how different variables such as fouling rates, temperatures and other heat exchanger variables are related.

iii) To make recommendations on how companies in the oil and gas industry can address the fouling problem with the aim of not only improving their profit margins, but also collaborating and adhering to environmental policies.

1.3 Research approach

The current study took a mixed methods approach, where both qualitative and quantitative data was collected and analysed. Qualitative data was mainly secondary data from previous studies, where the researcher critically analysed these findings in the context of the research questions. Quantitative data was obtained from Hexxcell. The data considered the effect factor in fouling, and it also contained some factors that seemed to have less or no relationship to fouling, and this was to warrant a detailed analysis to come up with a conclusive answer to the overarching question in this research. Data analysis was done using R software for quantitative data.

1.4 Dissertation outline

The study is divided into 5 chapters as follows;

Chapter 1; introduction

Details the background of the topic and states research objectives

Chapter 2; Literature Review

Involves critical review of previous studies on the research topic

Chapter 3; Methodology

Details the data collection strategy and procedure

Chapter 4; Results and analysis

Constitutes the presentation of results and the analysis of data to facilitate answering of research questions

Chapter 5; Discussion

Discusses the results based on the findings from literature as well as the analyses

Chapter 6; Conclusion

Summarizes the findings of the study

2 Chapter 2; Literature Review

2.1 The concept of fouling

When deposits accumulate in surfaces that are responsible for the transfer of heat, the effectiveness of the energy is lowered. Reducing the accumulation of deposits may prove costly as it requires regular cleaning and maintenance. Heat exchangers are used in the *transfer of the internal thermal energy between two or more fluids available at different temperatures* (Thulukkanam, 2013). When unwanted deposits assemble in this heat exchanger, fouling occurs, which in turn affect the transfer of heat between fluids.

Bott (1995) states that the fouling's characteristics are determined depending on whether the fluid is in gaseous or a liquid state. This is mainly because fouling occurs as a result of crystallization, corrosion as a result of chemical reactions or the presence of a biological or particulate matter. Fouling may also arise when decomposition of organic materials within the fluid occurs as a result of favorable conditions. The issue of fouling is a complex one and has been present since the inventions of heat exchangers were unearthed. Heat transfer is the nucleus of many industrial processes, and as a result, developments of suitable solutions that may improve the efficiency of heat exchangers despite fouling are underway.

Crude oil fouling on process machines surfaces causes significant, adverse effects on the operational and performance efficiency of the equipment. The primary operational hazard encountered by the chemical processing firms is the fouling of heat transfer equipment (Moulijn et al. 2013). Fouling caused a significant economic drain to most industries today. The estimated fouling related costs for industrialized countries exceed the US$4.5 annually. The estimates place the fouling of heat exchangers losses to about 0.25% to 30% of the industrialized countries GDP

(Ibrahim 2012). In line with Cuce and Riffat (2015), fouling in the boilers and heat exchangers occupies about the 15% of the total maintenance cost in most processing industries. The damages caused by fouling include deterioration cost, shutdown cost, maintenance costs, replacement costs of the corroded equipment and cleaning cost

Fouling causes detrimental effects such as loss of heat transfer blocked pipes, deposit corrosion, and pollution. Additionally, when the heat flux becomes high, it causes fouling leading to local hot spots that result of mechanical failure, which eventually leads to production losses and high maintenance cost (Moulijn et al. 2013). Fouling also causes significant problems since the accumulation of fouling residues plays a substantial effect on the hydraulic and thermal performance of the infected machine (Cuce and Riffat, 2015). The thermal efficiency of the materials decreases due to the resistance to the heat flow caused by the fouling deposits on the heat transfer surfaces. Crude oil fouling occurs in six different forms, which are crystallization, particulate, chemical, corrosion, biological, and solidification fouling (Harche et al. 2014).

Fouling is majorly responsible for the enormous emissions of carbon dioxide in the air. Cuce and Riffat (2015) suggest that crude oil fouling accounts for approximately 10% of the carbon dioxide emission in the air. Additionally, fouling causes the disposal of hazardous chemicals in the water during the cleaning process, affecting the water ecosystem (Ibrahim 2012) negatively. Wastes from the cleaning of the tubes and the heat exchangers consist of harmful residues such as lead, and chromium, that causes dangerous diseases such as cancer when consumed by human beings. Oily wastewater from the heat exchanger cleaning leads to the death of the water ecosystem (Basu and Chahar 2013).

The factors that affect the crude oil fouling in the tubes and heat exchangers include the chemical nature, density, viscosity, diffusivity, interfacial, colloidal and pour and cloud point factors. The rate and extent of the crude oil fouling depend on the chemical nature of the tube and heat exchangers (Huminic and Huminic 2012). The chemical composition of the feeds includes the stability and compatibility with each other in the pipes and heat exchanger surfaces, the availability of unstable unsaturated compounds and inorganic salts such as sulphur, nitrogen, and oxygen. The feeds form of storage and their exposure to oxygen affects the rate of the crude oil fouling (Ibrahim 2012). Additionally, the feed temperature, flow-rate of deposits, the geometry of the heat exchanger, the type of alloys used, and the surface wettability also affects the crude oil fouling deposits. The rate of fouling depends on the temperature between the inlet and outlet sides of the tube and heat exchanger. Uneven flow-rates and backflows lead to higher crude oil fouling rates and create shorter run lengths between the maintenance and periodic cleaning of the heat exchangers (Speight 2015).

Groysman (2016) attests that the first heat exchanger that was developed suffered the consequences of the deposits in the feed water. Salt deposits caused crystallization in the boilers that were used to raise steam, which was a requirement to keep abreast with the industrial revolution. However, over the years the problem was eliminated by introducing water treatment strategies in the steam raising technology. In Somerscales (1988) lectures on concepts of fouling, four eras are traced that were contributed to understanding fouling and the resulting scientific techniques that have been established. The first epoch is recorded during the period of up to 1920, where the problem of fouling is discerned, and methods are critically fabricated with little consideration on the scientific approach behind the problem. The second and the third epoch between 1920 to 1945 saw the development of fouling and ways of measuring it, and emphases were placed on the fouling factor, which is the numerical representation of the detrimental effects of unwanted deposits. The final epoch which is dated from 1945 to the end of the 20th century where fouling is described in a more scientific approach with details being placed on scientific mechanisms that can elucidate the phenomena.

Chung and Ezekoye (1995) state that the complexity of fouling is accredited to its uniqueness in particular designs, that is, it is difficult to devise a congruent solution when problems differ per system. There is a need to develop a sophisticated understanding of the fouling process and how it affects different heat exchanger designs. The initial step of understanding fouling involves comprehending the processes that initiate the accumulation of deposits and where the foulant is formed. The nature of the deposits determines if fouling on the equipment occurs rapidly or slowly, as deposits are either hard or soft to remove.

Bott (1995) identifies six mechanisms that are related to the emergence of fouling. The first mechanism is crystallization fouling, which is the formation of scale as a result of depositions of salts. Scaling occurs when aqueous solutions are used for cooing where sludge or a tenacious deposit form that hinder heat transfer efficiency. The second mechanism is particulate fouling which is common in liquid and gaseous fluids. The particulate matter may arise from corrosion or particles that may be present in the systems. The third mechanism involves biological deposition, which involves the growth of micro-organisms and macro-organisms such as algae and hydroids as a result of conducive environment generated from the water systems used for cooling. The fifth mechanism involves fouling resulting from chemical reactions which are more often than not related to organic chemicals rather than metals which act as catalysts in some reactions and inhibitors in others (Bott, 1995). Chemical reactions in oil refining such as autoxidation and cracking occur as a result of high temperatures which cause fouling. Oil refining is vulnerable to such chemical reactions especially since crude oils are preheated at $250^{o}C$ to $400^{o}C$ leading to cracking which increases the number of depositions in heat exchangers (Bott,1995). The final mechanism is corrosion fouling, which is a common problem in oil refineries and petrochemical plants. Corrosion fouling is associated with chemical reactions which give rise when the fluid attacks the surface in which they are processed in or the presence of impurities in the systems, which create a thick protective layer.

2.2 Fouling threshold

Fouling in crude oil tubes and heat exchangers impact the continuity of operations since the insulating layer of accumulated deposits that form, lower the temperature of the surface in the system. Coletti and Hewitt (2014) assert that, organic and inorganic depositions of matter on the heat exchangers offer significant challenges to the engineers such as lowering the heat transfer efficiency, reducing pressure in the pumps, production losses as a result of regular cleaning and environmental hazards as a result of waste disposal in the form of carbonaceous deposits. These shortcomings hinder the marginal profits that oil companies are set to achieve, and therefore the concept of fouling threshold is one of the mechanisms for mitigating the accumulation of deposits. Fouling has become a necessary problem that needs to be eliminated to reduce the economic and environmental impacts as a result of emissions of greenhouse gases, increased energy, furnace firing to compensate for inefficient heat transfer, and increased operating costs.

Deshannavar et al. (2010) identify five factors that influence fouling. The first one is surface temperatures, where fouling increases when the temperature of the surface ameliorates. This is expressed by the Arrhenius equation as;

$$\frac{dR_r}{dt} = A \exp(-\frac{E}{RT_s})$$

Where E= activation energy

A= proportionality or pre-exponential factor

T_s= surface temperatures

dRr/dt which can be expressed as k is the rate constant

R= universal gas constant

The second factor is flow velocity where an increase in the velocity of crude in the preheat trains corresponds to a decrease in the fouling rate. With this notion, Asomaning (1997) deduced that when the reaction is controlled, temperature reduces with increase in velocity and heat transfer. The third factor is the bulk temperature, which different researchers have come up with confuting analyses where others have highlighted that when the bulk temperature in the fluid increases, fouling rate decreases and vice versa, while other researchers have argued that when bulk temperature increases, thermal force increases and consequently the fouling rate also increases. Deshannavar et al. (2010) identify the fourth and fifth factors as crude type and crude blending. The amount of asphaltene in crude oils determines how light or heavy it is which subsequently affects the fouling rate. Heavy crude oils are more susceptible to rapid fouling compared to the light and medium oils. When crude oils are mixed unstable reactions occur which lead to the formation of asphaltene hence increases the rate of fouling.

The concept of 'fouling threshold' was introduced by Elbert and Panchal at an Engineering conference in 1995, as a way of curbing fouling through quantifying models. This method was meant to deal with crude oil fouling which Mansoori (2002) describes can either be caused by precipitates such as asphaltenes which lead to acute fouling or chronic fouling that may occur in the preheat trains as a result of chemical reactions. The threshold concept has been used to determine better heat exchanger designs and in particular, pre-heat train designs by identifying the highest temperature ad flow velocity at which fouling can be mitigated. The semi-empirical approach developed by Elbert and Panchal (1995) focused on the film temperature to analyse the activation energy rather than the surface temperature as depicted in the Arrhenius equation. The 'fouling threshold' has been verified using various experiments to determine the impact of film temperature and flow velocity as determinants of fouling. There have been models that have been developed to mitigate fouling using temperature and velocity as reaction terms. 'Threshold fouling' assumes that accumulation of deposits occur within a thermal boundary layer and are transported to the bulk flow through diffusion. Velocity is related to the wall shear stress where, in cases where the mitigating mechanism is introduced in crude oil fouling, and it becomes rapid than the accumulation of the deposits then fouling does not occur. The presence of competing mechanisms has been used by scientists such as Knudsen et al. (1999) in field studies where crude oil was passed through tubes with defined temperatures and velocity flow, and a linear rate was predicted that measured the deposition and the mitigation terms. The equation below was derived from the 'threshold fouling':

$$\frac{dR_T}{dt} = aRe^{\beta} \exp\left(-\frac{E}{RT_f}\right) - yT_w$$

Where a, β,y, and E are generated from the regression or experimental data,

yT_w = wall shear stress

T_f = film temperature of the crude oil

From the equation, Ebert and Panchal (1995) unearthed that, some crude oils had the ability to record a negligible fouling rate, a state that was later termed as the 'threshold condition.'

Panchal et al. (1999) argued that crude oil fouling was a result of formation and removal, where the formation is dependent on the temperature while removal is dependent on the fluid velocity. The difference between the rate of removal and rate of formation determines the rate of fouling. The quantitative model developed by the concept of threshold fouling is salient when designing heat exchangers as it identifies the favourable conditions for operation. Engineers are able to use field plots after identifying the maximum heat recovery level to design heat exchangers according to the operating conditions (Coker, 2014).

2.3 Economic impacts of crude oil fouling

The deposited layer that forms on the surfaces is bound to increases in strength depending on the aging time. The longer a deposit accumulates, the more they are subjected to chemical reactions such as re-crystallization, making it harder for removal by mass transfer or fluid shear. Harche, Absi, and Mouheb (2014) develop a three-stage deposit mechanism according to duration. The initiation phase, fouling is reliant on the type of the deposits and may take a few minutes to a few weeks to develop. The second stage involves the increase of the deposits which gradually leads to the final stage where fouling becomes constant.

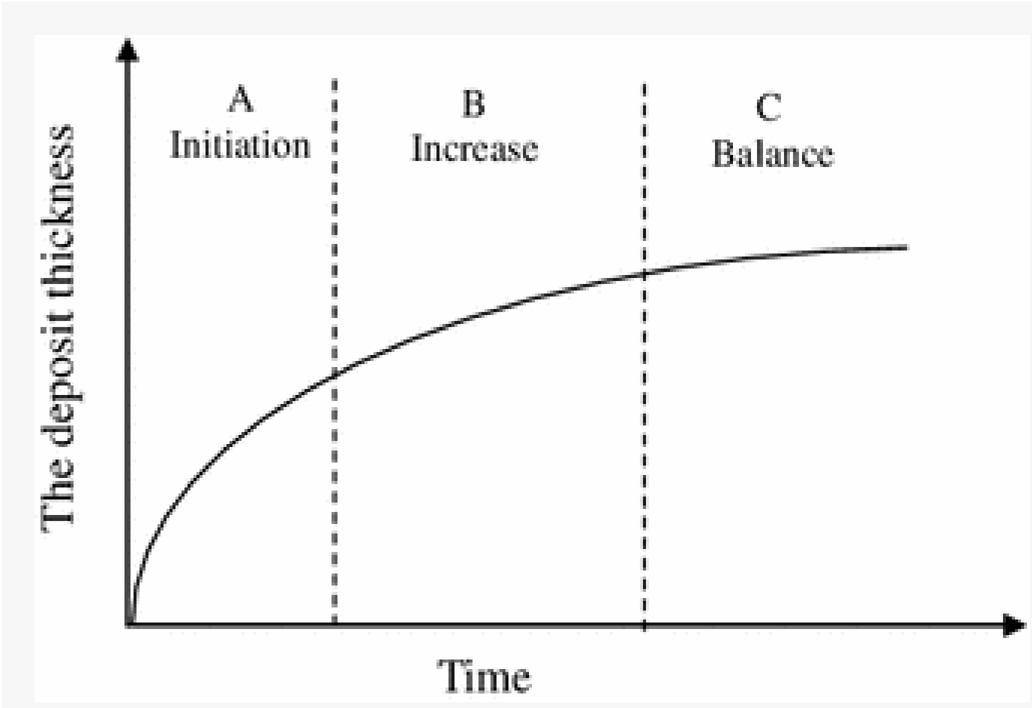


Figure 1: three stages of fouling

Source: Harche, Absi, and Mouheb (2014)

The duration in which fouling occurs has a significant effect on the cost of the fouling. Ibrahim (2012) states that fouling in industries of developed nations may cost up to US$ 4.4 milliard per year. Fouling leads to deterioration of heat exchangers and boilers which subsequently affect production and shutdowns of some plants. The cost of fouling is also discerned when prevention and mitigation technologies are implemented in the crude oil industries, as significant advancements in designs are required to ensure that fouling has minimum impacts on the operation and production processes. However, fouling mitigation models and mechanisms are being investigated, with the modern digital techniques expected to provide feasible solutions (Watkinson, 2007).

2.4 Causes of crude oil fouling in tube and heat exchangers

Crude oil is one of the key fossil energy resources in the globe today. The production and refining of crude oil face the challenge of fouling. Fouling refers to the deposition of solid particles on the heat exchangers' surfaces that leads to an increase in the thermal resistance, as well as the decreased transfer of heat (Yang et al. 2015).

Tube heat exchangers and customized shell are one of the great machines that are used for the processing and extraction of crude oil in countries such as Argentina, China, Canada, and the US. According to Coletti (2014), the refining process is highly prone to fouling, and this is an unexpected problem that is harmful, hence, common among many facilities that refine crude oil. Crude oil fouling is the major cause of energy insufficiency in most refineries and causes loss of production time. Additionally, fouling causes a high consumption of energy and decreased output by the crude fire heater (Yang et al. 2015). There are various causes of crude oil fouling in the heat exchangers:

2.4.1 Asphaltene precipitation

Various industries may experience different causes of fouling. In the processing of tight crude oil, fouling can occur due to the buildup of asphaltene precipitation. This is because the tight crude oil blends with other types of crude oil. In such a case, when the tight air finds its way into the heat exchanger, it tailbacks in the naphtha dispensation and crude overhead units (Emani et al., 2016). Most refineries blend these types of crude oil to allow the machines to work effectively. However, this particular practice contributes to the buildup of asphaltene precipitation that causes fouling. When crude oil types that are not compatible are blended, asphaltene becomes unstable in the solution, hence, resulting in a precipitate (Coletti, 2014).

According to Yang et al. (2015), a blend of 20% tight oil and 80% percent of other crude oil types will result in less asphaltene precipitation rather than a mixture of 30% and 70% respectively.

Tight crude oil possesses levels of naphtha which are relatively higher than other crude oil types. This largely contributes to the rapid production of asphaltene precipitation that potentially causes fouling in the heat exchangers or tubes (Emani et al. 2016).

2.4.2 Chemical reaction fouling

Chemical reaction fouling is termed as the deposition due to one or more chemical reactions amid reactants present in the crude oil (Emani et al. 2016). It is one of the main causes of heat exchanger fouling in various refining industries. It comprises of the two-step method of reaction.

Reactant (soluble) - Precursor (sparingly soluble) - Foulant (insoluble)

Fouling due to chemical reactions can take place in a variety of temperature ranges. These reactions are enhanced by raised levels of temperatures in the heat exchangers. In addition to the effect of temperature on the process of fouling, temperature can also be a factor in the retention of the foul deposit on the surface of heat exchangers (Yang et al. 2015). Due to chemical reactions, it is possible for the deposits to be obstinate and hard to remove. High temperatures may decrease the fouling incidence when above optimum. This shows evidence that chemical reactions are one of the main causes of fouling in the heat exchangers and tubes.

2.5 How fouling affects production efficiency

Fouling on the heat exchanger surface can have a significant negative impact on the efficiency of operation and has a mechanical, as well as a thermal effect on the heat exchangers (Ibrahim, 2012). The accumulation of the foul material causes a decrease in the thermal conductivity of the heat exchangers surface. This leads to a reduction in the activity and performance of the heat exchanger. The efficiency of the heat exchanger is reduced in respect of the transfer of heat. In general, the conductivity of the deposits is lower than metal so that a thin layer can cause thermal resistance (Diaz-Bejarano et al. 2017).

Fouling contributes to loss of heat transfer due to a decrease in charge outlet temperature and drops in pressure. In other circumstances, fouling can lead to blockage of process pipes, corrosion, and pollution. When the heat flux is increased, fouling results in local hot spots that will automatically lead to a mechanical catastrophe of the surface of heat exchangers (Smith et al. 2017). This will have a negative impact on the production of crude oil and increases the maintenance costs.

The loss of heat transfer and temperature diminution is due to the low thermal conductivity of the fouling layer, which is relatively lower than the thermal conductivity of the fluids. This lower thermal conductivity results in a general increase of thermal resistance to heat transfer, hence, a reduction in the effectiveness and efficiency of the heat exchangers (Ibrahim, 2012).

Additionally, fouling onset contributes to the reduction of the cross-sectional area of tubes and channels of flow. An increased roughness of the surface of the tubes due to foul deposition increases the resistance to flow of the crude oil. Such occurrences lead to pressure drop increase across the heat exchanger leading to blockage of flow. More so, due to the roughness of the foul deposit and flow restriction that is the cause of turbulence and heat transfer, pressure drop can increase drastically (Coletti, 2014).

Unless the fouling problem is recognized early and measures are taken, there are possibilities of adverse operating difficulties that may lead to shut down. This is because the heat exchanger losses its efficiency of heat transfer and the flow cannot be controlled due to excess drop of pressure (Smith et al. 2017). Generally, it is evident that fouling affects production efficiency due to its impact on the heat exchanger efficiency and performance.

2.6 Effect of temperature on fouling

2.6.1 Surface temperature

The effect of surface temperature on fouling has been investigated in several studies. These literature show that increased temperature may increase, decrease or have no impact on the amount of deposit material. However, Mostafa (2007) performed an experimental set up to study the effect of surface temperature on the fouling rate. Three electric heaters with varied surface temperatures were placed in a test tube. Each of the heaters was subjected to similar flow velocity, Foulant concentration, and material. The test tube was made of transparent material for easy visual observation. The test tube was part of a water tank, and a pump was introduced to extract water from the tank to the test tube.

After passing through the test tube, the water runs back to the tank through an open cooler before emptying into the test-tube again. The water has solid particles of 1gm/liter and is used as a test fluid with a velocity of 0.08 m/s. The electric heaters were operated at same conditions but different surface temperature from 55 to 95 degrees (Mostafa, 2007).

From the study, it was concluded that increasing the surface temperature decreases fouling on the heat exchangers significantly. The data collected in the experiment was seen to be significant in the practical presentation, and future work with other liquids of different particle concentrations was highly recommended. This study shows that surface temperature has the possibility of affecting fouling, more so, in the heat exchangers. Lower temperatures provide a slower buildup of foul in the tubes and easy removal of deposits (Emani et al. 2016). In other fluids, low surface temperature promotes solidification fouling at a high rate.

3 Chapter 3; Methodological approach

In order to achieve the aim of the research and answer the key research questions, it is imperative to collect data and analyse it, especially in the context of the variables of interest. This chapter outlines the approach that was used in this research to collect data that was later analysed, interpreted and used as the basis of answering the research questions. The relevance of the data is one of the fundamental aspects that must be taken into account Hanvey (2018), and since this research investigates the fouling phenomenon, some of the important variables that would be taken into consideration include the heat exchanger variable, the furnace variable, the inlet temperatures, the inlet flow rates,   and the fluid among many others.

As seen in the outputs, short form representations of the variables have been used, and the following table is a summary of the symbols and the variables they represent;

TI…	Temperatures
FC…	Mass Flowrates
total_Rf_deriv	fouling rates
tube	tube side of the exchanger
shell	shell side of the exchanger
T	temperature inside the exchanger
Tf	Film temperature

Tsurface	Temperature at the surface of the deposit
tau	shear stress
velocity	fluid velocity
Re	Reynolds number

Research method plays a very important role in research. William(2015) claim that we can use the combination of qualitative and quantitative analysis to improve the outcome of research, considering the area of research and the key aspects of research that is considered in the study.

In terms of qualitative analysis, we need to focus on some key aspect, which could lead to the fouling analysis and the determination of the various factors that influence the fouling process. Perhaps one of the things that this research can do is to increase the number of dependent variables. By focusing on many dependent variables, it would be possible to find out the relationship between fouling and the other independent variables. Reviewing some earlier research could provide some information about how independent variables affect fouling and which one has higher relation, its impact on the overall learning phenomena, and attainment of outcome that is envisaged from the process (William 2015). This would be fundamental in determining the causes of fouling and suggesting a solution on how oil and gas companies can reduce the effects of fouling in the production process.

In terms of quantitative analysis, the analysis that was done in this research was analysis for response group of industry, and this is primarily because the Hexxcell provide the industry data. The type of data was provided by Hexxcell, and this is why the data used in this research was very detailed and large. The data considered the effect factor in fouling. It also contained some factor that seemed to have less or no relationship to fouling, and this was to warrant a detailed analysis to come up with a conclusive answer to the overarching question in this research. The emphasis is split the problem. The main problem is what time is best time to cleaning? I can spit it to how much fouling need to clean and which factor will affect fouling rate. And analysis the data was done with the aim of answering these two questions.

3.1 Data analysis

The data analysis process was aimed at investigating the relationship between different variables, and this is an important step towards answering the fundamental research questions. As part of the analysis in this research, the researcher investigated the correlation between different variables especially those stated earlier in this chapter. The analysis is aimed at identifying which factor has the strongest effect on fouling formation and how it affects the fouling formation. The regression model was used in this study to find out the non-linear relation that exists between different variables on fouling rate. This was fundamental in determining what the time that can be considered ideal for cleaning.

One of the key aspects that have been carried out in this research is the review of previous findings on this topic and the factors that were identified as most significant as far as fouling is concerned. This research tested these too with the aim of establishing whether or not the findings of this study would be consistent with the findings of the previous studies. Furthermore, in the case of quantitative analysis, focus is the effect of fouling on industrial efficiency, which, as stated earlier on in this research, is the major problem and one of the main motivations of carrying out this research. Using neural network method to build regression model analyse cleaning time. Otherwise, the regression model also can be used to evaluate the key attributes which are integral to the process. The research also focused on how the key factor affects the fouling. Some variables are known as temperature, pressure, heat transfer coefficients among others.

The researcher could use classified model to evaluate how these factors affect fouling and what the critical value of fouling generation is. This model can also be improved based on the performance and this is fundamentally because the basic model could perform worse in real data. Based on the statistical and qualitative inputs, the correlation of the factors is considered for data interpretation, conclusion and recommendations on the subject study. In the next chapter, the researcher not only highlights the output of the analysis, but also presents the code that generated the output in R, as well as the interpretation of the various figures and graphs presented in the analysis.

4 Chapter 4; Data analysis

4.1 Introduction

This chapter presents the analysis of the data collected on the key variables stated in the previous chapter. This is one of the important steps in answering the research questions, and it involves the interpretation of the data in the context of the issues under investigation. Reimann et al (2017) defines data analysis as the process of systematically applying an array of statistical or logical techniques in an effort to describe, condense, illustrate, evaluate and recap data. All these processes are aimed at making sense of the often large volumes of data that do not make much sense, especially as far as the research question is concerned. The analysis is done using the R statistical package, wherein data was coded and the outputs presented and interpreted as shown in the subsequent sections. The fouling problem was investigated not only by looking at correlation analyses with different variables, but also by regression analysis to investigate linear and non-linear relationships. The markdown file is not included in the current paper, but it is attached for reference.

4.2 For loop code

The following code generates part of the output from which reference is made to answer the research questions in this research. The code is written using a loop, and was extracted from the R code.

```
i<-1
fouling<-data.frame()
for (i in 1:152) {
  if(y[i,24]<=-0.000068985){
    fouling[i,1]<--2
```

```
    i<-i+1
  }
  else  if(y[i,24]>-0.000068985&&y[i,24]<0){
    fouling[i,1]<--1
    i<-i+1
  }
  else  if(y[i,24]==0){
    fouling[i,1]<-0
    i<-i+1
  }
  else  if(y[i,24]>0&&y[i,24]<0.00010805){
    fouling[i,1]<-1
    i<-i+1
  }
  else  if(y[i,24]>=0.00010805){
    fouling[i,1]<-2
    i<-i+1
  }
}
fouling[,1]
```

4.3 Correlation analysis

Correlation analysis is one of the important statistical methods that can be used to investigate the strength of a relationship between two variables that are numerically measured and continuous. In this case, the researcher investigated the relationships between key variables that are relevant to fouling rates, and what the ideal time for cleaning is. Correlation would help the researcher achieve this since, as Reimann et al (2017) explain, correlation helps in determining whether there are any connections between variables.

In the current data set, an array of input variables are taken into account, including FC(Mass Flowrates) and Tsurface (Temperature at the surface of the deposit) among others. The new dataset has 73 input variables and 28 output variables. However, after the data cleaning job, the remaining objects were 152

The researcher then carried out the correlation analysis for output variables, and the fundamental reason behind this analysis is because in the current dataset, the researcher had too many output variables. In order to address this concern, the researcher tried to find which output variables are likely to have strong associations to other output variables, or which of the variables would most likely have strong relationships with our outcome variable. This is a good way of reducing the number of output variables.

1432 variables 377 objects

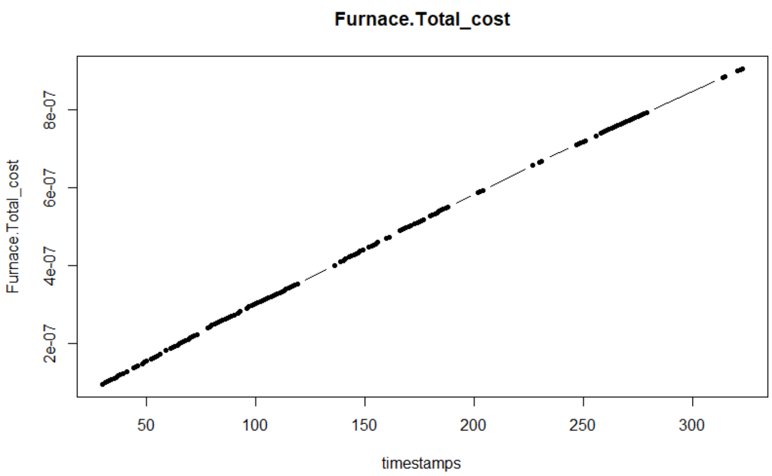
Input: tiemtamp,TI001, TI002, TI003, TI004, TI005, TI006, TI007, TI008, TI009, TI010, TI011, TI012, TI013, TI014, TI015, E01AB.tube_velocity, E02AB.tube_velocity, E03AB.tube_velocity, E04.tube_velocity, E05AB.tube_velocity, E01AB.shell_tau, E01AB.shell_Tf, E01AB.tube_tau, E01AB.tube_Tf, E01AB.wall_T, E02AB.shell_tau, E02AB.shell_Tf, E02AB.tube_tau, E02AB.tube_Tf, E02AB.wall_T, E03AB.shell_tau, E03AB.shell_Tf, E03AB.tube_tau, E03AB.tube_Tf, E03AB.wall_T, E04.shell_tau, E04.shell_Tf, E04.tube_tau, E04.tube_Tf, E04.wall_T, E05AB.shell_tau, E05AB.shell_Tf, E05AB.tube_tau, E05AB.tube_Tf, E05AB.wall_T, FC001, FC002, FC003, FC004, FC005, FC006, FC007, E01AB.shell_Re, E01AB.shell_Tsurface, E01AB.tube_Re, E01AB.tube_Tsurface, E02AB.shell_Re, E02AB.shell_Tsurface, E02AB.tube_Re, E02AB.tube_Tsurface, E03AB.shell_Re, E03AB.shell_Tsurface, E03AB.tube_Re, E03AB.tube_Tsurface, E04.shell_Re, E04.shell_Tsurface, E04.tube_Re, E04.tube_Tsurface, E05AB.shell_Re, E05AB.shell_Tsurface, E05AB.tube_Re, E05AB.tube_Tsurface (73)

Output: Furnace.Furnace_duty, Furnace.Total_cost, E01AB.duty, E01AB.shell_DeltaP, E01AB.total_Rf, E01AB.tube_DeltaP, E02AB.duty, E02AB.shell_DeltaP, E02AB.total_Rf, E02AB.tube_DeltaP, E03AB.duty, E03AB.shell_DeltaP, E03AB.total_Rf, E03AB.tube_DeltaP, E04.duty, E04.shell_DeltaP, E04.total_Rf, E04.tube_DeltaP, E05AB.duty, E05AB.shell_DeltaP, E05AB.total_Rf, E05AB.tube_DeltaP, E01AB.total_Rf_deriv, E02AB.total_Rf_deriv, E03AB.total_Rf_deriv, E04.total_Rf_deriv, E05AB.total_Rf_deriv, TR001 (28)

	Furnace.Furnace_duty	Furnace.Total_cost	E01AB.duty	E01AB.shell_DeltaP	E01AB.total_Rf	E01AB.tube_DeltaP
Furnace.Furnace_duty	1.00000000	-0.43076820	-0.23949114	-0.356506370	0.31469457	0.694066114
Furnace.Total_cost	-0.43076820	1.00000000	0.62457563	0.656998244	-0.58275657	-0.488655524
E01AB.duty	-0.23949114	0.62457563	1.00000000	0.512421893	-0.95781157	-0.609226744
E01AB.shell_DeltaP	-0.35650637	0.65699824	0.51242189	1.000000000	-0.42363745	-0.315638218
E01AB.total_Rf	0.31469457	-0.58275657	-0.95781157	-0.423637451	1.00000000	0.701324031
E01AB.tube_DeltaP	0.69406611	-0.48865552	-0.60922674	-0.315638218	0.70132403	1.000000000
E02AB.duty	-0.26244173	-0.03298405	-0.06226836	0.108796831	0.05321653	0.270215574
E02AB.shell_DeltaP	-0.30070585	-0.11213224	-0.02567919	0.001254049	-0.01771886	0.181175426
E02AB.total_Rf	-0.34952736	0.96250448	0.62639135	0.540575621	-0.59102175	-0.469004004
E02AB.tube_DeltaP	0.20146605	0.61962455	0.45850436	0.459622045	-0.34402266	0.236383221
E03AB.duty	0.04888605	0.09274346	-0.23480951	0.157288553	0.33879495	0.346331596
E03AB.shell_DeltaP	-0.30717347	0.51463004	0.16250540	0.476431179	-0.08725773	-0.050996376
E03AB.total_Rf	-0.40379630	0.90158363	0.68209148	0.482314235	-0.67310510	-0.539026142
E03AB.tube_DeltaP	0.24884159	0.48084013	0.45036541	0.380890072	-0.34224052	0.314100785
E04.duty	0.12597185	-0.47344721	-0.33258034	-0.550075940	0.19981318	0.129671685
E04.shell_DeltaP	-0.30789076	0.37410987	0.63575487	0.093904614	-0.62606097	-0.522767012
E04.total_Rf	-0.13169346	0.55366047	0.44749422	0.555573515	-0.29028445	-0.196013535
E04.tube_DeltaP	0.19201289	0.49655806	0.56310955	0.456985769	-0.42068374	0.049946860
E05AB.duty	0.08988883	-0.55268171	-0.30065983	-0.253831384	0.26117904	0.467447027
E05AB.shell_DeltaP	-0.30012908	-0.11219516	-0.02556674	0.001774864	-0.01752615	0.181978480
E05AB.total_Rf	-0.34336978	0.97373003	0.59251638	0.640548846	-0.52165894	-0.416661077
E05AB.tube_DeltaP	0.07715556	0.77288172	0.64561031	0.479525478	-0.58092534	-0.070787838
E01AB.total_Rf_deriv	-0.20392630	0.05545992	0.16575179	0.011746180	-0.23241405	-0.308623138
E02AB.total_Rf_deriv	-0.10433426	0.11403217	0.15568166	0.058716741	-0.23743231	-0.226342313
E03AB.total_Rf_deriv	0.10601995	0.03698639	0.05921142	0.141658814	-0.01117159	0.081161218
E04.total_Rf_deriv	0.05556005	-0.09260047	-0.01395053	-0.100429191	0.01257812	0.084095715
E05AB.total_Rf_deriv	0.08855422	-0.17145531	-0.12058651	-0.127391858	0.10498564	0.005964694
TR001	-0.78344083	0.38213820	0.32242901	0.405862981	-0.36619409	-0.319475050

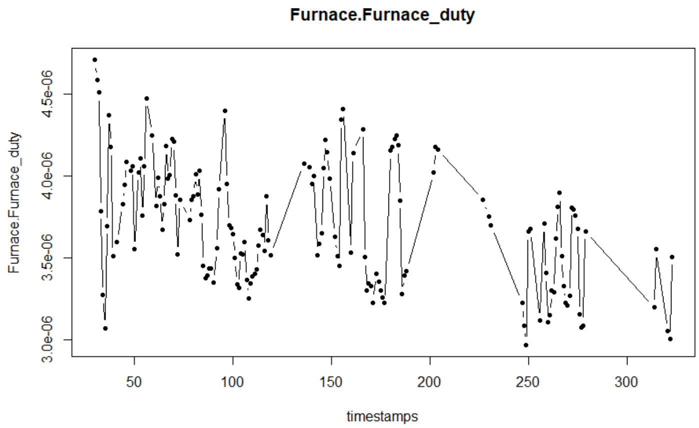
From the analysis above, it can be established that there is a very strong negative correlation between TR001 and furnace duty, which simply means that the furnace duty increases when the TR001 decreases. The variable total cost, on the other hand, was found to have a very high positive correlation with variable E05AB total fouling rate, with the correlation coefficient over 0.97. In other words, when the total fouling rate increases, the total cost also increases exponentially, and this hints why the fouling problem is a costly one, and why companies have been trying to deal with it.   There is also a strong correlation between the total and E03AB total fouling rate. What this means is that the results are consistent in different exchangers. The results also seem to be consistent on the shell side, as well as on the tube side, an indication that fouling affects all these areas just as much as it affects other areas.

The graph below shows the outcome of correlating the total cost of the fouling cleaning against time. There is a positive correlation that is linear and progressive, showing that with increase in time of fouling, there is exponential increase in costs. When the cost is almost at its highest level, it indicates that there has been a lot of accumulation of fouling, and thus it might



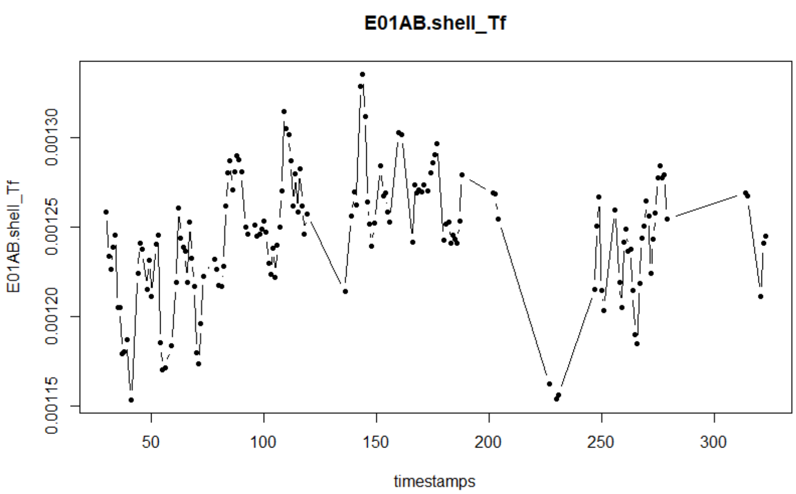

```
plot(y[,1], y[,3],xlab = names(y)[1],ylab = names(y)[3], type = 'b', pch=20, m
ain = names(y)[3]
```

The relationship between furnace and total furnace duty is direct, as it shows that the increase in functioning of the furnace wit time increases fouling. A higher furnace duty correlates to a very high cost, which thus means that fouling rate and eventually costs would be highest where the furnace duty is at its maximum.



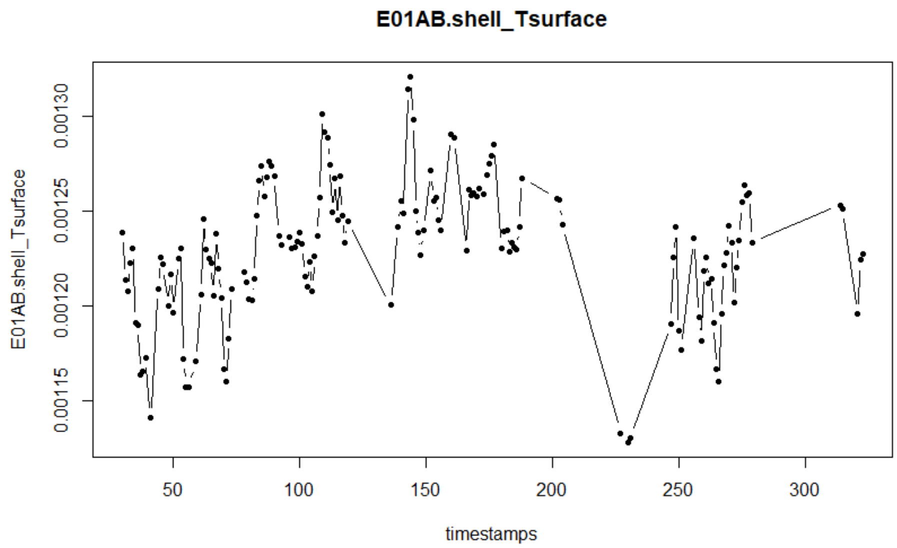

```
plot(y[,1], y[,2],xlab = names(y)[1],ylab = names(y)[2], type = 'b', pch=20, m
ain = names(y)[2])
```

The film temperature for the E01AB shell type of heat exchanger shows a tooth saw relationship as time progresses. This means that temperatures for this type of heat exchanger remain relatively average with time as shown below.



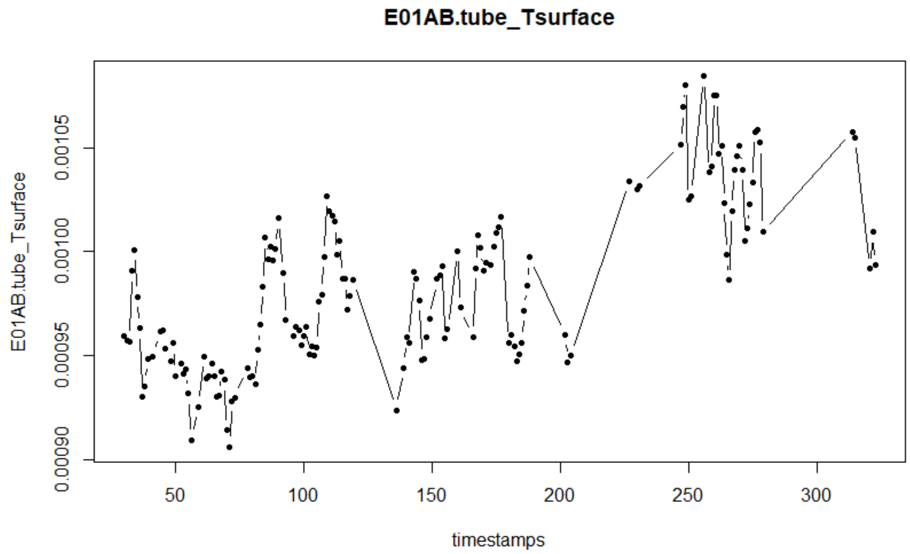

```
plot(x[,1], x[,23],xlab = names(x)[1],ylab = names(x)[23], type = 'b', pch=20,
 main = names(x)[23]
```

This result shows that the surface temperature of the E01AB on the shell side of the heat exchanger increases and then decreases with time to average out as time continues. Therefore temperatures for the shell surface are much more stable as fouling progresses as shown in the graph below.



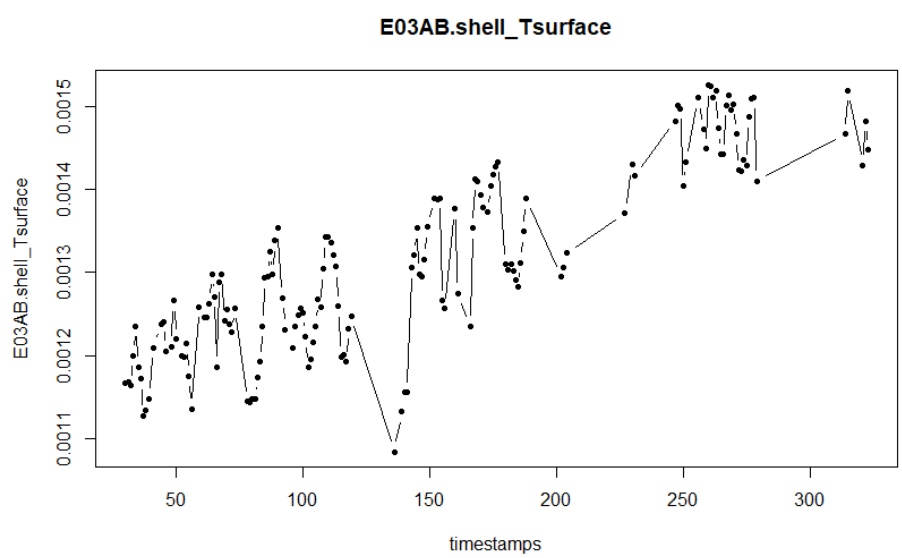

```
plot(x[,1], x[,55],xlab = names(x)[1],ylab = names(x)[55], type = 'b', pch=20,
 main = names(x)[55])
```

When it comes to the tube side surface of the E01AB heat exchanger, surface temperatures increase exponentially with time. This indicates that the tube surface has a higher likelihood of increased costs over time as shown below.

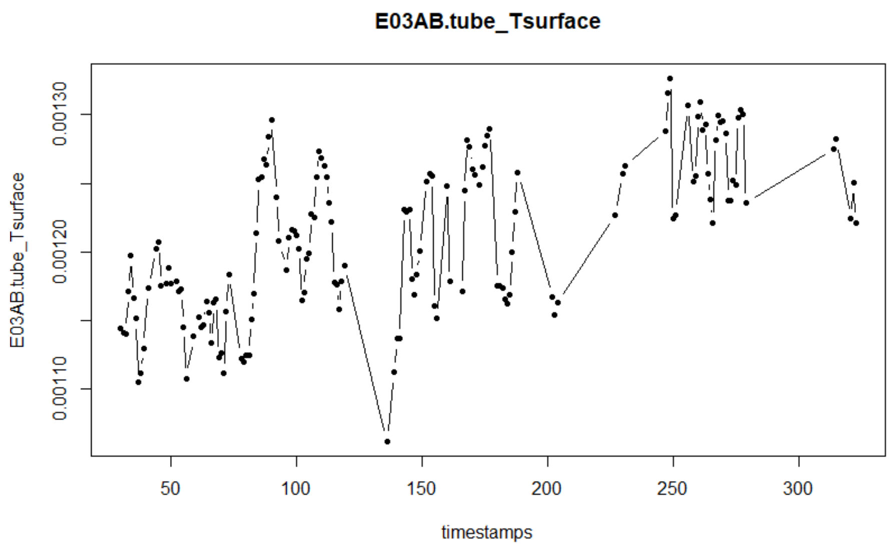



```
plot(x[,1], x[,57],xlab = names(x)[1],ylab = names(x)[57], type = 'b', pch=20,
 main = names(x)[57])
```

for the E03AB shell side surface temperature and E03AB tube surface side temperatures, both graphs below demonstrate a significant rise in the temperate over tine , which could indicate that they likely have a combined higher cost of fouling.

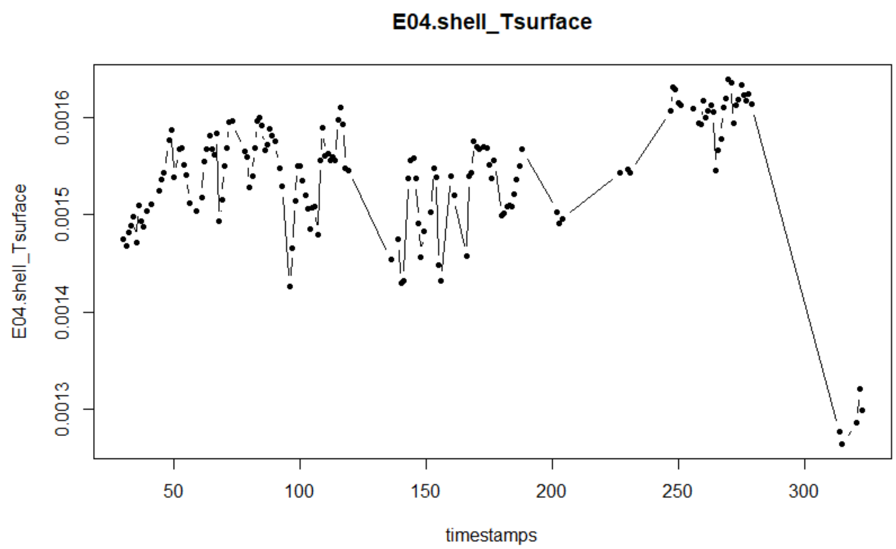


```
plot(x[,1], x[,63],xlab = names(x)[1],ylab = names(x)[63], type = 'b', pch=20,
 main = names(x)[63])
```

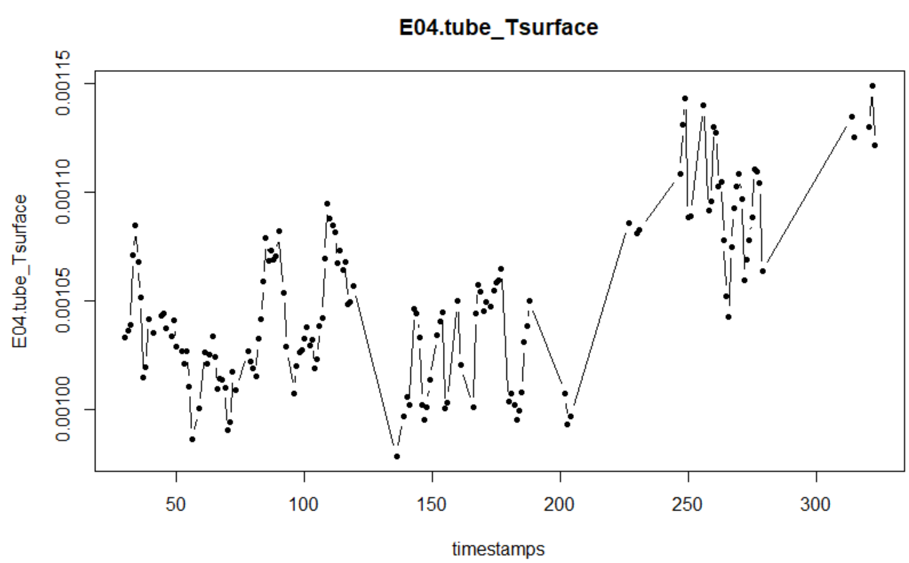



```
plot(x[,1], x[,65],xlab = names(x)[1],ylab = names(x)[65], type = 'b', pch=20,
 main = names(x)[65])
```

For the E04 shell side surface temperature and E04 tube side surface temperature, there is a significant difference in the behaviour of the temperatures when fouling as time progresses. The results show that the shell surface drops in temperature significantly as the fouling time continues.

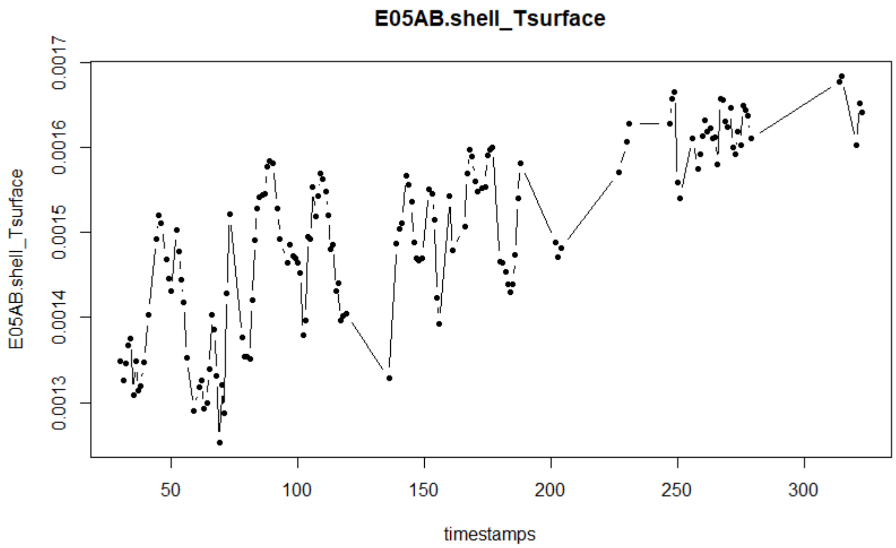



```r
plot(x[,1], x[,67],xlab = names(x)[1],ylab = names(x)[67], type = 'b', pch=20,
 main = names(x)[67])
```

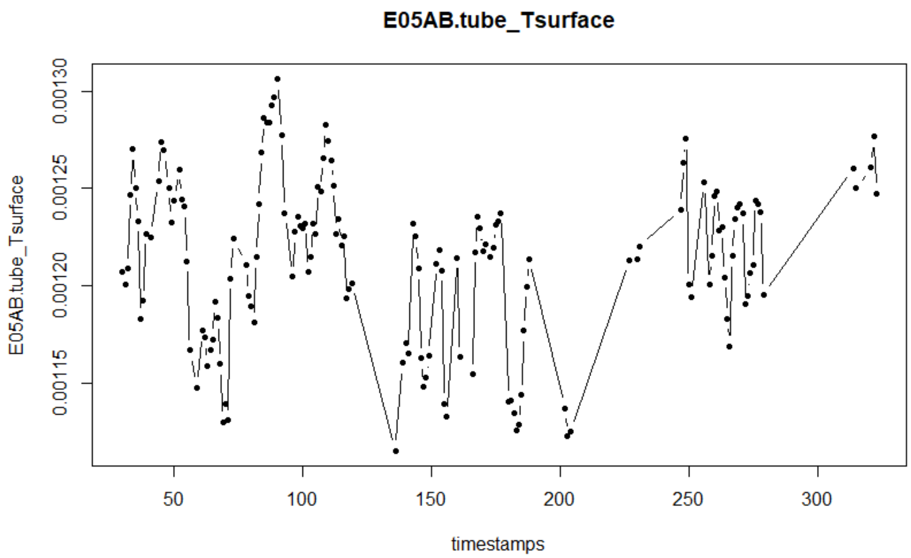



```r
plot(x[,1], x[,69],xlab = names(x)[1],ylab = names(x)[69], type = 'b', pch=20,
 main = names(x)[69])
```

both the shell and tube sides of the E05 surface temperatures increase exponentially as shown below, which could indicate a higher cost. The higher temperatures could indicate a higher effect when t comes to the overall cost.




```
plot(x[,1], x[,71],xlab = names(x)[1],ylab = names(x)[71], type = 'b', pch=20,
 main = names(x)[71])
```




```
#output variable in time series
par(mfrow = c(1,1))
```

```
plot(x[,1], x[,73],xlab = names(x)[1],ylab = names(x)[73], type = 'b', pch=20,
 main = names(x)[73])
```

4.4 Machine learning model prediction for TR001

Data is important in the context of any organization, especially when it is used to gain insight into the quality of operations, as well as strategies. There is need to implement a suitable decision model in every organization, and this is based on the feedback that is received from the collected and analysed data. A prediction model in R was implemented to predict TR001, using an algorithm referred to as the k-nearest neighbours (kNN).

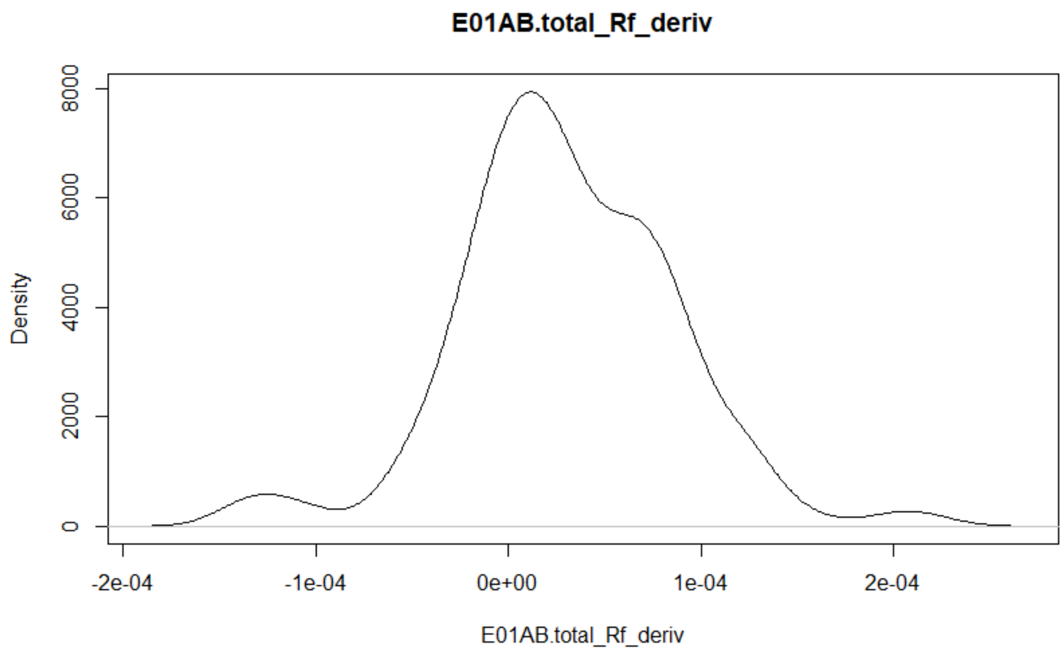
The figures below show that the variable E01AB, fouling rate, is very independent, and as can be established from the output, a majority of the dependent variables have low correlation with E01AB fouling rate. This is at the timestamps, TI001, TI007, TI010, TI011, TI014, tube velocity in E04 and E05AB, shell tau, shell average temperature and wall temperature in E01AB, E02AB shell tau, shell side average temperature and tube tau in E04, shell average temperature, shell tau, tube tau and wall temperature in E05AB, FC002,FC005, FC006, FC007. Shell side Reynolds number and temperature at the surface of the deposit in E01AB, Reynolds number in shell side and tube side in E02AB and E03AB, E04 shell temperature at the surface of the deposit and E05AB shell side Reynolds number and temperature at the surface of the deposit, which are lower than 10%. At this point, therefore, it is possible to try to use PCA to reduce dimensionality.

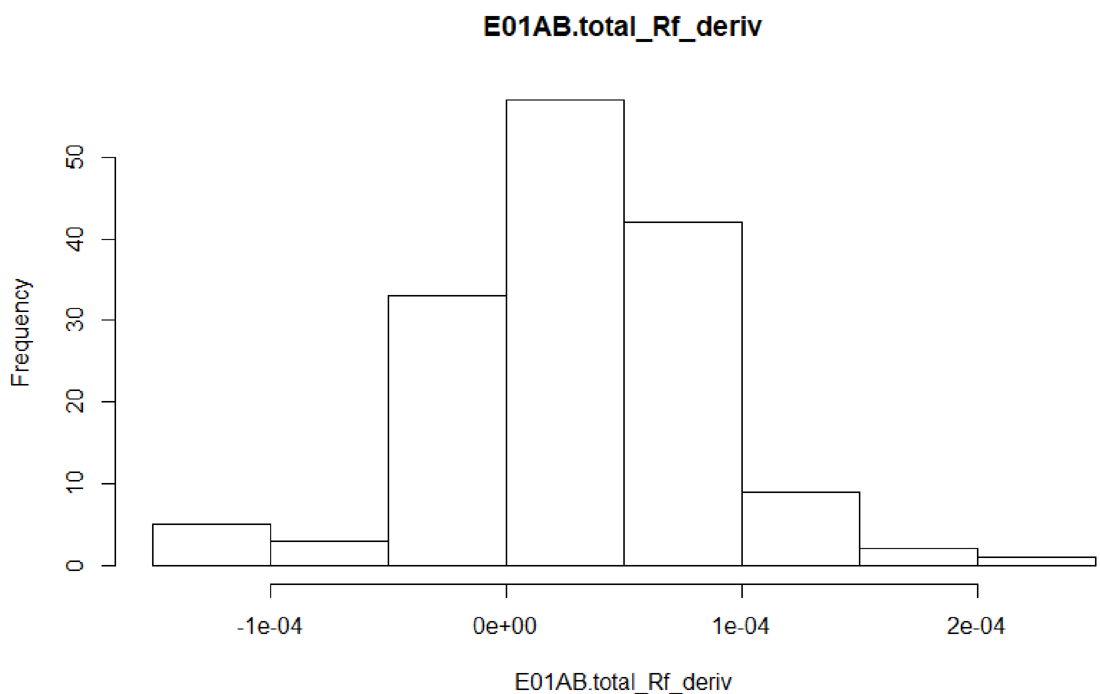
	E02AB.total_Rf_deriv	E03AB.total_Rf_deriv	E04.total_Rf_deriv	E05AB.total_Rf_deriv	TR001
锘縏imestamps	0.12327368	0.035810590	-0.088643279	-0.169738372	0.38182272
TI001	0.11884938	-0.050466460	0.020900871	-0.185970923	0.82370004
TI002	0.19936685	-0.020228660	0.002391019	-0.180058463	0.77644211
TI003	0.27627913	-0.052092451	0.038236275	-0.100989234	0.78191289
TI004	0.05412029	-0.030869038	0.062344692	-0.127434302	0.87399730
TI005	0.08597008	0.012175026	-0.017848985	-0.240932457	0.94574015
TI006	0.02910343	-0.042885892	-0.018883421	-0.214234562	0.91545637
TI007	0.02752442	0.096383466	0.083152987	-0.148808841	0.58044104
TI008	-0.04645708	0.068179596	0.088497420	-0.072469291	0.39760482
TI009	-0.18481933	0.054514125	0.135321672	0.061425930	0.23590345
TI010	-0.21500150	-0.039095710	0.062777731	-0.104679391	0.33035895
TI011	-0.06645070	0.105503076	-0.002819051	-0.294378685	0.72906640
TI012	0.04396630	0.062000182	-0.050946423	-0.283777549	0.81504486
TI013	0.10467072	0.039529799	-0.036761648	-0.263611845	0.82629172
TI014	-0.05988515	-0.021370868	0.042754715	-0.054034456	0.54469619
TI015	0.08976549	-0.016918601	-0.040455910	-0.256167557	0.74865194
E01AB.tube_velocity	-0.21178417	0.089450971	0.089599586	-0.010848339	-0.24636137
E02AB.tube_velocity	-0.10577210	0.098625771	-0.005427296	-0.252633280	0.30172834
E03AB.tube_velocity	-0.09802960	0.100806878	0.031168070	-0.237626028	0.35818830
E04.tube_velocity	-0.11110399	0.105823920	0.016951876	-0.212832371	0.15399008
E05AB.tube_velocity	0.09105753	0.120401547	0.007313561	-0.223778982	0.27686719
E01AB.shell_tau	0.07495530	0.118020746	-0.144423760	-0.066793657	0.15537879
E01AB.shell_Tf	-0.03797295	0.074005379	0.081105243	-0.099223733	0.44845193
E01AB.tube_tau	-0.22391664	0.082230472	0.085091040	0.008972506	-0.32858921
E01AB.tube_Tf	0.17274873	-0.024672307	-0.001923356	-0.197854544	0.80801660
E01AB.wall_T	-0.05805547	0.063502619	0.078704577	-0.078883564	0.38725250
E02AB.shell_tau	-0.09815192	0.028592894	0.023208819	-0.183792040	0.69541834
E02AB.shell_Tf	0.09041960	0.049538650	-0.043192658	-0.265811549	0.81921183
E02AB.tube_tau	-0.11607878	0.088139159	-0.010028450	-0.236250060	0.17135313
E02AB.tube_Tf	0.12165733	0.003185429	-0.008893487	-0.219462094	0.93363070
E02AB.wall_T	0.10038848	0.046686566	-0.042155180	-0.261962153	0.81325422
E03AB.shell_tau	-0.12072510	-0.082246104	-0.028162711	-0.185170111	0.39466393
E03AB.shell_Tf	0.09672855	-0.010073880	-0.030360631	-0.212772387	0.65604965
E03AB.tube_tau	-0.10709195	0.097638353	0.037077061	-0.210557437	0.19789702
E03AB.tube_Tf	0.06366597	-0.014895416	-0.019363985	-0.237299262	0.93928193
E03AB.wall_T	0.10638080	-0.006684785	-0.033472457	-0.218802510	0.66471210
E04.shell_tau	0.03121953	-0.043048070	0.041331483	-0.124634657	0.32816453
E04.shell_Tf	-0.22406995	-0.041412857	0.085933070	-0.061670383	0.31337836
E04.tube_tau	-0.12489546	0.105709683	0.012039664	-0.200446099	0.07651486
E04.tube_Tf	0.26725181	-0.047860479	0.032037999	-0.118697101	0.78799180
E04.wall_T	-0.07416130	-0.055261930	0.078362917	-0.103102763	0.57408272
E05AB.shell_tau	-0.10027453	0.029343870	0.022812873	-0.183729992	0.69435739
E05AB.shell_Tf	0.00484730	0.080648624	-0.053654138	-0.290813176	0.80190936
E05AB.tube_tau	0.08515689	0.115295423	-0.006805621	-0.212031348	0.17587894
E05AB.tube_Tf	0.11068090	-0.046090153	0.073389316	-0.093034287	0.85575773
E05AB.wall_T	0.01608411	0.076362500	-0.058390820	-0.286991113	0.79384981
FC001	-0.07222643	0.132662119	0.109863804	-0.080293478	-0.09713796
FC002	0.02439547	0.125263117	0.132384848	-0.055528624	-0.08993613
FC003	-0.25967380	0.091007859	0.062981975	-0.115963472	-0.02832684
FC004	-0.03604409	-0.103329173	0.123423943	0.048007544	0.06168514
FC005	-0.06710375	0.045494558	0.017301249	-0.173218847	0.72004758
FC006	-0.09605390	-0.079262507	-0.018110386	-0.165121625	0.40417506
FC007	0.06908055	0.144563391	-0.104321035	-0.117444520	0.37585728

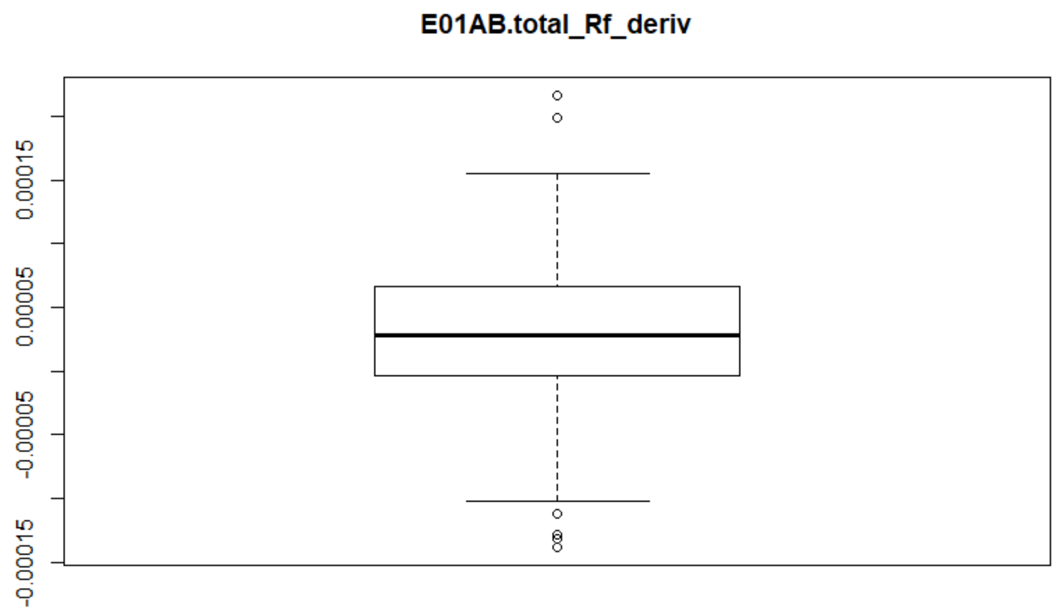
E01AB.shell_Re	0.03797602	0.135526664	-0.001320771	-0.149319155	0.56252626
E01AB.shell_Tsurface	-0.05524785	0.065143859	0.078951920	-0.081900088	0.39654766
E01AB.tube_Re	-0.02842190	0.079522107	0.098062567	-0.183864557	0.44733214
E01AB.tube_Tsurface	0.17757929	-0.019818381	-0.004850479	-0.195773790	0.78869487
E02AB.shell_Re	0.01781272	0.052516894	-0.006774936	-0.241417443	0.87010733
E02AB.shell_Tsurface	0.09942857	0.046901611	-0.042162355	-0.262315890	0.81439184
E02AB.tube_Re	-0.05995557	0.070807887	0.010365521	-0.277701731	0.69815386
E02AB.tube_Tsurface	0.11320795	0.005578209	-0.009806026	-0.221971678	0.94062636
E03AB.shell_Re	-0.03237731	-0.054270321	-0.031293848	-0.208690826	0.53629879
E03AB.shell_Tsurface	0.10502990	-0.007153669	-0.033238889	-0.218454778	0.66403350
E03AB.tube_Re	-0.08401769	0.056369697	0.012186746	-0.277825215	0.73310706
E03AB.tube_Tsurface	0.05827640	-0.019096585	-0.018682346	-0.234279932	0.93484707
E04.shell_Re	-0.02371556	-0.041220471	0.046399798	-0.122616229	0.33741252
E04.shell_Tsurface	-0.23235052	-0.037455574	0.074899391	-0.073898314	0.30371853
E04.tube_Re	0.09748625	0.070679188	0.067715248	-0.213830280	0.53983908
E04.tube_Tsurface	0.27887434	-0.052836537	0.038458813	-0.104207436	0.78078123
E05AB.shell_Re	-0.04423622	0.064807271	-0.005940263	-0.237920283	0.84424286
E05AB.shell_Tsurface	0.01483751	0.076682190	-0.057923254	-0.287438586	0.79580028
E05AB.tube_Re	0.13111173	0.082166813	0.096898980	-0.193009562	0.63441448
E05AB.tube_Tsurface	0.09349464	-0.043085127	0.074284001	-0.091820328	0.84389701

It is also possible to establish or verify that fouling rate in Exchangers are very independent variables, however, it is hard to find which variable directly affects fouling rate from the correlation result. This is why the next best alternative is to use PCA to reduce dimensionality when the model has low accuracy. However, another very important variable TR001 shows different levels of correlation, where, some have very strong correlation, such as TI005, tube side temperature at the surface of the deposit in E02AB and E03AB, while others show very weak correlation, such as tube tau in E04, FC001, FC003 and FC004. This is why it is key that the accuracy of the model is increased as much as possible.

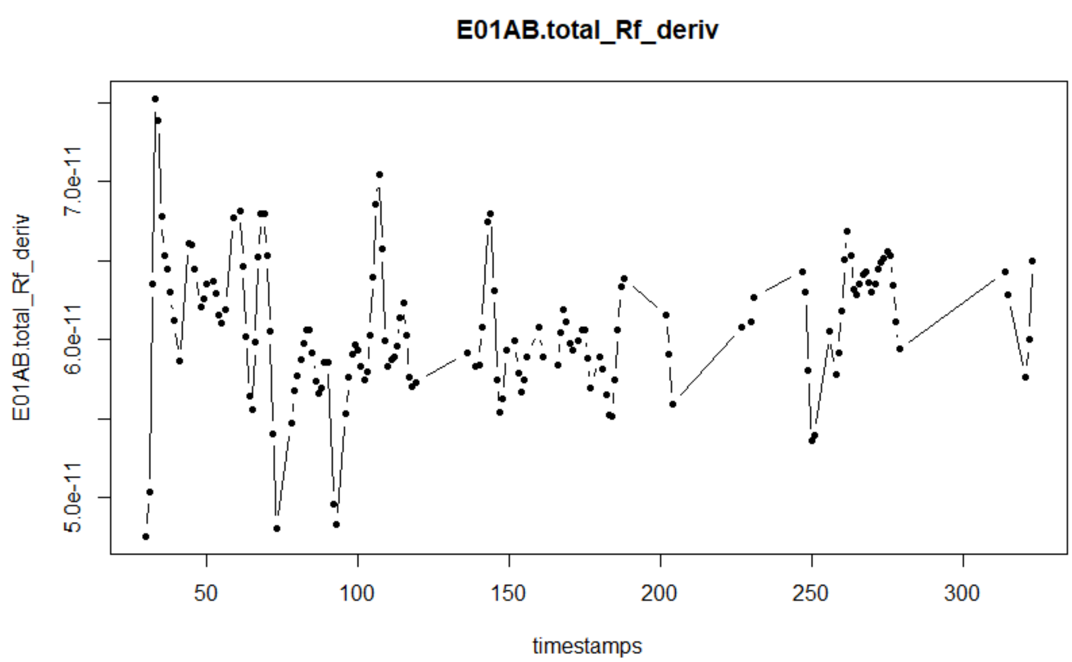
What is done next is the distribution analysis for the key output: fouling rate and TR001


E01AB.total_Rf_deriv
Density
0
2000
4000
6000
8000
-2e-04
-1e-04
0e+00
1e-04
2e-04
E01AB.total_Rf_deriv

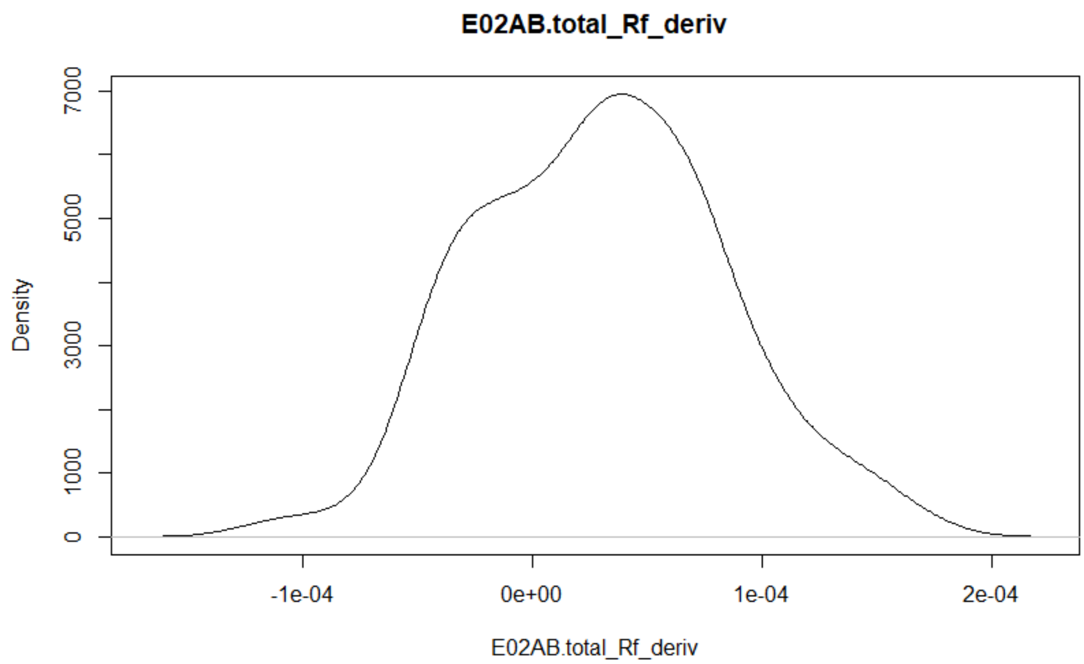

E01AB.total_Rf_deriv
Frequency
0
10
20
30
40
50
-1e-04
0e+00
1e-04
2e-04
E01AB.total_Rf_deriv

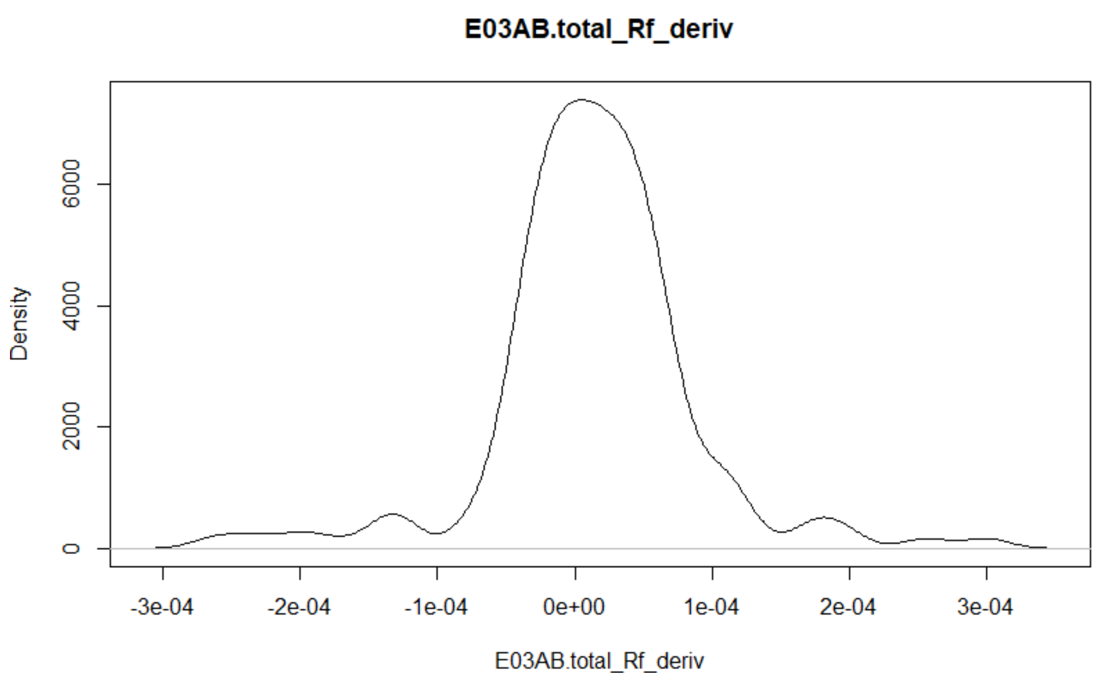


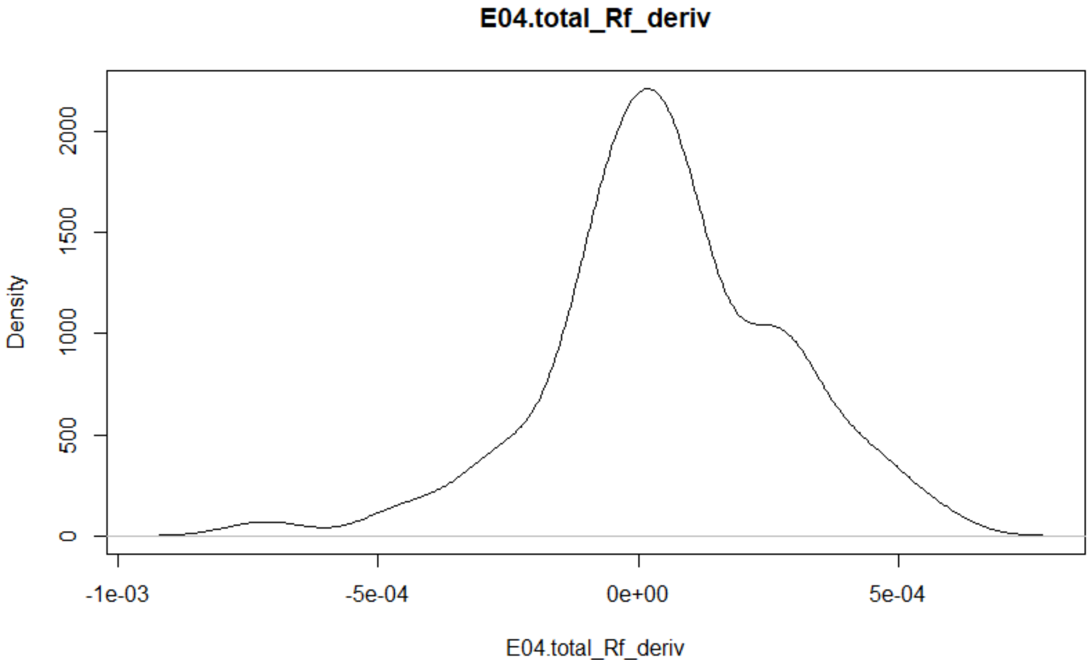
From these three figures above, it is now possible to know the E01AB fouling rate is normal distribution in general. The data concentrates at 0.00005, and there are few outlier values. The range of E01AB fouling rate is about -2e-04 to 2e-04.

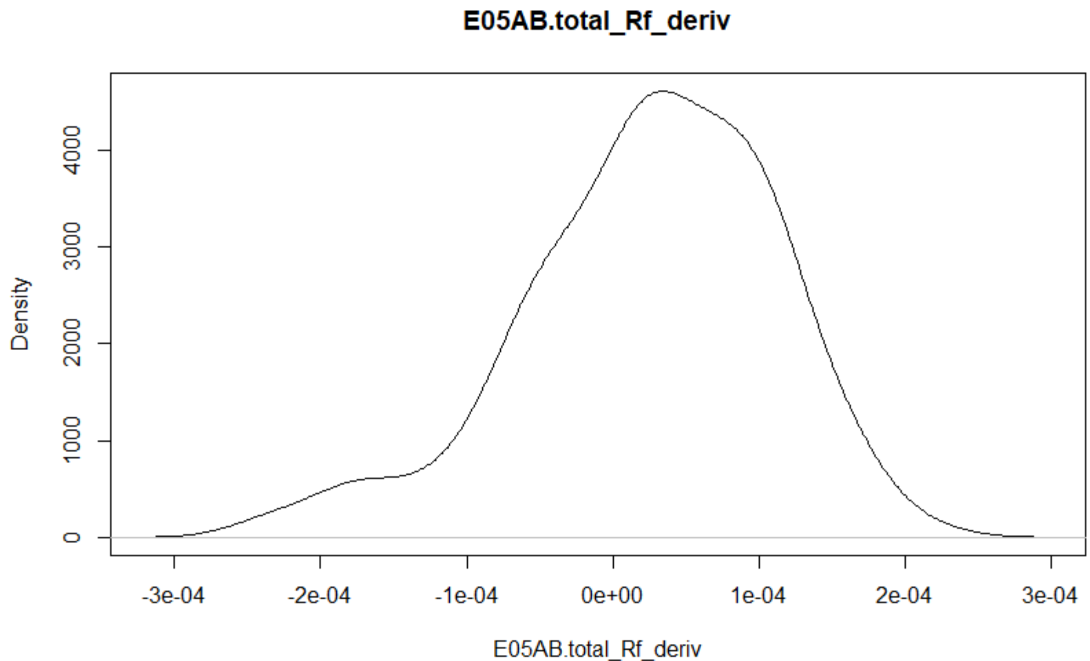


The pattern observed, as shown above, is an up and down surrounded by 0 at the E01AB fouling rate figure with timestamps. It has significant change at beginning, but it has few big changes with an increase in time. There are some stability in the middle area , but this could be due to the fact that most data lies at the middle.

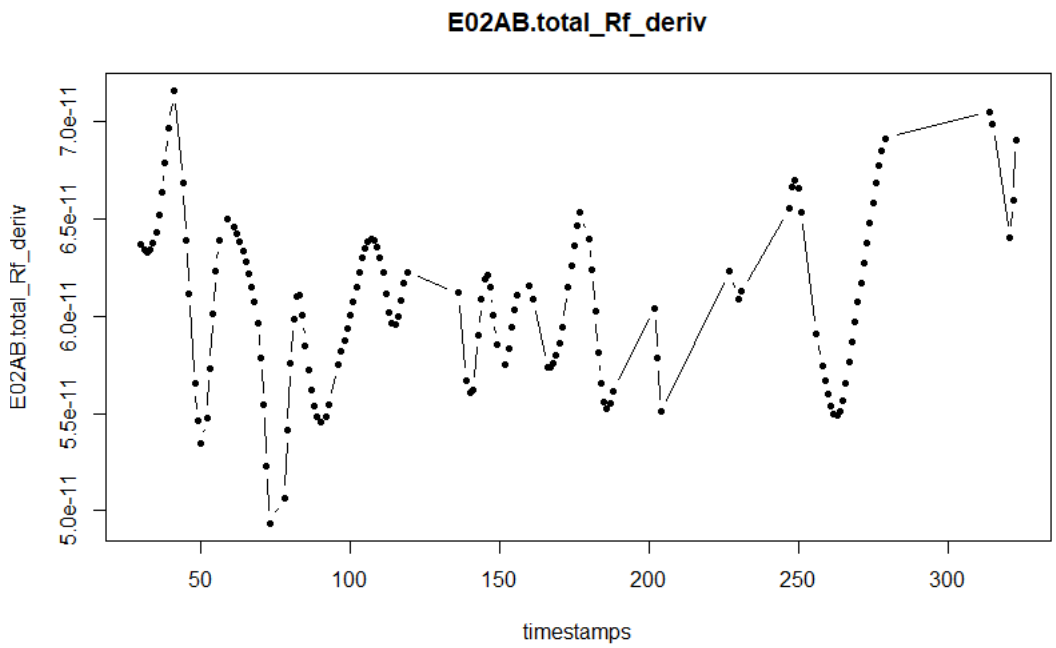

E02AB.total_Rf_deriv
Density
0
1000
3000
5000
7000
-1e-04
0e+00
1e-04
2e-04
E02AB.total_Rf_deriv

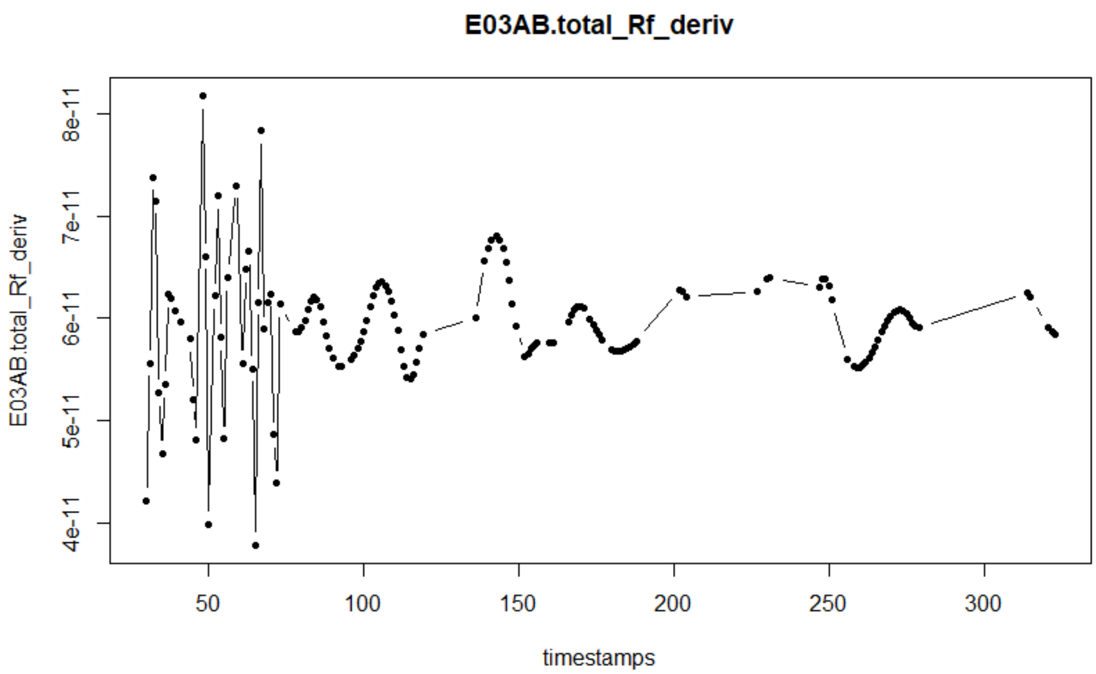

E03AB.total_Rf_deriv
Density
0
2000
4000
6000
-3e-04
-2e-04
-1e-04
0e+00
1e-04
2e-04
3e-04
E03AB.total_Rf_deriv

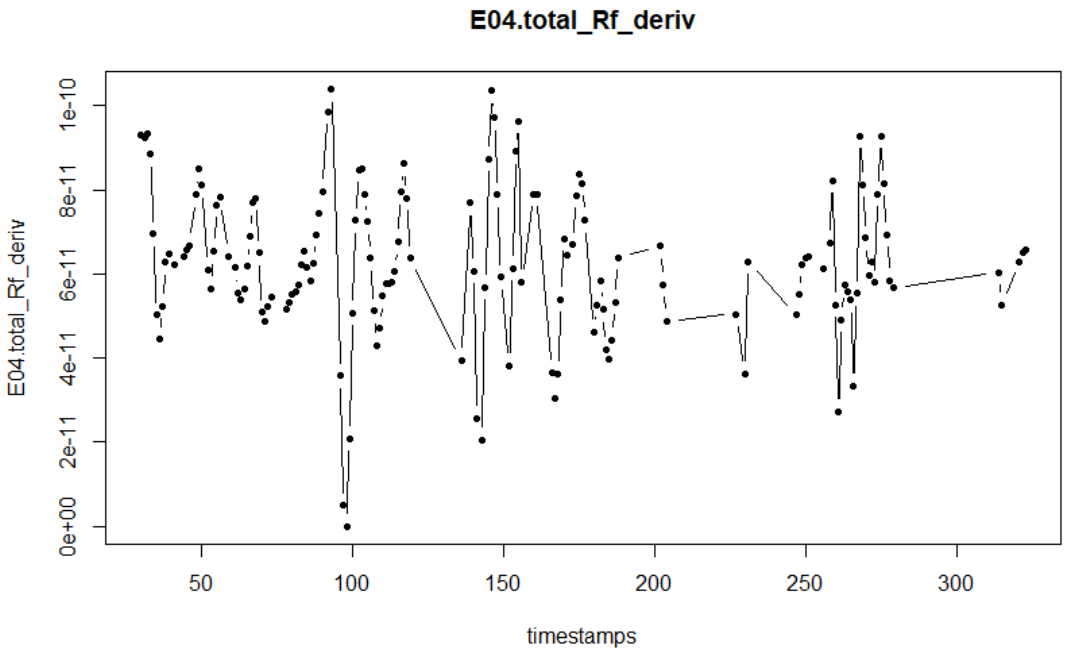


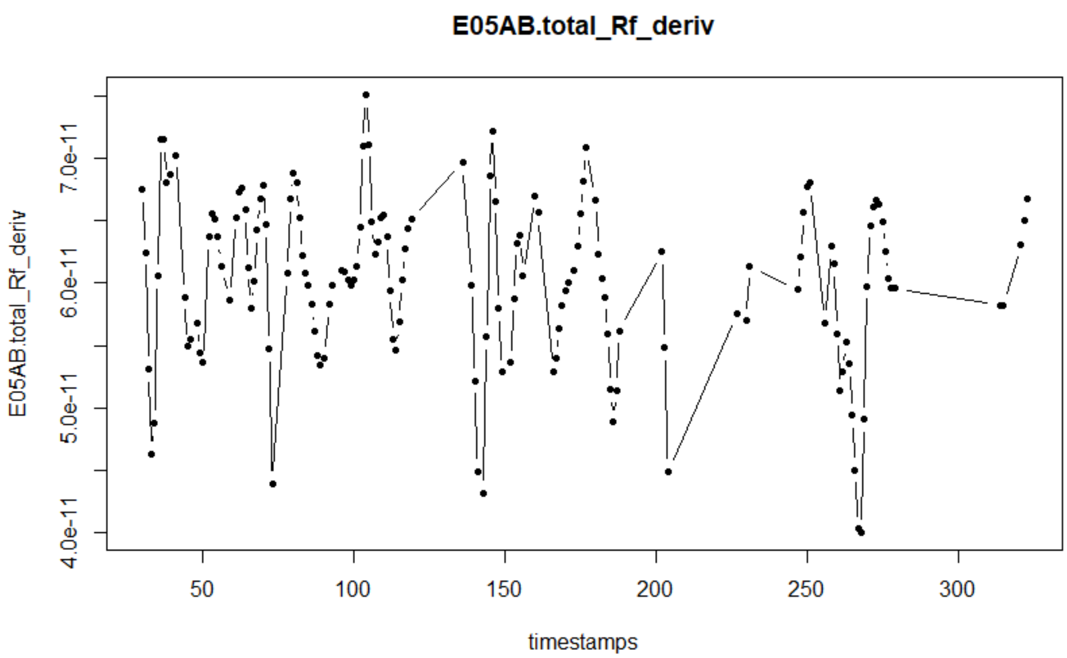


It can also be observed that there are few different of density maps of fouling rate inE02, E03, E04 and E05. The E03AB fouling rate concentrates more at -1e-04 to 1e-04 area. It means E03AB fouling rate value shows at a smaller area compare to other exchangers, but E03AB has more outlier values

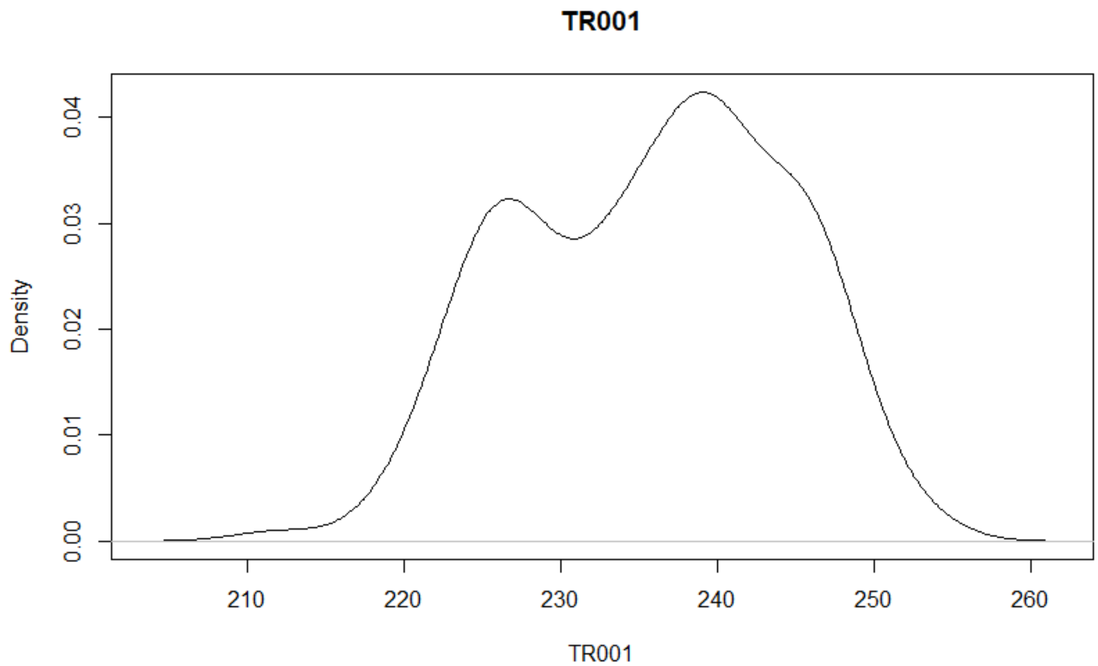

E02AB.total_Rf_deriv
E02AB.total_Rf_deriv
timestamps
5.0e-11
5.5e-11
6.0e-11
6.5e-11
7.0e-11
50
100
150
200
250
300

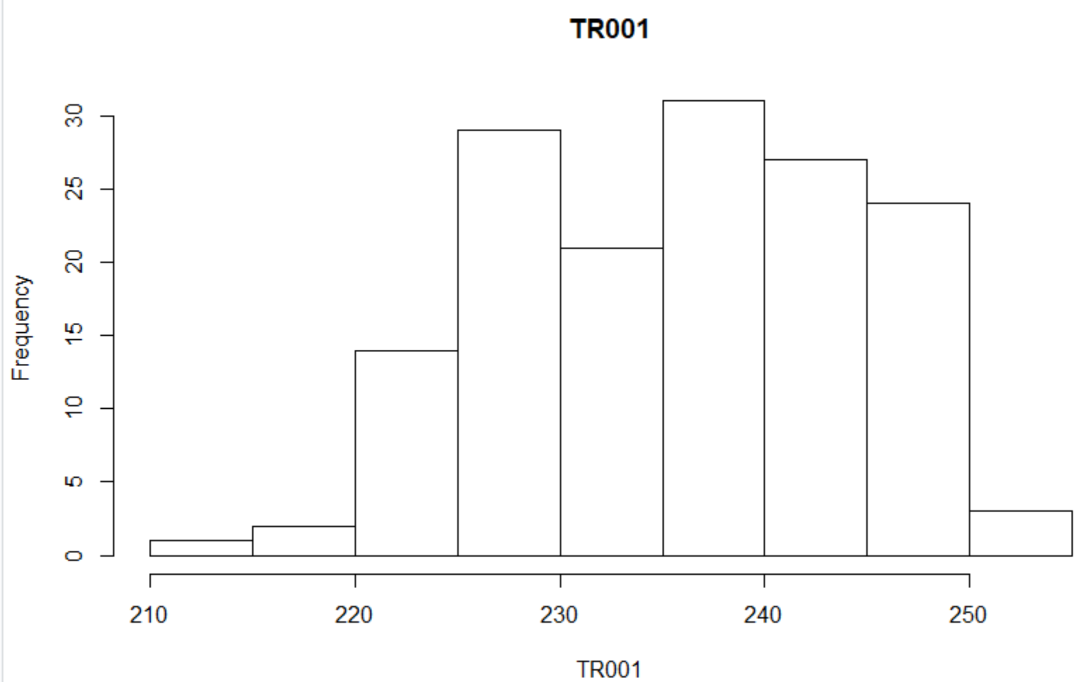

E03AB.total_Rf_deriv
E03AB.total_Rf_deriv
timestamps
4e-11
5e-11
6e-11
7e-11
8e-11
50
100
150
200
250
300

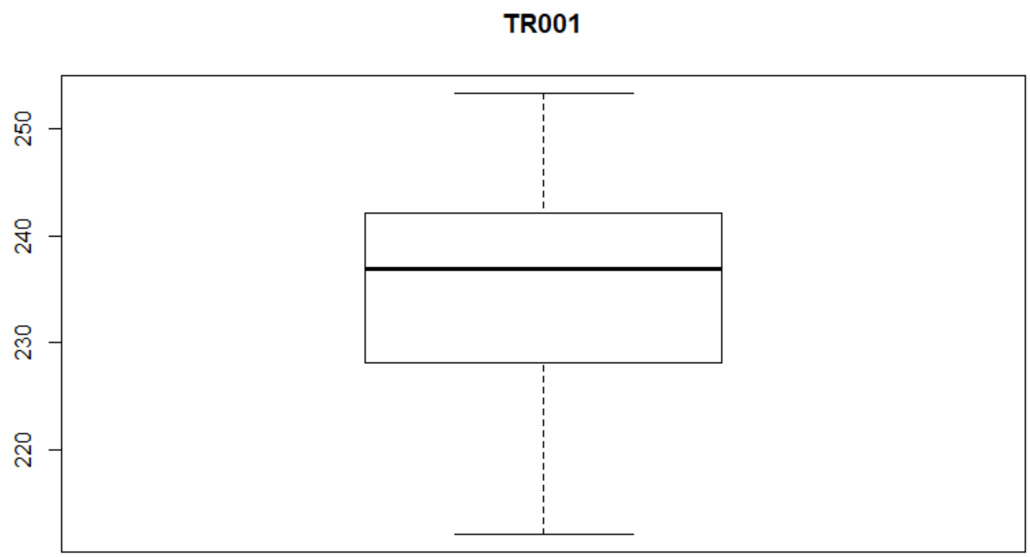




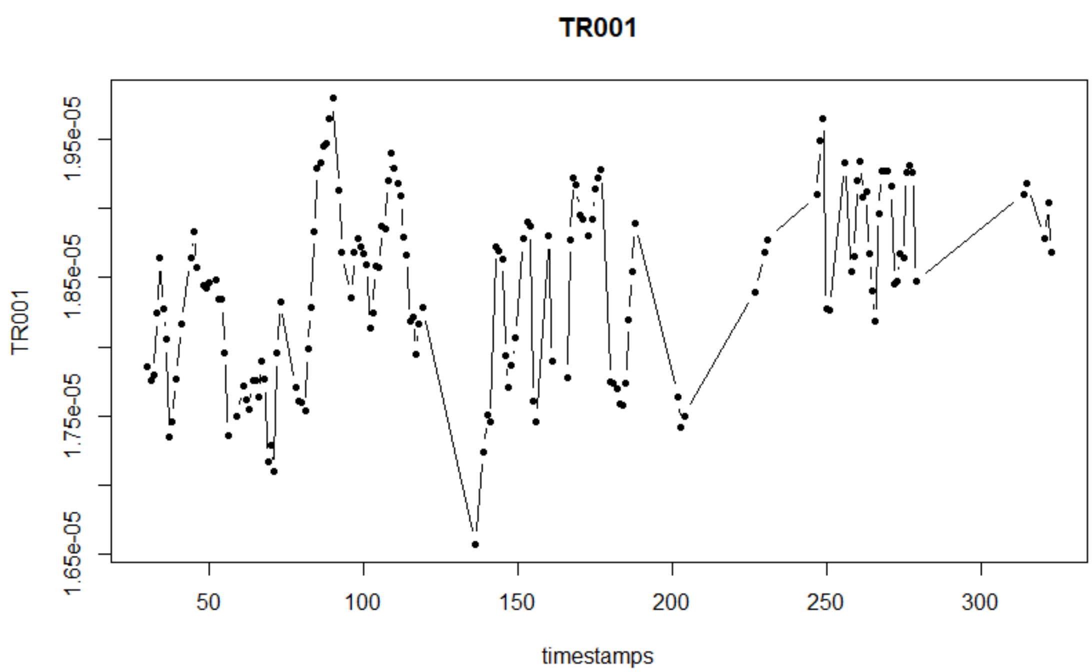
At distribution map, each exchanger fouling rates are shown up and down and surrounded by 0. The E03AB looks like the fouling rate has big change more often at the beginning, and E05AB fouling rate, on the other hand, has a big change the entire time. The E04 has big change at the middle about 100 to 150 days.


TR001
Density
0.00
0.01
0.02
0.03
0.04
210
220
230
240
250
260
TR001


TR001
Frequency
0
5
10
15
20
25
30
210
220
230
240
250
TR001



The variable TR001 is different to fouling rate variable, since the value distributes at a big range between 225 and 250. The frequency of TR001 has huge drop after 250, thus the TR001 has very few outlier values. The mean of TR001 is about 238, and the value concentrates at 237 and 240.



TR001 with timestamps figure shows that the temperature between 225 and 230 are a special line. The temperature will increase when the temperature decrease to this level. Most of time, the temperature has small change about 10 degrees, but it could have very big change.

Next, is to try to build the classified model to find how the variable affects the fouling rate. First of all, the researcher changed the fouling rate value to 5 levels:-2 = fast decrease, -1= decrease, 0 = no change, 1 = increase and 2 = fast increase and this is because these are no 0 in dataset so there are only have 4 levels. Then the researcher combined with input variables, and the new dataset is shown below:

```
'data.frame':   152 obs. of  78 variables:
 $ V1                   : Factor w/ 4 levels "-2","-1","1",..: 1 1 3 4 4 4 3 3 3 3 ...
 $ V2                   : Factor w/ 4 levels "-2","-1","1",..: 3 3 3 3 3 3 4 4 4 4 ...
 $ V3                   : Factor w/ 4 levels "-2","-1","1",..: 1 2 4 4 2 1 2 3 3 3 ...
 $ V4                   : Factor w/ 4 levels "-2","-1","1",..: 4 4 4 4 3 2 2 2 3 3 ...
 $ V5                   : Factor w/ 4 levels "-2","-1","1",..: 4 3 2 1 1 3 4 4 4 4 ...
 $ 锘縏imestamps        : int  30 31 32 33 34 35 36 37 38 39 ...
 $ TI001                : num  165 163 164 171 172 ...
 $ TI002                : num  182 183 183 189 191 ...
 $ TI003                : num  194 195 195 201 204 ...
 $ TI004                : num  231 230 232 239 243 ...
 $ TI005                : num  200 199 201 208 211 ...
 $ TI006                : num  226 225 224 228 234 ...
 $ TI007                : num  247 242 240 241 241 ...
 $ TI008                : num  230 227 226 229 230 ...
 $ TI009                : num  323 321 320 322 322 ...
 $ TI010                : num  246 246 250 249 252 ...
 $ TI011                : num  327 322 325 326 326 ...
 $ TI012                : num  242 238 242 247 249 ...
 $ TI013                : num  205 203 206 212 215 ...
 $ TI014                : num  338 337 335 330 332 ...
 $ TI015                : num  209 208 209 214 218 ...
 $ E01AB.tube_velocity : num  2.39 2.25 2.22 2.03 1.81 ...
 $ E02AB.tube_velocity : num  2.03 1.92 1.9 1.66 1.48 ...
 $ E03AB.tube_velocity : num  2.97 2.8 2.75 2.42 2.18 ...
 $ E04.tube_velocity   : num  2.34 2.3 2.3 2.11 1.95 ...
 $ E05AB.tube_velocity : num  2.23 2.19 2.19 1.97 1.81 ...
 $ E01AB.shell_tau     : num  4134 4455 4537 4470 4453 ...
 $ E01AB.shell_Tf      : num  234 230 228 231 232 ...
 $ E01AB.tube_tau      : num  12.75 11.46 11.19 9.3 7.55 ...
 $ E01AB.tube_Tf       : num  176 176 176 182 184 ...
 $ E01AB.wall_T        : num  230 225 224 227 229 ...
 $ E02AB.shell_tau     : num  34.3 30.2 32.1 31.2 30.2 ...
 $ E02AB.shell_Tf      : num  211 209 212 219 222 ...
 $ E02AB.tube_tau      : num  8.92 8.08 7.88 6.05 4.87 ...
 $ E02AB.tube_Tf       : num  195 194 196 203 207 ...
 $ E02AB.wall_T        : num  206 205 208 215 218 ...
 $ E03AB.shell_tau     : num  10.37 9.69 7.59 5.34 5.72 ...
 $ E03AB.shell_Tf      : num  228 228 226 232 238 ...
 $ E03AB.tube_tau      : num  18.3 16.5 15.9 12.4 10.2 ...
 $ E03AB.tube_Tf       : num  211 210 210 216 221 ...
 $ E03AB.wall_T        : num  216 217 216 223 229 ...
 $ E04.shell_tau       : num  19 18.7 21.3 17 17.7 ...
 $ E04.shell_Tf        : num  278 277 279 280 282 ...
 $ E04.tube_tau        : num  11.75 11.44 11.42 9.62 8.26 ...
 $ E04.tube_Tf         : num  191 191 192 198 200 ...
 $ E04.wall_T          : num  234 234 236 239 241 ...
 $ E05AB.shell_tau     : num  35.5 31.2 33.2 32.2 31.1 ...
 $ E05AB.shell_Tf      : num  260 256 260 263 264 ...
 $ E05AB.tube_tau      : num  9.96 9.6 9.57 7.8 6.6 ...
 $ E05AB.tube_Tf       : num  222 221 222 230 234 ...
 $ E05AB.wall_T        : num  250 246 250 254 255 ...
 $ FC001               : num  185 177 175 156 138 ...
 $ FC002               : num  97.1 95.4 94.8 85.2 78.2 ...
 $ FC003               : num  91.8 86.5 84.8 73.3 65.2 ...
 $ FC004               : num  15.7 15.5 16.3 14 14.2 ...
 $ FC005               : num  39.4 37 38.1 37.5 36.9 ...
 $ FC006               : num  15.5 15 13.2 11 11.4 ...
```

```
$ FC007                  : num  187 195 196 195 195 ...
$ E01AB.shell_Re         : num  154294 155201 154580 155109 155850 ...
$ E01AB.shell_Tsurface: num  231 226 225 228 229 ...
$ E01AB.tube_Re          : num  56393 53242 52526 50313 45340 ...
$ E01AB.tube_Tsurface : num  179 178 178 185 187 ...
$ E02AB.shell_Re         : num  6470 5931 6362 6763 6842 ...
$ E02AB.shell_Tsurface: num  206 205 208 215 218 ...
$ E02AB.tube_Re          : num  58357 55081 54704 50296 45810 ...
$ E02AB.tube_Tsurface : num  196 196 197 205 208 ...
$ E03AB.shell_Re         : num  3542 3409 2936 2507 2780 ...
$ E03AB.shell_Tsurface: num  217 217 217 223 230 ...
$ E03AB.tube_Re          : num  65909 61844 60859 55545 51238 ...
$ E03AB.tube_Tsurface : num  213 212 212 218 223 ...
$ E04.shell_Re           : num  13882 13659 14823 13381 13777 ...
$ E04.shell_Tsurface     : num  274 273 276 277 278 ...
$ E04.tube_Re            : num  61675 61054 61078 58194 54523 ...
$ E04.tube_Tsurface      : num  193 193 194 200 202 ...
$ E05AB.shell_Re         : num  11759 10531 11237 11332 11211 ...
$ E05AB.shell_Tsurface: num  251 247 250 254 256 ...
$ E05AB.tube_Re          : num  75820 73953 74399 70157 66161 ...
$ E05AB.tube_Tsurface : num  225 223 225 232 236 ...
```

V1 V2 V3 V4 V5 are fouling rate in E01 E02 E03 E04 E05.

The method that is used in this case is SVM (Support Vector Machine) and decision tree, and the reasons why they are used is because SVM is good method in performing classified problems. In other words, it is good at high-dimensional dataset. The dataset I used have 73 input, thus SVM is good method to this problem and decision tree performs well at both classified and regression problems.

SVM result is shown below

Linear kernel for E01AB fouling rate

```
> lk_svm_results_table1
    actual
svm  -2 -1  1  2
  -2  0  1  1  2
  -1  0  4  5  1
  1   1  5 22  3
  2   0  0  0  1
> acc_lk_svm1
[1] 0.5869565
```

The result shows correct prediction concentrate at 1. The -2 is less correct value. These are non-success prediction.

Linear kernel for E02AB fouling rate

```
> lk_svm_results_table2
     actual
svm   -2 -1  1  2
  -2   1  1  0  0
  -1   0  4  5  2
  1    0  7 21  4
  2    0  0  0  1
> acc_lk_svm2
[1] 0.5869565
```

The result shows 1 is the most correct number value. It has 21 times success prediction. -2 and 2 are less success predict value.

Linear kernel for E03AB fouling rate

```
> lk_svm_results_table3
     actual
svm   -2 -1  1  2
  -2   0  1  2  0
  -1   2  7  4  1
  1    0  5 22  2
  2    0  0  0  0
> acc_lk_svm3
[1] 0.6304348
```

The result shows success prediction is concentrated. It concentrates at 1 and -1. There is non-success prediction in -2 and 2.

linear kernel for E04 fouling rate

```
> lk_svm_results_table4
     actual
svm   -2 -1  1  2
  -2  1  0  0  0
  -1  0  8 10  2
  1   1  7  9  3
  2   0  0  4  1
> acc_lk_svm4
[1] 0.4130435
```

This result show low accuracy; the main mistake happened at -1 values. The correct times are 8 and incorrect times are 12.

Linear kernel for E05AB fouling rate

```
> lk_svm_results_table5
     actual
svm   -2 -1  1  2
  -2  1  0  0  1
  -1  0  6  3  4
  1   1  6 11  5
  2   0  0  4  4
> acc_lk_svm5
[1] 0.4782609
```

This result also has really low accuracy, since it is lower than 50%. The prediction result performs poorly at all four levels.

Radial basis kernel for E01AB fouling rate

```
> rbf_svm_results_table1
     actual
svm   -2 -1  1  2
  -2  0  0  0  0
  -1  0  2  2  0
  1   1  8 26  7
  2   0  0  0  0
> acc_rbf_svm1
[1] 0.6086957
```

This result shows the main correct prediction concentrate at 1 and main mistake happened at -1.

Radial basis kernel for E02AB fouling rate

```
> rbf_svm_results_table2
     actual
svm  -2 -1  1  2
  -2  0  0  0  0
  -1  0  2  1  0
  1   1 10 24  7
  2   0  0  1  0
> acc_rbf_svm2
[1] 0.5652174
```

The result shows the main prediction area s -1 and 1. It has over 80% value. -1 only success 2 time and fail 10 times.

Radial basis kernel for E03AB fouling rate

```
> rbf_svm_results_table3
     actual
svm  -2 -1  1  2
  -2  0  0  0  0
  -1  2  4  6  1
  1   0  9 22  2
  2   0  0  0  0
> acc_rbf_svm3
[1] 0.5652174
```

The result shows the main correct value concentrate at 1. It has 78% success rate in predicting 1.

Radial basis kernel for E04 fouling rate

```
> rbf_svm_results_table4
     actual
svm  -2 -1  1  2
  -2  0  0  0  0
  -1  1 10  7  2
  1   1  5 16  4
  2   0  0  0  0
> acc_rbf_svm4
[1] 0.5652174
```

The result shows the prediction accuracy is average. -1 and 1 have a little bit higher accuracy, and there are about 65%.

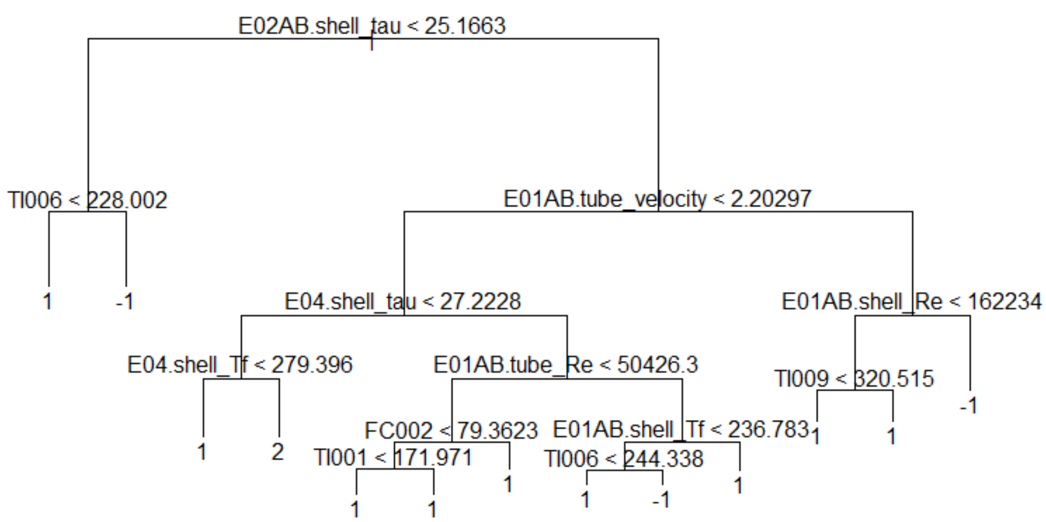
Radial basis kernel for E05AB fouling rate

```
> rbf_svm_results_table5
     actual
svm   -2 -1  1  2
  -2   0  0  0  0
  -1   0  1  1  1
  1    2 11 17 13
  2    0  0  0  0
> acc_rbf_svm5
[1] 0.3913043
```

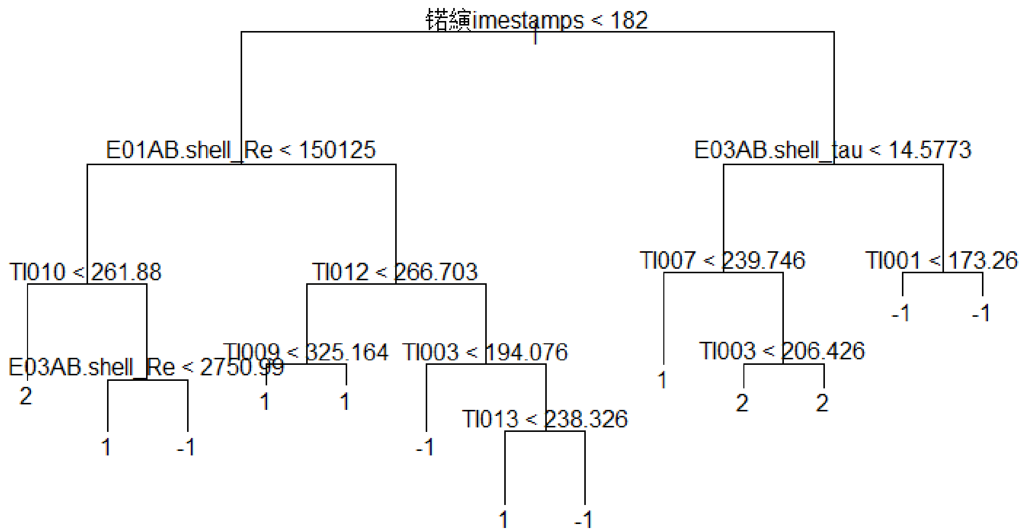
This result shows poor prediction performance. The worst prediction is level 2, since it has 13 fail with no correct times. From the result, I can know the linear kernel performs better in E02AB, E03AB and E05AB. The radial basis kernel performs better in E01AB and E04. But these are a problem, all the models only have about 50%-60% accuracy. To increase the accuracy, there is need to reduce some low correlation variable subsequently.

The next step was to use the method of decision tree to perform the model

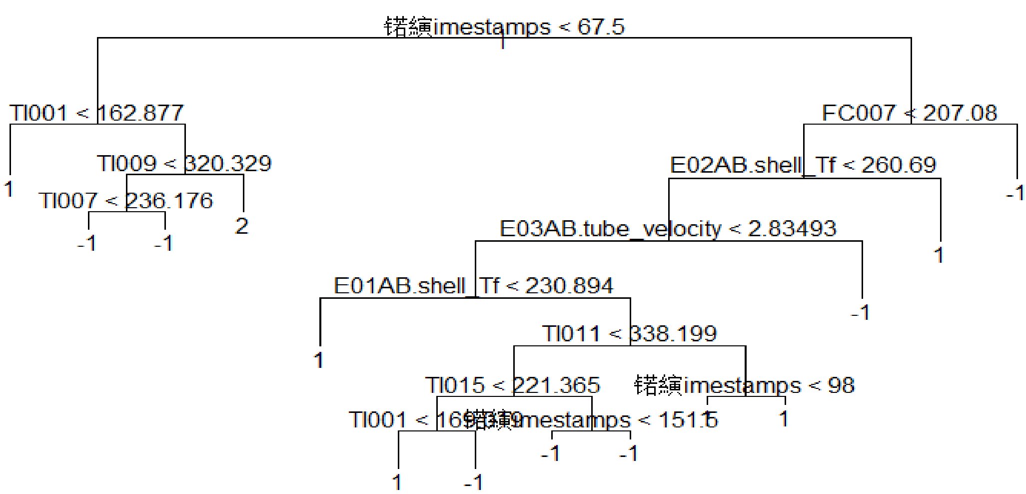
E01AB fouling rate decision tree



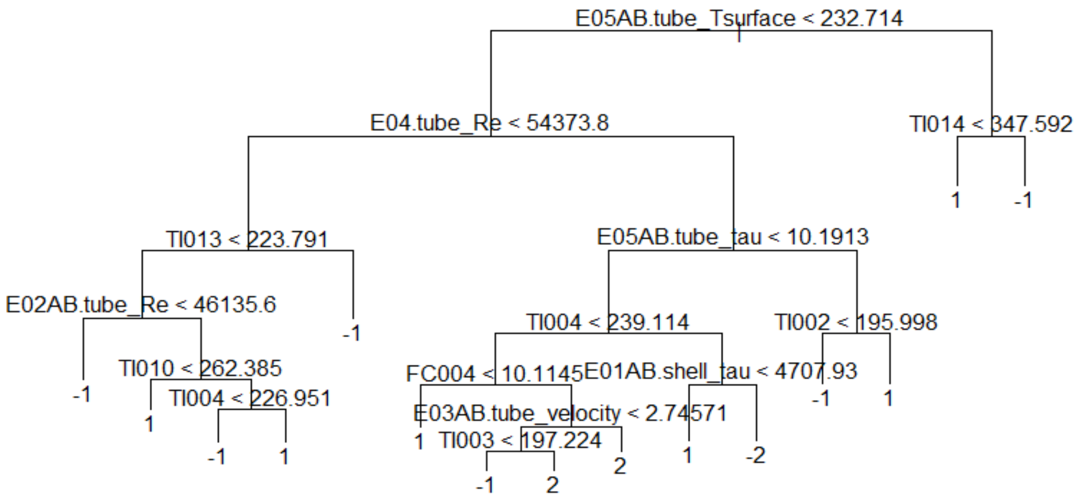
E02AB fouling rate decision tree



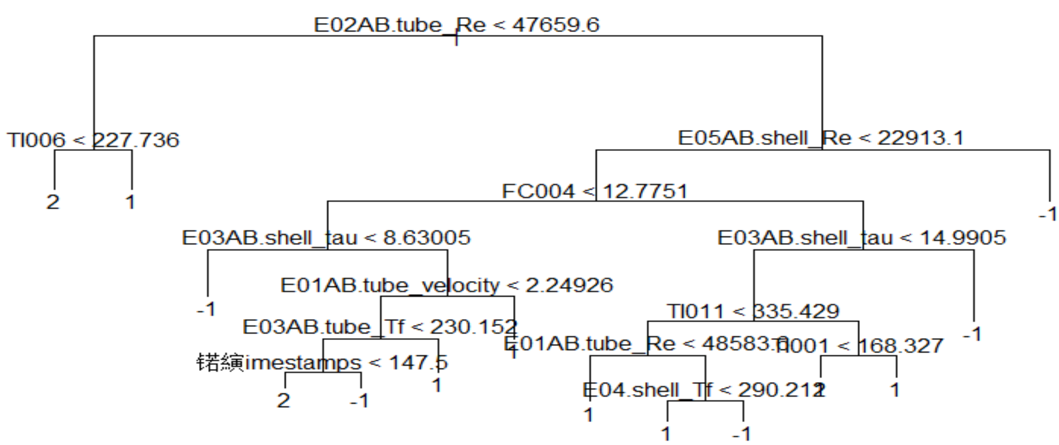
E03AB fouling rate decision tree



E04 fouling rate decision tree



E05AB fouling rate decision tree



E01AB fouling rate decision tree result

```
> unpruned_results_table1
      unpruned
actual -2 -1  1  2
    -2  1  0  1  0
    -1  0  6  8  1
    1   0  6 18  3
    2   0  1  1  0
> acc_unpruned1
[1] 0.5434783
```

From the result, it can be established that -2 has the highest accuracy, and that it is 100% but it only has 1 time so the results have no comparing value. The value 1 also shows the highest time correct prediction. The possible reason is 1 has more prediction times.

E02AB fouling rate decision tree result

```
> unpruned_results_table2
      unpruned
actual -2 -1  1  2
    -2  0  2  1  0
    -1  0  7  4  3
    1   0  6 14  4
    2   0  1  0  4
> acc_unpruned2
[1] 0.5434783
```

The E02AB decision tree prediction result is very similar to E01AB.

E03AB fouling rate decision tree result

```
> unpruned_results_table3
      unpruned
actual -2 -1  1  2
    -2  0  0  2  2
    -1  0  9  3  0
    1   0  9 20  0
    2   0  1  0  0
> acc_unpruned3
[1] 0.6304348
```

This result shows the decision tree has good performance in E03AB. The reason is the prediction has high accuracy in 1, which is 80%.

E04 fouling rate decision tree result

```
> unpruned_results_table4
      unpruned
actual -2 -1 1 2
    -2  0  0 0 0
    -1  0  9 7 3
    1   0  9 6 5
    2   0  2 3 2
> acc_unpruned4
[1] 0.3695652
```

This model performs really poorly. The accuracy is only 36%.

E05AB fouling rate decision tree result

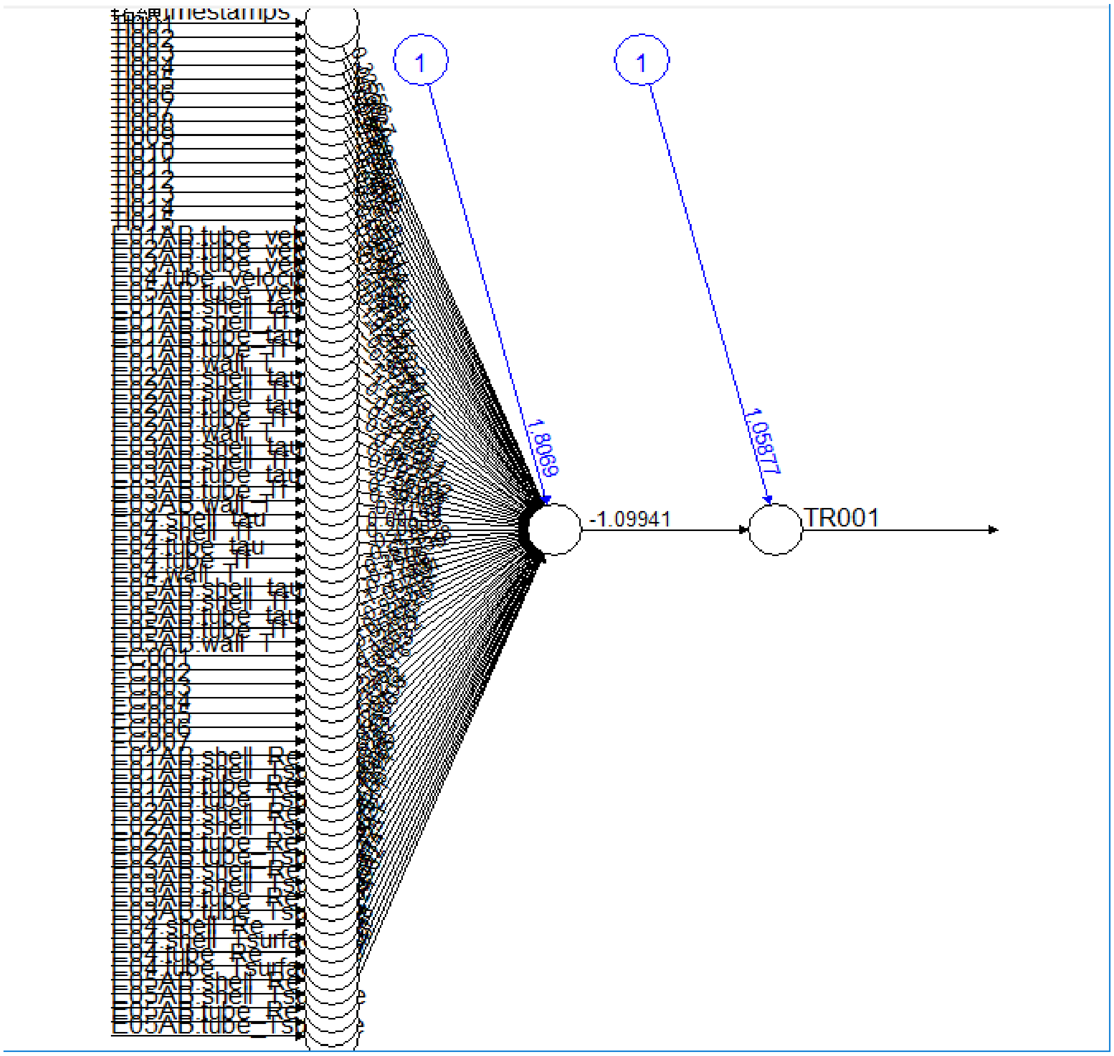
```
> unpruned_results_table5
      unpruned
actual -2 -1  1  2
    -2  0  1  2  0
    -1  0  6  4  1
    1   0  7 14  3
    2   0  1  5  2
> acc_unpruned5
[1] 0.4782609
```

The result shows the accuracy performance average at all 4 levels

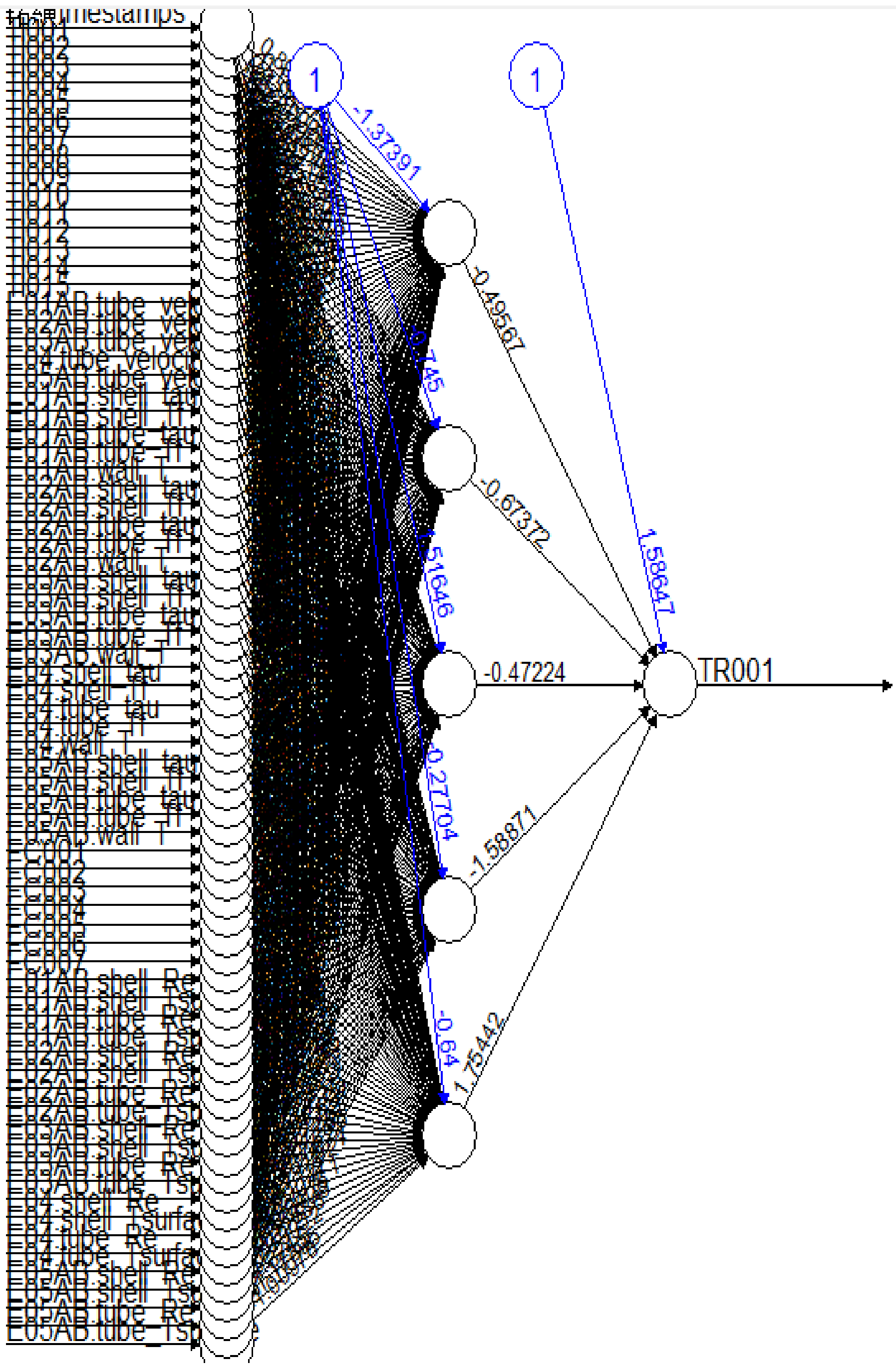
From the classified model, it can be established that the model does not perform very well in prediction. The possible reason is the sample size limitation and data is original data. Maybe it needs more processing, which is why there is need for data modification.

The last model is natural network, which was used to predict variable TR001. The advantage of natural network is that it performs well in both regression and classified model. It is good at learning from data. So the accuracy could be really high. But the neutral network could require more time to learn and the result are generally harder to interpret or   hard to explain.

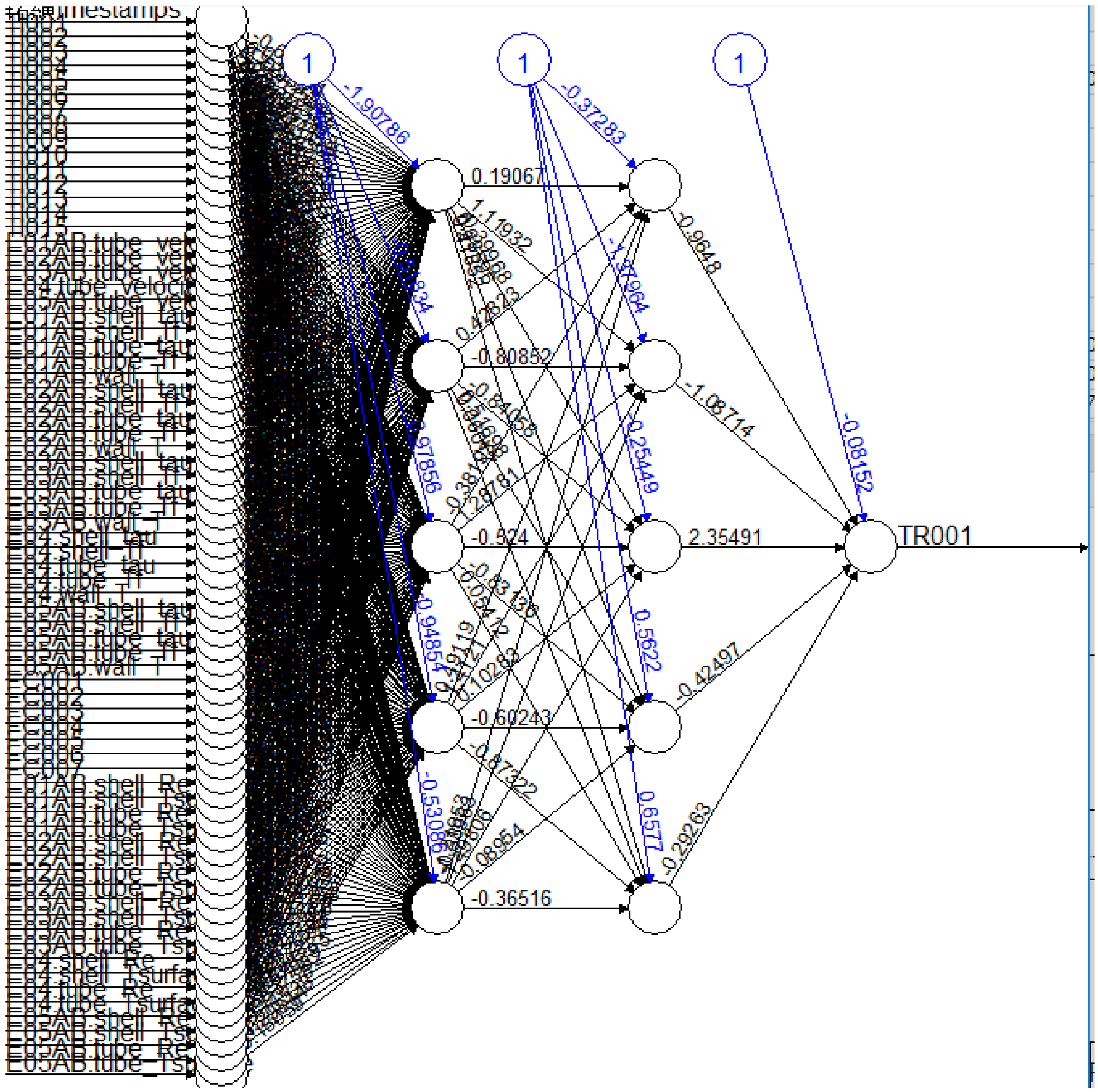
The model of 1 hidden node shows below



Model with 5 hidden nodes on 1 layer



Model with 5 hidden nodes on 2 layers

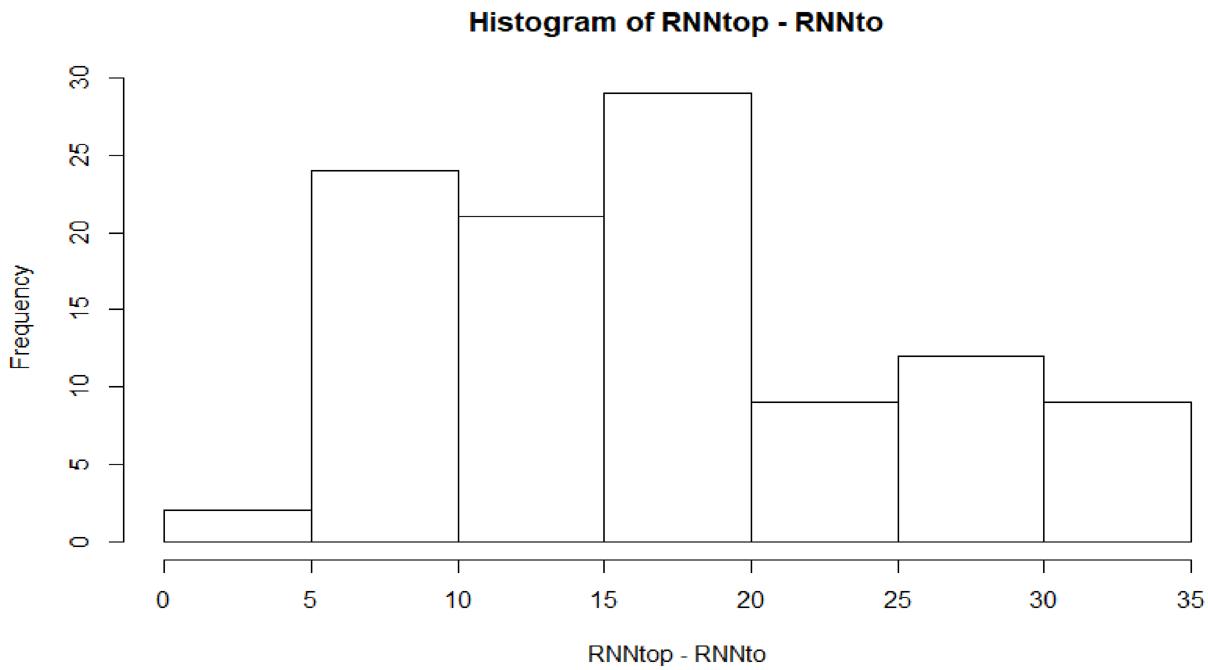


And the results show below

```
> cor(TR_results[,'actual'], TR_results[,c("nn_1","nn_5", "nn_55")])
             nn_1         nn_5        nn_55
[1,] 0.9947158968 0.9691670738 0.9866760788
```

It can be established that the neural network performs very well in TR001 prediction. The highest one is 1 hidden node model, where the accuracy is over 99%. Although, it could be as a results of few objects in dataset but it generally performs well. The other two models also have good performance, which have 96% and 98% accuracy.

Next, I try using recurrent neural network(RNN) to increase the model performance. RNN provide the memory to Neutral Network. The model could use the memory recurrent training. The method RNN I use it to train TR001 prediction model. The model circuit training 10 times and prediction error shows below.



The RNNtop is prediction value and RNNto is real value. And the value of TR001 is between 72.05 to 274.56. the mean is 235.66. Thus, the prediction results show about 70% prediction value lower than 10% error. However, there are only about 24% prediction value lower than 5% error. The RNN method perform not very well. The next step is to delete most of the low correlation variables to reduce dimensionality.

4.5 Key findings on fouling from secondary research

Crude oil fouling in heat in tubes and heat exchangers is majorly limited to deposits as thermal resistance. However, the thickness change and evolution characteristic of the deposits because of ageing also causes a significant impact on the thermal and hydraulic fouling (Kazi 2012). The unwanted deposits from the crude oil on tubes and heat transfer surfaces cause's significant effects during heat recovery, thus leading to significant energy losses, difficulty in operation, high fuel consumption and carbon dioxide emissions fouling (Kazi 2012). The preheat train (PHT) of crude oil acts as the primary essential facility for the efficiency of the energy refineries. Crude oil fouling significantly affects the end part of the PHT. Therefore, any mitigation in the PHT facilities may lead to substantial energy and fuel savings (Obama 2017).

The tubes, heat exchangers design, and monitoring techniques majorly rely on the fixed crude oil fouling to illustrate the additional fouling resistance on the heat transfer surfaces. However, the dynamic process of fouling leads to gradual degradation of the performance of the thermal heat exchangers (Kazi 2012). The fouling rate of crude oil depends majorly on the development expressions initiated to capture the speed of change in the thermal resistance in a specified period. The commonly model used to measure the rate of crude oil fouling in processing refineries is the semi-empirical model, also known as the threshold model, according to Costa et al. (2013). The threshold model mostly identifies the fouling rate as the difference between the deposition and suppression processes. The model also shows the pragmatic approach to explain the primary variables that affect crude oil fouling providing a valuable tool to study the influenced effects of fouling on the refinery operation. However, the threshold model does not put in the consideration the kinetics and mass transfer that limits the fouling process, making it still unresolved problem (Costa et al. 2013).

The resistance to heat transfer produced, by crude oil fouling deposits depends on both the crude oil fouling rate and the thermal conductivity of the sediments. The deposited layer in the crude oil fouling acts as the entity showing the difference between the thermal hydraulic performance and the fouled cleaner exchanger (Bin Rostani 2013). Therefore, it differentiates the modeling-fouling rate and the modeling of the deposits. The crude oil fouling causes significant hydraulic effects to the tubes and heat exchangers as it reduces the tubes cross-sectional a real resulting to a restricted flow of deposits, decreased pressure leading to full blocking of the tubes (Pental 2012). The slow flow of the deposits causes an increase in the shear forces driving to a reduced deposition rate. According to Diaz-Bejarano (2016), coupling the thermal fouling model and the average thickness of the deposit layers via thermal conductivity reduces the hydraulic effect of crude oil fouling deposits on tubes and heat exchangers. However, the coupling only works if the thickness of the layer is less than the inner diameter of the PHT tubes with specific thermal conductivity, neither constant nor uniform across the PHT tubes (Diaz-Bejarano 2016).

Furthermore, the substantial progress of the crude oil fouling deposits in the tubes and heat exchangers relies also on ageing. Ageing of crude oil fouling deposits involves the degradation of fresh organic deposits into coke at extremely high temperatures (Yang et al. 2014). The ageing in the microstructure of the fouling deposits affects the thermal conductivity that increases modifying the heat transfer and hardening the deposits making them difficult to remove. According to Goode et al. (2013), the fouling rate reduction causes fouling resistance because of organic layer cooking in the crude oil furnaces. However, Ishiyama et al. (2013) state that ageing is because of the evolution of the fresh deposits from the low conductivity to the coke conductivity that acts as a temperature function. The kinetic ageing model conforming to (Yang et al. 2014) can refine ageing in the crude oil fouling deposits. The dynamic ageing model distributed axially and radially overcomes the challenges faced in the multi-layer process. The ageing captures the change in the layer conductivity, reducing the potential impact of extended operation and couples the deposits for correct operational use. However, due to insufficient measurements, the ageing kinetic model cannot possibly validate the rate of crude oil fouling in tubes and heat exchangers (Yang et al. 2014).

Despite the mitigation processes, the crude oil fouling always builds up, the tubes, and the heat exchangers require periodic cleaning to restore their entire and efficient performance. The cleanup involves washing machines with high-pressure water jets that can circulate the water and chemicals through the tubes and the heat exchangers (Baweja and Bartaria 2013). The mechanical cleaning process requires switching off the heat exchangers for about a week, resulting in completing the removal of the fouling deposits. Additionally, chemical methods used to clean the fouling deposits in the tubes and heat exchangers results in a similar effect on operations (Goode et al. 2013). However, the chemical process requires no specific procedure; it can be either done with the heat exchangers on or without dismantling the heat exchangers and takes much less time compared to the mechanical cleaning (Diaz-Bejarano 2016). Both cleaning processes depend on the efficacy of the choice of chemicals in line with the deposit composition and the level of the stickiness of the deposits in the tube surfaces (Baweja and Bartaria 2013).

The decision to clean and remove the crude oil fouling deposits in the tube and heat exchangers mainly depends on the economic tradeoff between the energy losses, the cost, and the loss of production. Generally, cleaning restores the pipes and heat exchangers to their original form with fixed cleaning times (Goode et al. 2013). However, the effectiveness of the cleaning process depends on the method and the fouling layer properties. According to Baweja and Bartaria (2013), the total cleaning using the mechanical method restore the equipment performance while partial purification using the chemical process removes only the gel layer. The partial cleaning process involves a fixed time and the cooking state of the crude oil fouling deposits in tube and heat exchangers. Due to the simplicity of the chemical cleaning process, it is mostly and commonly used to optimize the cleaning schedules in the refinery industries (Diaz-Bejarano 2016).

4.5.1 How fouling in crude oil can be stopped

Fouling in heat exchangers and resulting cleaning methods are common in many companies. The cause of fouling in heat exchangers and availability of several deposits in the water cycle is the high amount of dissolved minerals, high temperatures and dirt problem. Fouling alters the heating and cooling activity of the heat exchangers making deposits thick and hard leading to less transfer of heat. Several mechanisms have been implemented to solve this issue of fouling in heat exchangers. Studies have identified strong and effective mechanisms to solve fouling. Wilson et al. (2005) study identified the following mitigation mechanisms:

1. Increased tube velocity.
2. Shifting crude oil from the sides of the tube to sides of the shell, these benefits from the variation between the outer and inner surface area of the heat exchanger's tube. Lower heat concentration on the outer surface mitigates the surface temperatures significantly.
3. Applying inserts such as Turbotal and HiTran which provide an improved transfer of heat and the flexibility of fouling but with high pressure drop for the same flow rate.
4. Using alternative types of tubes and baffles.
5. Accept fouling but ensure regular cleaning of heat exchangers.
6. Use of chemical additives.

4.5.1.1 Chemical cleaning

It involves mass transfer of chemicals to the fouling layer and a mixture of the substances back to the liquid phase, and hence enabling the removal of fouling layer from the solution (Liu et al, 2001). Fouling can be reduced by addition of several substances such as detergents, antioxidants, metal deactivators, size limiters and coke suppressants to the solution (Wilson, 2005). Antioxidants suspend the formation of the fouling layer by converting harmful oxides of hydrogen to stable compounds or collecting peroxyacid radicals. Metal deactivators decrease the incorporation property of metallic ions while dispersants and detergents reduce the formation of permanent fouling deposits. Considering the threshold model, for heat exchanger working at a velocity and temperature higher than the fouling threshold, a lot of deposits are expected to be formed in the heat exchanger. Deposition in the heat exchanger that is operating at conditions above threshold, the fouling can be reduced by adjusting the fouling state towards threshold. The extremity of the fouling will reduce as the working conditions of the heat exchanger are adjusted towards the threshold. If the conditions fall below the threshold, negligible amount of deposits are formed. Increase in velocity and decrease of surface temperature in the heat exchangers shifts the working conditions to a favourable region. Rodriguez and Smith (2007) study suggested an appeal that combines the optimization of the working state and management of cleaning operations in a comprehensive reduction strategy. This approach results to low costs of operation, high savings of energy and few interruptions in the operational process. Studies revealed that that the velocity of 2m/s and the surface temperature below 300°C are significant solutions to design heat exchangers that are resistant to fouling through a low-foul design method (Nesta & Bennett, 2005). This method will reduce the operational costs and significantly increase the run time between the cleanings.

4.5.1.2 Zero fouling design

D.G.Klaren et al. (2007) study shows the benefits of zero fouling design that requires only a third of the heat transfer surface of the crude heat exchanger hence longer operational intervals can be attained between the cleanings. This mechanism operates on the concept that ‘let the deposition occur’ but the fouling deposits are removed as they are formed. The mechanism of zero deposition shell and tube heat exchangers in extremely handling fouling process is practical by applying self-cleaning technology which uses the movement of cleaning particles and a technical design of the shell side.

4.5.1.3 Action of paint coatings

Paint coatings have matrixes that contain a soluble compound which diffuses the fouling deposit slowly. Application of paint coatings which contain heavy metals (such as zinc, copper, mercury and arsenic) on metallic structures will result to formation of a protective coat therefore an anti-fouling paint should be applied to prevent formation of galvanic deposits. Cuprous is considered as the suitable antifouling paint which is a combination of several compounds (Saleh and Sheikholeslami, 2005).

4.5.2 Dispersion mechanism

This mechanism is explained in three steps as shown below;

4.5.2.1 Wetting of the suspended solid

The wetting process relies on the characteristics of surface particles, stabilizer and the dispersion medium. Non-ionic polymers are considered as surfactants which wets the suspended particles on heat exchange surface. These dispersants inhibit the formation fouling deposits by making the surfaces wet.

4.5.2.2 De-agglomeration of the large particles

Before any particle is subjected to the wetting liquid aggregates it has to be completely broken down. This process requires significant amount mechanical energy so as to be effective. Different features of particles such as the type of the particle, bonds within the cluster particles and wetting characteristics effects this mechanism therefore mitigating fouling on the surface heat exchanger tubes (Goldel et al., 2010).

4.5.2.3 Stabilization of the primary particles

Studies show that fouling materials in cooling waters are slightly negative charged. Adding anionic dispersant polymers to the solution is efficient because they result to an increase in surface charges and hence prevent clumping and formation of deposits by keeping particles apart, dispersed and stabilised (Elias et al., 2008).

5 Chapter 5; Discussion

In terms of the factors that influence fouling, there have been key findings in the current research, as well as from previous studies. Bulk temperature, bulk velocity, crude blending, surface temperature and crude type are the factors that influence the rate of fouling process according to (Yeap, Wilson, Polley, and Pugh, 2004).

Bulk velocity; increase in velocity results to an increase or decrease in the rate of fouling. Watkinson (2005) argued that for a controlled fouling reaction, the rate of fouling decreases with increase in bulk velocity under a given bulk temperature and heat flux. Considering this, heat transfer coefficient increases with velocity hence reducing the surface and film temperatures. This is consistent with has been established in the current study. However, if the mass transfer is controlled by fouling species from the bulk fluid, the velocity increases with increase in mass transfer coefficient from the bulk fluid to the surface hence resulting to an increase in the fouling rate. Crittenden et al. (2009) observed a model of oil gas fouling and found that the initial fouling is inversely proportional to mass flow rate.

Bulk temperature: Rafeen et al. (2010) study show that decrease in bulk temperature results to increase in fouling rate. At a constant velocity and temperature, reduction in bulk temperature leads to an increase in thermal driving force which eventually increases the fouling rate. In contrary some studies such as (Watkinson, 2005) show that increase in bulk temperature results to an increase in fouling rate, which is also consistent to the findings of this research. Asphaltenes are large, insoluble and complex ring molecules in crude oil. The insoluble property of asphaltenes is regarded as the main cause of fouling in crude oil systems (Saleh, 2005).

Crude type: crude oil is a combination many hydrocarbons such as naphthenes, aromatic, paraffin and asphaltenes. They are categorized as light, medium and heavy basing on their measured API gravity. Heavy hydrocarbons contain a lot of asphaltenes hence they are more likely to foul than light ones.

Crude blending: Blending results to unstable reaction which precipitates crude oil species such asphaltenes which triggers rapid fouling (Wilson and Polley, 2001). Incompatibility of crude oil and asphaltenes precipitation during blending of crude oil causes serious fouling and cooking in crude pre-heat in train.

The timing of cleaning was one of the fundamental aspects of investigation in this research. The timing of a cleaning plays a significant task in the development of hydraulic and thermal achievement attained. When the cleaning is done earlier the advancement in the heat duty becomes substantial (Mostafa, 2007). A study on the cleaning of heat exchanger shows that cleaning after three months recovers about 45% of the clean heat duty while a similar task performed after nine months recovers about 17% of the initial heat duty. The drop in heat value is due to fouling build up on the surfaces of the heat exchanger. Considering the performance of the hydraulic, enhancement in the pressure drop is more detectable when cleaning process is carried out later. Comparing the performance of the hydraulic and heat duty an increase in heat flux has a positive impact on the production efficiency while increase in the fouling rate affects production efficiency negatively (Lavaja & Bagajewicz, 2004). Earlier cleaning results to removal of considerable amount deposits but a faster return of thickness and thermal achievement obtained before carrying out the cleaning (Macchietto et al., 2015). It is also evident that greater heat duty is saved when cleaning is done early than when it is done later. Assertive cleaning results to significant advancement in hydraulic and thermal achievement (Macchietto, 2015). The effectiveness of cleaning is achieved by proper time timing. Later cleaning leaves a high percentage of deposits in the tube but it attains a high reduction in pressure.

The findings of this study also implied that there is need to do the cleaning as early as possible, since this increased the effectiveness. From most of the outputs on different heat exchangers, this study established that cleaning should be done before the 50th day. These results were consistent both in the shell and tube sides.

From previous studies (secondary research), this study also investigated the fouling mechanisms. Understanding of fouling mechanism and factors affecting fouling is important in the development of suitable fouling models. Fouling mechanism are categorized into corrosion fouling, chemical reaction fouling, particulate fouling, biological fouling and crystallization fouling. According to Yi Cho et al., 2006 corrosion, deposition of particulates crystallization of inorganics, chemical reaction of organics or combination of all these play a vital role. Polley (2004) argued that fouling mechanism occur in a sequence as demonstrated below.

> *Initiation and delay period*; this is the time of cleaning the surface before dirty accumulates. Small amount of deposits accumulation can enhance heat transfer respective to cleaning the surface and might result to a negative fouling rate and a negative total

fouling amount. This initiation period lasts for seconds or days and the duration of this phase is as a result of surface temperature, surface condition and the type of fouling.

Transport and migration to fouling sites

Diffusion, impaction and inertia are transport mechanisms that prevail in the turbulent flow as the size of the particle increases (Kazi, 2001).

Diffusion

During diffusion smaller molecules move with the fluid and they are taken to the surface by Brownian motion of the fluid molecules.   Din et al. (1999) argued that smaller particles can be treated as larger particles so that the transport factor equals to the convectional mass transfer factor which is attained through relevant theoretical equations. Small particles have a higher tendency of depositing and it is evident that it is difficult to filter small particles therefore they are likely to foul a surface.

Inertia

Particles in inertia regime are always large in that they gain a transverse velocity from turbulent eddies which is not completely debauched in the viscous sub-layer and these molecules therefore possesses enough energy to get to the walls. Some particles move slowly towards the surface by migrating down the agitation potency slope.

Impaction

In impaction regime the velocity particles to the surface reaches the friction velocity and the stopping distance of particles equals the diameter of the pipe. The response of large particles towards turbulent eddies become limited and this makes transport coefficient to stop increasing.

According Wilson (2004) when particles get larger their response to turbulent fluctuations become more sluggish and the transport coefficient begins to drop.

Deposition

Attachment of particles on the walls of heat exchanger is a result of size and concentration of particles' bulk fluid density and bulk fluid velocity (Pugh et al., 2017). Deposition can also be as a result of interfacial characteristics of the fouling substance and the wettability and roughness of the surface where fouling is most likely to take place. However, Smooth and wetly surfaces slow the process of fouling. At the time fouling precursors approach the heat transfer walls, they can stick to the walls' surface, leave the surface or they can combine to form substances that coats the surface. Chemical reaction, diffusion and adhesion can applied to control deposition.

Removal; When a deposit layer starts building on the walls of the heat exchanger, some part of it might be removed through fluid shear and mass transfer action. The strength of the deposit layer determines the amount of deposit that has to be detached. Mass transfer can also be used to remove the deposit by removing the fouling precursors from the surface of the heat exchanger. *Aging*; the nature of the fouling material, temperature, composition of the fluid material and flow rate influences the rate at which deposits grow and accumulate on the surface of the heat exchanger. Aging increases the strength of deposit surfaces hence resulting to hardening of the deposits. This is achieved through re-crystallization of surfaces, polymerization and dehydration. These findings from secondary research also play an important role in creating perspective on what has been obtained from the analysis.

5.1 Fouling prevention and mitigation techniques

Fouling in heat exchangers can be reduced or prevented by putting certain measures into action. To begin with, the use of smooth heat exchanger surfaces can decrease the scale of adhesion to the surfaces. Steel coated with Teflon resists oxidization and reduces the fouling rate in the exchangers (Carvalho et al. 2018). Additionally, depressing the film temperature and increasing the velocity of the fluid can reduce the rate of foul formation. The water quality passing through the heat exchanger has an impact on the foul formation in the surfaces (Hou et al. 2017).

In this case, industries must control the PH and hardness of the fluid. PH should be maintained at 6 or 7 to reduce fouling and corrosion too (Fouling-in-heat-exchangers.wikispaces.com, 2018). Chemicals can also be used to reduce or prevent fouling in the heat exchangers. Phosphates and acids upsurge the solubility of the foul buildup. After that, modification of crystal can be performed through the use of chemical additives. These have the role of removing the foul deposits easily.

There are mechanical cleaning methods such as the hydro-blasting method that directs water under high pressure through tubes to remove foul buildup. Alternatively, drills or brushes can be used to clean the tubed plugged with particles. For effective removal of deposits, pressure of 36 bar of water has to be maintained (Hou et al. 2017). This is because water pressure is safer and more effective than air pressure. This is because gases result in rapid expansion and compression. However, the use of mechanical methods has its limitations such as shutting down the heat exchanger, increasing the cost of labor, corrosion, and time (Wang et al. 2017).

Prevention and mitigation of fouling in heat exchangers are imperative as they save on costs of labor, maintenance, and risks of shut down of the industries. For this reason, all industries that produce crude oil must put these measures into actions for efficiency.

6 Chapter 6: Conclusion and recommendations

Fouling is a process that is defined as accumulation of deposits in the form of unwanted materials that could result into reduced efficiency (Thulukkanam, 2013). Fouling occurs in heat exchangers and boilers, with the deposits appearing on either the internal surface or external surfaces. Heat exchangers are a form of equipment where there is continuous or semi-continuous transfer of heat from a hot to a cold fluid through a surface that could be separating the two fluids. The heaters exchangers according to Harche, Absi and Mouheb (2014) are made up of tubes, pipes, or coils.

Fouling is a process that has negative outcomes for most companies today, as it forms part of a major cost to remove, maintain, and make plants that resist fouling. In heavily industrialised countries, fouling has been estimated to cost at least US $4.4 billion annually (Coletti and Hewitt, 2014). In a certain study, the losses as a result of fouling in industrialised countries could cost anywhere between 0.3% and 30% of the total country GDP according to Coletti and Macchietto (2015). KumarMohanty and Singru (2014) further mentions that the cost of maintenance in a plant with boilers and heat exchangers could be up to 15%, with more than half being caused by fouling alone.

Colleti and Hewitt (2015) also mentions the various sources of costs as a result of fouling might include areas like direct cost of removal of fouling, delays from unplanned shutdowns due to excess accumulation of fouling, lagging production due to the unplanned or planned shutdowns, replacement of materials corroded or damaged from fouling, purchasing of chemical or mechanical anti fouling equipment, and so much more. Diaz-Bejarano, Coletti, and Macchietto (2018) estimate that the costs of cleaning in one fouling range between US $40 thousand and US $50 thousand for every heat exchanger cleaned.

The rate of fouling according to Colleti and Hewitt (2015) is the deposits on the surface loading per unit surface area of unit time on average. The description of the fouling amount often utilises deposit thickness given in µm, and the porosity given in %. Groysman (2017) adds that based on the conditions, mechanisms, and materials used, the fouling rate might be seen as linear, falling, asymptotic, saw toothed, or accelerating. The shape of the graph resulting from the tube type heat exchanger fouling rate was characterised as saw-toothed.

This study found out that fouling rate has a positive correlation with total cost, and it increases exponentially in an accelerating manner. To attempt to explain such a phenomenon, one reasoning could be the type of material used in the making of the crude oil heat exchangers in this case. Harche, Absi and Mouheb (2014) mentions that different types of heat exchangers have a general variation in the way they respond to the heat exchange rate. For example, shell and tube are considered to have a very poor risk as well as poor response, hence are more easily susceptible to fouling. Compared to graphite materials, lamella, or double pipe, they have a better response to fouling. A new developed of the scraped surface heat exchange type has the best responds to fouling, meaning that it has the lowest fouling rate. Therefore, with a higher rate of fouling, the shell and tube type heat exchangers would have a positive and higher correlation to cost. These results were similar to studies conducted by Colleti and Hewitt (2015) and Thulukkanam, 2013).

This study found that the temperature of the furnaces have negative correlation with furnace duty for the tube heat exchanger. Groysman (2017) found that for all the crudes tested, the fouling rate strongly increased with increase in surface temperature.

Fouling can be prevented to some degree and controlled as well. However, the process is highly complex and very costly, but can be done. The difficulty stems from the different types of heat exchangers, varying designs in construction, different operational and maintenance systems, and so much more. The future performance and prediction of what will happen to the fouling process is also very difficult to determine when working with heat exchangers. One of the ways to mitigate against this is to utilise multiple regression analysis, which is a critical method for being able to predict the future. This method is utilised to oversee what point the fouling will require cleaning, as it uses the current reading to extrapolate the possible outcomes of fouling, and thus allow planning and budgeting for the costs to avoid unnecessary shutdowns.

6.1 Recommendations

One of the key recommendations based on the findings of this study is that various design and operational variables should always be considered, and a good example of how this can be done is by designing the heat exchange equipment such that the surface temperature is kept at a minimum, while on the other hand, the fluid velocities should be maintained at a high level. This should happen on the shell side.

The current study also applied various numerical methods by utilizing data to make important predictions, and according to Coletti and Hewitt (2014, there is need to utilize reliable data, especially for crude fouling threshold behavior. This is because the analysis of such data would provide important information that would be used to either design plain-tubed exchangers that have little or no fouling, or to provide key information that would help in the identification of cases where mitigation devices are essential.

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