# HEAT TRANSFER TO TWO PHASE FLOW AND FOULING MITIGATION BY SYNTHETIC FIBRE ADDITIVES

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# FACULTY OF ENGINEERING UNIVERSITY OF MALAYA KUALA LUMPUR

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# HEAT TRANSFER TO TWO PHASE FLOW AND FOULING MITIGATION BY SYNTHETIC FIBRE ADDITIVES

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## DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE IN MASTER OF MECHANICAL ENGINEERING

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# HEAT TRANSFER TO TWO PHASE FLOW AND FOULING MITIGATION BY SYNTHETIC FIBRE ADDITIVES ABSTRACT

One of the most notable logical premiums is the investigation of the conduct of fibre suspension streams, since adding a little amount of fibre to the water modifies the stream's behavior. Textile industries are one of the most important businesses that use fibre suspensions, which has led to a rise in the use of synthetic fibres as an alternative source. As a result, investigating the heat transfer and fouling resistance patterns of synthetic fibre suspension in annular flow appears to be critical. A total of six concentrations with six different velocities ranging from 0.0025 wt. percent up to 0.1 wt. percent and from 0.1 m/s to 0.35 m/s were used in this study for a specific synthetic fibre, the Nylon 6,6 fibre, in which a total of six concentrations with six different velocities ranging from 0.0025 wt. percent up to 0.1 wt. percent and from 0.1 m/s to 0. The varied concentrations and velocities were then evaluated under three distinct constant heat flux boundary conditions, with specimen surface temperatures of 50°C, 60°C, and 70°C, respectively. Heat transfer was found to be enhanced. For carbonate fouling in de-ionized water (DI Water), an experimental study was conducted using a combination of sodium bicarbonate and calcium chloride. Using a constructed monitoring system, the impacts of various factors on the calcium carbonate scale development process were explored experimentally. The rates of calcium carbonate deposition in suspension with and without Nylon 6,6 additions (only DI Water) were compared. Analytical microscopy was used to evaluate the shape of the deposit layer on the surface.

# [PEMINDAHAN HABA KEPADA ALIRAN DUA FASA DAN MITIGASI FASA OLEH TAMBAHAN FIBRE SINTETIK] ABSTRAK

Salah satu premium logik yang paling ketara ialah penyiasatan kelakuan aliran ampaian gentian, kerana menambahkan sedikit jumlah gentian ke dalam air mengubah suai gelagat aliran. Industri tekstil adalah salah satu perniagaan terpenting yang menggunakan penggantungan gentian, yang telah menyebabkan peningkatan dalam penggunaan gentian sintetik sebagai sumber alternatif. Akibatnya, menyiasat pemindahan haba dan corak rintangan mengotori suspensi gentian sintetik dalam aliran anulus nampaknya kritikal. Sebanyak enam kepekatan dengan enam halaju berbeza antara 0.0025 wt. peratus sehingga 0.1 wt. peratus dan daripada 0.1 m/s hingga 0.35 m/s telah digunakan dalam kajian ini untuk gentian sintetik tertentu, gentian Nylon 6.6, di mana sejumlah enam kepekatan dengan enam halaju berbeza antara 0.0025 wt. peratus sehingga 0.1 wt. peratus dan dari 0.1 m/s hingga 0. Kepekatan dan halaju yang berbeza-beza kemudiannya dinilai di bawah tiga keadaan sempadan fluks haba malar yang berbeza, dengan suhu permukaan spesimen masing-masing 50°C, 60°C dan 70°C. Pemindahan haba didapati dipertingkatkan. Bagi kekotoran karbonat dalam air nyah-ion (Air DI), satu kajian eksperimen telah dijalankan menggunakan gabungan natrium bikarbonat dan kalsium klorida. Menggunakan sistem pemantauan yang dibina, kesan pelbagai faktor terhadap proses pembangunan skala kalsium karbonat telah diterokai secara eksperimen. Kadar pemendapan kalsium karbonat dalam ampaian dengan dan tanpa penambahan Nylon 6,6 (hanya Air DI) telah dibandingkan. Mikroskopi analisis digunakan untuk menilai bentuk lapisan deposit di permukaan.

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## LIST OF SYMBOLS AND ABBREVIATIONS

A	:	Area, m2
С	:	Concentration, wt.%
Ср	:	Specific heat, J/kg.K
Di	:	Inner diameter of the pipe, m
Do	:	Outer diameter of the pipe, m
Н	:	Head loss, m
hc	:	Heat transfer coefficient
k	:	Thermal conductivity,
		K.W/m2.K
l	:	Length of the pipe, m
m	:	Mass flow rate, kg/s
Nu	:	Nusselt number
Pr	:	Prandt number
Q	:	Heat flux, W/m2
Re	:	Reynolds number
Т	:	Temperature, oC
u	:	Velocity, m/s
Greek		
$\Delta P$		Pressure drop
3		Roughness of the pipe
μ	:	Viscosity, kg/m2.s
ρ	:	Density, kg/m3

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#### **CHAPTER 1: INTRODUCTION**

#### 1.1 Background Study

Heat exchangers are without a doubt one of the most significant and commonly utilized pieces of process equipment in industrial settings. Regardless of the industry, temperature management will almost certainly be required, and heat exchangers will most likely be used to do this. Exchangers can be used for either heating or cooling, although they are predominantly employed for cooling Industrial heat in the industrial sector, notably in plants and refineries. exchangers, as their name indicates, are pieces of industrial equipment that are used to exchange or transfer heat from one medium to another. The primary objective of the heat exchange is to heat or cool the elements. Cooling is the most common function in the industrial sector, since it prevents equipment or volatile chemicals from overheating. Heat exchangers come in a variety of shapes and sizes, each with its own set of benefits and drawbacks that are customized to certain applications and industries. Heat exchangers are used in a wide variety of industries. They're found in air conditioning and cooling systems, as well as heating systems. Many industrial processes need a certain amount of heat to work; nevertheless, extreme caution must usually be exercised to prevent these processes from becoming excessively hot. Heat exchangers are used in industrial facilities and factories to maintain equipment, chemicals, water, gas, and other substances at a safe working temperature. Heat exchangers can also be used to absorb and transmit steam or heat exhaust that is produced as a by-product of a process or activity, allowing the steam or heat to be utilized more efficiently and saving the company money. Heat exchangers function in a variety of ways, with a variety of flow arrangements, equipment, and design characteristics. All heat exchangers have one thing in common: they all operate

to expose a warmer medium to a colder media, therefore exchanging heat, whether directly or indirectly. A collection of tubes contained within some form of casing is commonly employed to accomplish this. Other components and equipment, such as heat exchanger fans, condensers, belts, coolants, extra tubes and lines, and other components and equipment, all serve to enhance heating and cooling efficiency or flow.

We must solve the Reynold's Number (Re) as well as the Nusselt (Nu) Number in order to determine the traditional heat transfer coefficient. Both numbers, like a common approach of reducing fluid mechanics equations, are dimensionless.

#### Re = velocity / surface length / kinematic viscosity

Data on the fluid's speed, direction, length or "wetted distance" if dealing with internal flows, and kinematic viscosity (the density of the viscosity of the fluid divided by the density of the fluid) are all necessary. Because the Reynolds number is used to identify whether a flow is laminar or turbulent, we must first understand the flow properties.

If the flow is laminar, the Nusselt Number must be calculated: Nu=hL/k, where h is the convection coefficient. As a result, you can solve for h... h=Nu\*k/L. Here, L is the characteristic length (the same length used in the Re number calculation), Nu is the dimensionless Nusselt number (which has yet to be calculated), and k is the fluid's conductivity, which should not be confused with the conductive coefficient of the solid surface from which heat is convected.

Nu=0.336\*Re.8\*Pr.333 is the Nusselt number for a laminar flow.

#### **1.2 Problem Statement**

Currently industries with heat exchangers are facing issues on the efficiency of heat exchange process that leads to machinery overheating, damage and product quality failure. There are several factors that caused the heat exchanger to be less efficient. Firstly, water hammering is happened due to shock waves caused by the sudden acceleration or deceleration by the liquid in heat exchangers. Next is vibration which happened when the heat exchanger is placed near to a compressor or mechanical chillers might cause the tube failures (crack or break). The flow rate of liquid also plays an important role in keeping the heat exchange process to happen efficiently. Factor of temperature is also to be considered to maintain for the liquids so that it doesn't consume much energy for the heat exchange process to happen. Concentration of liquid to be taken in count as well which affects the time of heat transfer coefficient.

For fouling issue in heat exchanger, the present situation chemical additives are used for fouling mitigation where some of the chemicals are hazardous to the people and environment. So it has become essential to provide some ecofriendly method to retard fouling. Addition of synthetic fibres for fouling mitigation is less prone to environmental threat than the hazardous chemicals usage. Present approach of fouling mitigation by synthetic fibre will be a desired friendly approach of fouling mitigation.

#### 1.3 Objectives

Present study will focus on the following objectives:

- i. To investigate heat transfer of synthetic fibre suspension in annular flow passage heat exchanger.
- ii. To investigate on the rate of mineral fouling on heat exchanger surfaces.

iii. To analyse mitigation of fouling by synthetic fibre additives and characterization

#### 1.4 Scope of Study

Low concentration of fibres in suspension could enhance heat transfer, so in this investigation little amount of polymeric fibre in suspension will be used for augmentation of heat transfer. Heat transfer to two phase flow of water synthetic fibre suspension will also be investigated for the planned use of fibres in cooling liquids for fouling mitigation. Deposition of undesired suspended and dissolved materials on heat exchanger surfaces are recognized as fouling. It retards the heat exchanger performance and incur losses due to unscheduled plant shutdown and maintenance costs. Present research will focus on mitigation of fouling on heat exchangers surfaces from dissolved salts in cooling water. Apart from conventional method, an innovative approach of synthesized polymeric fibres will be used for mitigation of fouling.

Positive results from this research will be helpful for synthesis of cooling liquids, which will curb fouling deposition, prolong continuous operation of heat exchangers, save production and maintenance costs of a plant.

#### 1.4.1 Operating Parameters

A double pipe heat exchanger is used to test the annular flow regime. The following are the heat exchanger's operational parameters:

Conditions	Parameters
Nylon Concentration	0.0025 - 0.1 wt%
Hot Fluid; Heat Flux	Constant at 60°C of hot distilled water supplied in the annular pipe
Velocity in Cold Stream	0.1-0.35 m/s
Cold Fluid	30°C

#### **Table 1-1 Heat Exchanger's Operational Parameters**

#### 1.5 Thesis Organization

- The first chapter covers the history of textile research as well as issues that arise during the production process. This chapter contains the research's objectives, scope of investigation, and operational conditions.
- ii. Chapter 2 is a narrative overview of previous research on several forms of heat exchangers, such as circular and annular, as well as different types of fibres and their qualities, as well as the impact of fibres on the paper and textile sectors. This section also discusses the patterns in heat transfer coefficients for fibre suspension as a function of Reynolds number. In addition, this section discusses other people's efforts to investigate the effect of extra fibres on the friction loss of fibre suspensions.
- iii. The test apparatus, materials, and experimental technique are all described in Chapter 3. The procedure for gathering data is described in full. The preparation of fibre suspensions in various concentrations, the preparation of distilled water, and the characterisation of fibres are all described. The experimental conditions and steps for conducting the experiment are discussed in further detail.

- iv. Chapter 4 compares the experimental results of distilled water to the conventional formulae by computing the Nusselt number, Reynolds number, and friction factor. At various temperatures and speeds, the heat transfer coefficient are calculated. This chapter delves into the heat transfers of fibre suspensions in circular flow.
- v. Chapter 5 brings the research to a close by providing a summary of the study's most important findings. In addition, this chapter recalls suggestions for future research for the current study.

#### **CHAPTER 2: LITERATURE REVIEW**

#### 2.1 Annular Phase Heat Exchanger

Heat exchangers are devices that are used to transfer heat from one fluid to another. It is one of the most essential devices for storing and transferring thermal energy. Heat exchangers, in general, are quite complicated due to their construction and the numerous types of materials that are widely accessible. To locate an appropriate heat exchanger for each process and demand, an extensive and thorough investigation is required. According to Ranjith and Shaji (2016), among all the heat exchangers available on the market, double pipe heat exchangers are the easiest and simplest to analyse and construct. This does not detract from a twin pipe heat exchanger's efficiency, since its dependability can be compared to its widespread use in the industry.

Shell and tube heat exchangers are extensively employed in many sectors, but each process need a thorough examination of the heat exchanger's compatibility. According to a comparative research, annular flow double pipe heat exchangers are more cost effective and provide greater benefits, particularly in the paper and textile sectors. To promote the movement of solid suspensions and avoid clogging, industrial double pipe heat exchangers are said to have a large inner tube diameter. For industries that utilise fibre suspensions, this is particularly relevant. Aside from the flexibility and the long body axis that minimises stagnation, double pipe heat exchangers are exceptionally easy to clean on an industrial scale (Peccini, Lemos, Costa, & Bagajewicz, 2019).

One of the most significant advantages of a twin pipe heat exchanger is that the outer diameter of the tubes is smaller, which is extremely beneficial for any operation that requires high pressure. According to S. N. Kazi, Duffy, and Chen (2014c), annular flow has gained a lot of attention recently, particularly in the process and textile sectors, because of its flexibility in conveying solid suspensions. The annular regime study encourages fluid transportation because it will make it easier to move chemical fluid through a twin pipe heat exchanger in the process sector (G. G. Duffy et al., 2011).

Concentric tube heat exchangers function by passing parallel fluid streams of different temperatures separated by a pipe. This design creates forced convection, which allows heat to be transferred to and from a product.

These heat exchangers feature a simple design and a sturdy construction that allows them to operate at high pressures. They're commonly utilised for material processing, food preparation, and air conditioning in a range of sectors.

The heat transfer coefficient in the test segment, h, was calculated using the following energy balance equation 1 and equation 2:

$$Q = m C_p (T_{a,out} - T_{a,in})$$
<sup>(1)</sup>

$$m = mass flow rate , Cp = specific het capacity$$

$$Q = h(A_s \Delta T_s + A_f \Delta T_f)$$
(2)  
Ts = Surface Temperature , As = Surface Area

#### 2.2 Synthetic Fibre (Polymeric Fibre)

Synthetic fibres might have a polymeric or mineral basis. Fibreglass and carbon are examples of mineral fibres, which will be discussed later. Polyester and polyamide are synthetic polymer fibres used in orthoses (Nylon and Aramid). Fabrics are commonly used in prosthetic socks, tubular stockinette, straps, lining, harnesses for upper-limb prostheses, and fastening and base material in less rigid orthotic supports such fabric stabilizing spinal corsets. Prosthetic socks and stockinet are the most common applications. Wool, cotton, or a combination of these natural fibres blended with nylon, acrylics, or other synthetic materials are widely used. Rubber can be added to fabrics to provide an elastic material that can be used for straps in upper limb prosthetic harness systems. Hook and loop (Velcro) straps, which are frequently used to keep an appliance in place in an easier fashion than buckles and laces, are a prominent usage of nylon. Nylon or polyester can be used to make webbing straps, which are sturdy flat strips of woven fabric. Felt, a nonwoven fabric manufactured from textile fibres like polyester or wool, has a fine surface and can be used as a filler material in lamination or for cushioning. Nylon textiles are increasingly used as coverings for neoprene items and as the outer layer of various prosthetic liners. Lanyard suspension system and body-powered prosthesis control both use nylon in the form of rope and cable, respectively. The final look of a covered modular prosthesis will be improved with cosmetic nylon stockinet.

#### 2.2.1 Structural Properties of Nylon 6,6

Nylon is a kind of synthetic fibre. Poly-condensation of hexa-methylene diamine with acidic acid produces nylon 6,6. In a reactor, an equal amount of hexa-methylene diamine and acidic acid are mixed with water. Nylon salt, an ammonium or carboxylate combination, is made by crystallizing this. The nylon salt is placed in a reaction vessel, where it is polymerized either in batches or constantly.

Oil transfer pipelines (the Trans-Alaska pipeline), oil well operations, firefighting, field irrigation, and the transport of slurries and suspensions are only a few of the key uses of drag reduction. When compared to a pure liquid at

the same flow circumstances, polymer addition (even at low percentages) results in a lower pressure drop in pipe flow. The key factors that determine the drag reduction generated by a polymer are the length of the polymer chain, radius of gyration, hydrodynamic volume, concentration, and molecular weight, with the latter being the most significant player.

The kind of drag reducing agent also has a role in determining the amount of drag reduction. In terms of molecular structure and mechanical strength, polymer drag reducers are divided into flexible and rod-like molecules. Polyacrylamide and polyethylene oxide are examples of flexible polymers with a high molar mass. High shear rates, such as those observed in slick water hydraulic fracturing, cause mechanical deterioration in these polymer chains, which is a serious limitation for practical applications. Rod-like polymers, which are more resistant to shear breakdown, make up the second group of drag reducers.

Moisture absorbance decreases when the spacing of the amide groups grows (by adding additional methyl groups) and the polarity of the amide groups decreases. Because the methyl unit portions of the chain are more flexible and mobile, their resistance to heat deformation is reduced. This link is readily seen in the case of Nylon-6,6 and Nylon-6,12. Nylon-6,12 has a lower modulus, elongation, and strength than Nylon-6,6, as well as a lower thermal distortion temperature, lower hardness, and lower melting point. Nylon-6,12, on the other hand, absorbs half as much water as Nylon-6,6. Thus, while the characteristics of Nylon-6,12 may not be as excellent as Nylon-6,6 under dry circumstances, they will be far more consistent when employed in situations where water may be present. The characteristics of nylon are significantly affected by water absorption.

Because of the higher hydrogen bonding demonstrated in Nylon-6, 6 as illustrated in figure 2-1, it has better strength than Nylon-6. Because of the increased hydrogen bonding between neighbouring chains, the melting temperature and crystallinity rise. However, this is not a typical result. The quantity of CH2 groups present in between the CONH groups determines whether the melting point rises or falls. When the amides in neighbouring chains have an opposing or antiparallel orientation, the odd number of CH2 groups between them permits full hydrogen bonding, but not when they have the same or parallel orientation (as shown in the figure 2-1)

$$\begin{array}{ccc} \begin{pmatrix} \mathbf{H} & \mathbf{H} & \mathbf{O} & \mathbf{O} \\ \mathbf{I} & \mathbf{I} & \mathbf{I} & \mathbf{I} \\ \mathbf{N} - (\mathbf{C}\mathbf{H}_2)_6 - \mathbf{N} - \mathbf{C} - (\mathbf{C}\mathbf{H}_2)_4 - \mathbf{C} & \mathbf{I} \\ \mathbf{N} \mathbf{J} \mathbf{I} & \mathbf{I} & \mathbf{I} \\ \mathbf{N} - (\mathbf{C}\mathbf{H}_2)_6 - \mathbf{N} - \mathbf{C} - (\mathbf{C}\mathbf{H}_2)_4 - \mathbf{C} & \mathbf{I} \\ \mathbf{N} \mathbf{J} \mathbf{I} & \mathbf{I} \\ \mathbf{N} \mathbf{J} \mathbf{I} \mathbf{I} & \mathbf{I} \\ \mathbf{N} \mathbf{I} \mathbf{I} & \mathbf{I} \\ \mathbf{N} \mathbf{I} \mathbf{I} & \mathbf{I} \\ \mathbf{N} \mathbf{I} \mathbf{I} \\ \mathbf{I} & \mathbf{I} \\ \mathbf{I} \\ \mathbf{I} & \mathbf{I} \\ \mathbf{I}$$

Figure 2-1 Molecular Structure of Nylon 6,6

In the odd-numbered scenario, switching from a parallel to an antiparallel array necessitates reversing the whole molecular chain. When there are an even number of -CH2 groups, as in the instance of Nylon-6, 6 with its intervening number of 4 and 6 -CH2 groups, just a segment lateral movement is required. The lower melting temperature and % crystallinity of Nylon-6 compared to Nylon-6, 6 is due to this odd-even characteristic. Nylon-odd and Nylon-odd even

have lower melting points than equivalent or identical Nylon-even-even for this reason.

#### 2.2.2 Rheology of Fibre Suspensions

Fibre suspensions are thought to have extremely complicated properties that vary depending on the flow rate. To meet the correct needs of particular unit activities, it is necessary to understand the fibre characteristics and rheology of fibre suspensions. Fibre suspension flow, according to Geoffrey G Duffy (2006), contains at least four separate particles which are fibres, floccettes, flocs, and network. These fibre particles have their own unique properties. For example, in a wood pulp suspension, all of these particles are present at the same time, making wood pulp suspensions extremely difficult to research and comprehend in terms of rheology.



Figure 2-2 The particle of fibres that exist in a fibre suspension (Duffy, 2006)

The optimization and design of processes involving fibre suspensions need a detailed and deep investigation. Many companies find it difficult to regulate the interconnections of fibre-fibre networks, therefore this poses a difficulty (Tozzi, Lavenson, McCarthy, & Powell, 2013). Settling of fibre particles, the creation of bubbles, the existence of depleted layers of fibres in the pipe surface, and the disruption of floccettes are only a few of the primary challenges that hinder the flow of fibre suspensions, particularly on an industrial scale. If the rheology and complicated research of fibre suspensions are not thoroughly examined, industrial equipment will have a weak structure, resulting in large equipment. Plants will utilize an excessive amount of energy as a result of this (Maria Rasteiro, Ventura, & Garcia, 2008).

Fibre suspensions can exist in three fundamental flow mechanisms depending on the velocity of the pipe flow. The turbulent flow of fibre suspensions must be researched at greater flow rates, whereas mixed flow and plug flow must be studied at lower flow rates (Berstrom, 2005).



Figure 2-3 Three different types of flows that exist for fibre suspension (Malayeri & Watkinson,2011)

Fibre suspensions, for example, can be seen passing through several units in the pulp and paper sector to be treated. As a result, different types of fluxes and shear stress will be applied to the suspension of fibres. In turbulent regime pipe flow, shear stress flow affects the entire pipe, but in plug flow, where lower flow rates are used, the fibre accumulations will move in unison. As a result, it's critical to investigate each flow's orientation influence. Fibre suspensions can be classified as a fluid system. When there are many phases in the suspension, fluid systems are classified as one phase or multiphase flow. Solids fluidized by gas, or solids suspended in water, are an example of a commonly used multiphase fluid system. Different velocity and concentration behavioral of fibres are important aspects to consider, especially for solid-fluid systems (Bellani, 2008).

The hydrodynamic behavior of fibres is influenced by the measurements of fibre suspensions. Fibre length, strength, tensile index, and fibre aspect ratio are some of the main features of fibre measures that must be investigated in order to relate to the flow of fibre suspensions.

A typical fluid characteristic does not apply even to a simple flow of fibre in water. Geoffrey G Duffy (2006), for example, said in a research of wood pulp fibre that it does not follow Newtonian laws and that wood fibre pulp does not use Non-Newtonian flow. As a result, comparison analysis for the study of fibre suspension is not conceivable, and only actual flow through laboratory investigations can achieve a near accurate model. This supports the argument that not only is fibre flow utilized to research fibre suspensions, but fibre characteristics in terms of strength, fibre length, and fibre aspect ratio is also important.

Early in 1995, the heat transmission mechanism against fibres was initially developed, with wood pulp fibres and synthetic fibres suspended in water being fully examined. As time goes on, research on fibre suspensions tends to provide more inputs to a variety of sectors, such as papermaking and textiles, and elements such as concentration and velocity against fibre suspension have been further researched. Heat transfer coefficient has a very near approximation to defining specific fibre qualities, according to earlier studies (Khan, Kazi, Syed, Nasar, & Kakar, 2018).

According to Geoffrey G Duffy (2006), some of the latest breakthroughs in fibre study research include the impacts of changes in physical characteristics of fibres, channel size adjustment, and the use of chemicals in fibre suspension for improvement.

#### 2.3 Heat Transfer

In the simplest terms, two key elements impact the order of heat transmission, temperature and the rate of heat transfer (Equation 3). Temperature refers to the degree to which warm vitality is accessible, whereas heat stream to a large part, refers to the growth of warm vitality. As a result of the temperature differential, heat will be transferred from hot to cold, or in other words, heat will be received and derived between two objects. There will be no heat transmission if there is no temperature differential. When analysing the release of energy by exhausting heat, the presence of pressure differences and shear stresses with temperature differenture differences is particularly essential (S. N. Kazi et al., 2014b). When a liquid flow through a circular or annular flow encounters resistance due to pipe roughness, this scenario is well-known and investigated.

$$\boldsymbol{Q} = \boldsymbol{m} \boldsymbol{C}_{\boldsymbol{p}} \Delta \boldsymbol{T}$$
<sup>(3)</sup>

#### 2.3.1 Heat Transfer Study Based on Concentration Effect

Numerous researchers have focused on the heat transmission coefficient of fibre suspension. G. G. Duffy et al. (2011) completed one of the most recent studies, which looked at the heat transmission and pressure drop characteristics of fibre suspension in annular flow. Three types of wood pulp fibres and five types of synthetic fibres were investigated in this study. The impact of various wood pulp fibre concentrations as a function of velocity on heat transfer can be divided into two different analyses. For velocity greater than 0.5 m/s, the heat transfer decreases as the fibre concentration increases due to the increased presence of fibres, which causes the transmission of turbulence eddies to be delayed. When the velocity is less than 0.5 m/s, on the other hand, the heat transfer coefficient rises as the concentration rises. At lower shear rates, there is a limited network and few fibre to fibre connections. The effect varied for this low velocity because of the limited network and few fibre to fibre to

The previous researchers evaluated three different concentrations of kenaf bast mechanical pulp from 0.2 wt. percent to 0.6 wt. percent at the same range of velocities. Despite this, the link between concentration and heat transfer coefficient contradicts prior research, which found that a low fibre concentration of 0.2 wt. percent had a greater heat transfer coefficient than the rest of the group, including water (Ahmed et al., 2017). A research on pinus radiata fibre suspensions came up with similar results (M. S. N. Kazi, Duffy, & Chen, 1999). To assess the influence of concentration on heat transfer, heat transfer coefficients for both acacia magium and kenaf bast fibre were tested at

concentrations of 0.2 wt. percent, 0.4 wt. percent, and 0.6 wt. percent with velocities ranging from 0.4 m/s to 2.8 m/s. When the velocity is more than 2 m/s, the influence of concentration is more obvious. When the concentration of the suspension increases, the heat transfer coefficient falls. Despite the fact that fibre has a poorer thermal conductivity than water, heat transfer is boosted at extremely low fibre concentrations due to increased energy conveyance via turbulent eddies in the presence of fibres (Khan et al., 2018).

#### 2.3.2 Study of Heat Transfer using Particle Characterization

The turbulence eddies of fibre suspension are also impacted by fibre characterization, thus the greatest concentration of 0.4 wt. percent is investigated further for both wood pulp fibre and synthetic fibres to better understand the influence of flexibility and length of fibre against water. The heat transfer coefficient for both wood pulp and synthetic fibres is above water at lower speeds below 0.5 m/s and below water at higher velocities between 0.8 m/s and 2.0 m/s. Lower denier polymeric fibres enhance heat transfer coefficient at low speeds, however this effect reverses once the speed exceeds 0.6 m/s. This is because at lower speeds, there is more opportunity for the fibres to collide and entrap each other, resulting in a more conduction-ruled suspension. The longitudinal fibre flexibility impacts the elastic modulus and increases the heat transfer interaction at lower denier.

Another research looked at the effect of flexibility, finding that when the length and denier of the fibre are the same, lesser flexibility results in a greater heat transfer coefficient. Non-wood fibres, such as kbm, kbcu, and kbcb, have increasing fibre wall thickness and breadth as their flexibility decreases, contributing to a higher heat transfer coefficient (Ahmed et al., 2017). Due to the unbending character of the dividers, it is inversely related to the heat transfer coefficient in the fibre lumen (Soszynski & Kerekes, 1988).

The relationship between fibre length and coarseness for wood pulp fibres is also shown to be straightforwardly matching to the heat transfer coefficient.

#### 2.4 Fouling Process

As illustrated in Figure 2-2, fouling is a dynamic process that is always characterised as the production and buildup of undesired materials deposit on the processing equipment surfaces. Each of the five generic kinds of fouling (crystallisation, particle, chemical reaction, corrosion, and biological) is divided into five phases (Epstein, 1983). Fouling initiation, transit to the surface, attachment to the surface, removal from the surface, and ageing at the surface are the five steps (J.W. Mullin, 2001). The overall fouling process is commonly seen to be the outcome of two concurrent sub processes: a deposition and a removal process as shown in equation 4:

$$\frac{dm_f}{dt} = m_d - m_r \qquad m_d = \text{mass of deposition}$$
(4)

 $m_r = \text{mass of removal}$ 



Figure 2-4 Fouling Layer Deposition and Removal Illustration on Heat Transfer Surface (Hou,2017)

#### 2.4.1 Fouling on Heat Exchanger Surface

In the water processing industry, scale deposits on heat exchangers result in a significant loss in heat transfer capacity (Morra, 2000). Furthermore, scale buildup causes changes in tube diameter, resulting in a major reduction in flow rate or an increase in pressure drop across heat transfer equipment. This is a serious problem, which is compounded by the deposit's rough surface. Fouling has been demonstrated to be a severe problem, costing the industry hundreds of millions of dollars in lost output each year (Gleick, 2003).

By adopting an appropriate and green environment mitigation method, the equipment life may be significantly extended. As a result, measures are urgently needed from both an economic and an environmental standpoint.

#### 2.4.2 Fouling Mitigation and Control

The challenges and costs associated with heat exchanger fouling in New Zealand businesses were highlighted in 1993 (Steinhagen, Müller-Steinhagen, & Maani, 1993). They identified the most efficient methods to take when designing heat exchangers for industrial use.

- i.) Selecting an appropriate heat exchanger type
- ii.) Improving industrial working conditions, such as greater flow rates
- iii.) Improve the design of heat exchangers

Several approaches for controlling fouling have been developed in recent years. Chemical, mechanical, and physical water treatment procedures are the three types of treatments available.

#### **CHAPTER 3: METHODOLOGY**

#### 3.1 Overview

The Gantt plan, list of chemicals, apparatus and equipment, and experimental procedures will all be divided into four phases. The operating settings will be detailed in the experimental process.

#### 3.2 Process Flow

Figure 3.1 shows the research process in depth, from theoretical research to experimentation and data analysis.





#### 3.3 Materials, Chemicals & Machines

#### 3.3.1 Materials & Chemicals

The Fouling and Corrosion lab used a filtering system to obtain distilled water as the major raw material. Mini Fibres Inc. provided the Ny 6,6. Scanning Electron Microscopy was used to characterize Nylon 6,6 fibres, allowing for a more in-depth examination of the fibre characteristics.
Materials / Chemicals	Description
Distilled water	The main raw materials used to study heat transfer on annular type heat exchanger test rig is shown in Figure 3.2. For the nylon fibre suspension preparation also required the distilled water.
Tap water	The tanks and pipes of heat exchanger test rig is cleaned by using the raw water from tap
Decon	To prevent contamination of other chemicals, Decon (Figure 3.3) is used to wash the test rig
Nylon Fibre 6,6	The concentration and temperature effect as in Figure 3.4 is studied by varying the concentration of nylon fibre.
Nylon Fibre Suspension	The diluted solid fibre samples were dissolved in distilled water and disintegrated to be used in the test rig as shown in Figure 3.5
	disintegrated to be used in the test shown in Figure 3.5

### Table 3-1 Characteristics of Materials & Chemicals



Figure 3-2 Distilled Water



Figure 3-3 Decon, Test Rig Cleaner



Figure 3-4 Synthetic Fibre, Nylon6,6



#### **Figure 3-5 Nylon Suspension**

#### 3.3.2 Machines

a) Weigh Balancing – To weigh the required amount of nylon to vary the concentration of suspension

b) Magnetic Gear Pump - To circulate the solution throughout the system, two gear pumps (Araki EX-100RM magnetic driven seal-less chemical pump were utilized in the solution flow cycle and hot flow cycle.

c) Inverter - In the hot flow loop and solution flow loop, Hoffman Muller inverters were applied to control the pump speed.

d) Electromagnetic flow meter- N-FLO-25 Throughout the experiment, an electromagnetic flow meter was utilized to detect fluid flow rate. A magnetic flow meter is a volumetric flow meter with no moving components that is suited for wastewater applications or any conductive or water-based filthy liquid. Magnetic flow meters are also well-suited to applications requiring low pressure drop and minimal maintenance.

#### 3.4 Heat Transfer

A twin pipe heat exchanger (customized design to avoid galvanic corrosion with 1300mm length) test rig was developed and placed at the University of Malaya's Fouling and Corrosion Lab for the experimental run. Figure 3-6 depicts the experimental setup.



Figure 3-6 Experimental Test Rig Consist of Double Pipe Heat Exchanger

This test rig has two separate water flows, both of which run in the opposite direction. As illustrated in Figure 3-7, the blue line represents the nylon suspension solution and the red line represents the hot water flow. The solution tank has a chiller to keep it cool, whilst the hot water tank has a heater rod that is thermostatically regulated by software.



Figure 3-7 Piping and Instrumentation Design of the Test Rig

#### 3.4.1 Method of Suspension Preparing

This experiment necessitates the suspension of many concentrations of nylon fibres. Solid fibre particles of nylon 6,6 (also known as polyamide) were acquired (MSDS in appendix). Each concentration of nylon suspension necessitates the determination of a precise amount of solid sample based on mass calculations. For 12 hours, a precise amount of solid nylon fibres is disseminated in 2L of distilled water. The solution is then disintegrated four times at 5000 rpm until the fibres are completely distributed (Gharehkhani et al., 2017). The combination is known as a nylon suspension once the fibres have decomposed in distilled water. The nylon suspension was put to an 18-litre solution tank and homogeneously distributed using an in-tank agitator. Nylon suspensions were made at concentrations of 0.0025, 0.0075, 0.0125, 0.025,0.05, and 0.1 wt%.

#### 3.4.2 Method of Distilled Water Preparing

The TYPE DP 4000 distillation device for manufacturing distilled water has been identified for preparing lesser volumes of distilled water. It took around 4 litres of water and an hour to prepare distilled water. Figure 3-8 depicts the arrangement. The test setup takes 30L of distilled water for a full run. The process of distilling water usually consumes two days.





#### 3.4.3 Procedure of Test Rig

By altering the concentration and velocity, heat transfer of nylon fibre suspensions were examined in an annular flow regime. To study the influence of nylon concentration, temperatures, flow rates, and differential pressure were recorded. Before beginning the experiment, the cold and hot tanks were filled with distilled water and ran at their utmost speeds to evaluate the system's leakage. The system's validity is next tested by heating and chilling the water. To clean the pipes and assure data repeatability, the experimental setup was cycled with distilled water and Decon. By diluting nylon solid fibre samples in 2L distilled water and disintegrating them with a pulp disintegrator, nylon suspensions ranging from 0.0025 wt.% to 0.1 wt. % were created. The solution tank was filled with 18 litres of distilled water, and the temperature was kept at 30 °C with the help of a chiller. The chiller set point was set at a very low temperature, and after the temperature of 30 °C was maintained, the chiller stopped working automatically, only to restart when the cold storage tank temperature increased. The 2L of nylon suspension was then added to the cold solution tank, and the in-tank agitator was turned on at 1000 rpm to ensure smooth mixing and avoid the fibres from coagulating and becoming caught in the pump. The heater was then switched on after filling the hot water tank with 7L distilled water. The Scada Interface kept the heater temperature constant.

Once the solution was stable in each tank, the cold solution flow velocity was modified to meet our goals, ranging from 0.1 to 0.35 m/s, while the hot solution flow was maintained at 1 m/s. Because the temperature sensor was extremely sensitive, the experimental run data for the hot flow was kept at 50°C, 60°C, and 70°C, respectively, while the cold flow was kept at 30°C. For computations, the average values were used.

Concentration (wt%)	Velocity (m/s)
0.0025	0.1, 0.15, 0.2, 0.25, 0.3, 0.35
0.0075	0.1, 0.15, 0.2, 0.25, 0.3, 0.35
0.0125	0.1, 0.15, 0.2, 0.25, 0.3, 0.35
0.05	0.1, 0.15, 0.2, 0.25, 0.3, 0.35
0.075	0.1, 0.15, 0.2, 0.25, 0.3, 0.35
0.1	0.1, 0.15, 0.2, 0.25, 0.3, 0.35

#### **Table 3-2 Data Summary of Variation**

Table 3-2 shows the variation made for the heat transfer coefficient test. Each concentration is tested for 6 times with different velocity as stated. The test is been carried out for three different temperature which is 50°C, 60°C, & 70°C. Therefore, 36 tests is been carried out for each temperature.

#### 3.5 Fouling Test

To explore the deposits rate in solution with additives, an experimental setup comprising a twin pipe heat exchanger fouling test rig was created. With controlled variables, a test will be run using the same rig as the heat transfer test to determine fouling resistances and total deposition generated on the heat transfer surface. The solution with additives will run the test for 72 hours to observe on the fouling formation. To begin, every equipment must be subjected to a leakage test to guarantee that no extraneous factors will interfere with the data acquired throughout the experiment. After that, the equipment is carefully cleaned and washed with distilled water. Using appropriate amounts of calcium chloride (CaCl2) and sodium bicarbonate (NaHCO3) powders, an artificial fouling bulk solution with a concentration of 0.3 grammes per litre calcium carbonate CaCO3 solution is created. After that, the powders were mixed separately in two beakers before eventually combining them together to produce the needed concentration. Equation 5 below shows how calcium chloride and sodium bicarbonate combine to generate calcium carbonate:

$$CaCl_2 + 2NaHCO_3 \rightarrow CaCO_3 + 2NaCl + H_2O + CO_2$$
(5)

Because the stirrer is set to the minimal RPM of 250, the flow of the artificial fouling bulk solution is anticipated to be very low. The stirrer's job is to constantly mix the solution in order to avoid any loss of concentration or sedimentation of the bulk solution, as well as to provide uniform temperature mixing between the hot and cold exchange surfaces. The hot water flow rate within the test specimen tube, on the other hand, is set at 2.7 litres/min. Throughout the experiment, the hot water flow temperature is set at 60°C, while the cold-water flow temperature is kept at 30°C.

Throughout the experiment, the fouling bulk solution concentration is kept constant at 0.3 gram/litre. Every 6 hours, the concentration of the bulk solution will be determined using the EDTA complex titration technique. Small batches of calcium carbonate solution will be added if the bulk solution's concentration falls below a certain level. The quantity of top-up needed is estimated empirically and applied to keep the bulk solution concentration constant. A data logger will be used to measure and record the temperatures of the thermocouples at the hot water intake, hot water outflow, and the bulk solution. Over the course of 72 hours, the temperature will be measured every 20 minutes.

After the experiment, the test specimen is allowed to dry for one day at room temperature. The deposits that have accumulated may be observed on the specimen's exterior surface.

In the presence of additives, progressive fouling buildup on the pipe surface was observed and evaluated. By studying the deposited scale on the test pipes, measurable data on the progressive build-up of scale deposits, deposition rate, as well as the composition and crystal shape of the deposits were analyzed after each experimental run. In the bigger concentric pipe heat exchanger in the center, fouling on solution with additives was tested. Consistent flow rate throughout the system provided a uniform flow condition at the pipe surface. The rate of calcium carbonate deposition was examined when additives were added to the solution.

#### 3.6 Equipment Setup

Figure 3-10 depicts a schematic representation of the experimental setup. The equipment is divided into two flow loops, each with two separate tanks holding artificial fouling solution (blue line) and hot water (red line), as well as a test portion (Heat exchanger). A frequency-controlled magnetic gear pump, an N-Flow magnetic flow meter, pipes with various metal surfaces, and a thermostatically controlled heater maintain a constant hot inlet temperature  $(60\pm0.5^{\circ}C)$  in the heater tank. To avoid heat loss along the flowing line, the hot line outside the test area is well insulated. A jacketed artificial fouling solution tank, a frequency-controlled magnetic gear pump, transparent HDPE piping for

the flowing line, a Burkert inline paddle wheel flow metre, a RW20 digital stirrer, and a chiller are also included in the cold flow loop to keep the artificial fouling solution at a constant cold inlet temperature  $(30\pm0.5^{\circ}C)$ . The Araki Magnet Pump is a cold line magnetic gear pump with specs of 2800 rpm, 1.1 amps, 260 W motor, 120L/minute capacity, and a maximum head of 8.6m.

A counter current double pipe heat exchanger with a length of 130 cm is used in the test portion. The hot water goes into the pipe and the cold artificial fouling solution flows into the annular space of the pipe in this exchanger. The inside pipe is made up of several metals with the same measurements (outer diameter of 12.7 mm and inner diameter of 8.48 mm). The outer pipe is made of clear HDPE piping with a 42.1 mm inner diameter and a 46.8 mm outer diameter.

Using four RTD sensors, the inlet and outlet temperatures in the hot and cold lines were monitored at the inlet and outlet of the test section, respectively. A PLC programme data collection system was added to gather data and automatically maintain the set temperatures in the hot and cold intake sections. A YOKOGAWA Differential Pressure Transmitter was used to monitor the pressure drop variation in both lines over the test segment (0-200 mbar). The volume flow rate, pressure drop, and inlet and outlet temperatures for hot and cold lines were all recorded throughout the fouling test.

The hot line pipe was fully insulated and the cold line pipe was built of HDPE piping, which is ideal for minimizing heat loss to the environment, to highlight the key differences between the heat transfer characteristics of clean and fouled conditions. The following Table 3-2 contains the details of the insulating materials:

Insulation Thickness (t)	Insulation Thermal Conductivity(ks)	Heat Transfer coefficient for the outside of insulation	Emissitivity of the insulation (E)
25 mm	0.038W/m.K	$10 \text{ W/m}^2.\text{K}$	0.8

#### **Table 3-3 Insulating Materials**

In addition, a mitigation strategy was implemented that included the use of additives to reduce fouling on heat transfer surfaces. The fouling experiment was carried out to examine the efficiency of Nylon 6,6 in treating the fouling problem in a twin pipe heat exchanger.

#### 3.7 Test Materials

The experimental pipes are 1300mm long with a 2.11 mm wall thickness and a 12.7mm outer diameter. The coupons were put in the centre of the test area, as shown in Figure 3-9. Figure 3-10 shows the fabrication of a double pipe heat exchanger. Metal pipes were placed in the centre of a 47.1mm outer diameter and 42.7mm inner diameter acrylic pipe. Figure 3-11 shows a diagram showing the dimensions of a twin pipe heat exchanger. Following the completion of the fouling test, the fouling deposition on the surfaces was characterized.



Figure 3-9 Stainless Steel Test Coupon



Figure 3-10 Double Pipe Heat Exchanger



Figure 3-11 Cross-Sectional Dimension of Double Pipe Heat Exchanger

#### Table 3-4 Physical Properties of Stainless Steel Coupon at 300K

Materials		Properties at 300 K		
TARGET HULS	p ( kg/m <sup>3</sup> )	C <sub>p</sub> (J/kg.K)	K ( W/m.K)	$R_a$ (µm)
Stainless Steel	8238	468	16	1.27

#### Table 3-5 Physical Properties of Nylon 6,6

	Nylon 6/6
Tensile strength	8.2 x 104 kPa
Crystalline melting point	509°F / 265°C
Density	1.2 g/ml
Typical moulding shrinkage ratio	1.5%

#### 3.8 EDTA Titration Method

In a 250ml conical flask, take 25ml of calcium carbonate solution from the bulk holding tank and dilute it with 25ml of distilled water. 2ml of pH10 ammonium chloride buffer solution and 1ml of 0.1M magnesium EDTA solution are added to the calcium carbonate combination. Due to the colour of the magnesium EDTA solution, the colour of the solution will shift from colourless to light pink. The solution is then turned wine red by adding 3 drops of Eriochrome black T solution. Titrate the solution with 0.01M EDTA solution until it becomes blue instead of wine red. At the corresponding neutralisation point, the blue should exist without any residues of previous red in the combination. The calibrated amount is then used to compute the amount of EDTA titrated as shown in equation 6.

$$1ml of \ 0.01M \ EDTA \ used = 0.545mg \ Ca^{++} \tag{6}$$

The calibrated quantity stated here is derived empirically after testing the EDTA with the prepared bulk solution. As a result, it is critical that this calibrated amount be obtained prior to the experiment because many factors can contribute to the difference in the calculated amount, such as the dissolubility of mixtures, the presence of impurities, differences in the manufacturing process of the components involved, and so on.

#### 3.9 Fouling Bulk Solution Preparation Method

Calcium carbonate has been chosen as the fouling material present in the bulk solution for the purposes of this investigation. Hard water is another name for this. Each run of the fouling test will utilise 7 litres of bulk solution. With distilled water, calcium chloride CaCl2 and sodium bicarbonate NaHCO3 powder will be combined. The following is the response of these two components shown in equation 7.

$$CaCl_2 + NaHCO_3 \rightarrow CaCO_3 + 2NaCl + H_2O + CO_2 \tag{7}$$

Because sodium chloride is a soluble salt with a high solubility at these temperatures, its production can be overlooked. In comparison to calcium carbonate, sodium chloride has a lower solubility. For the fouling tests, a concentration of 0.3 gram/litre is necessary. The mass of calcium chloride and sodium bicarbonate necessary can be estimated as stated in the Table 3-5 below:

Components	Atomic Mass
Calcium, Ca	40.078
Chlorine, Cl	35.453
Sodium, Na	22.99
Hydrogen, H	1.007
Oxygen, O	15.99
Carbon, C	12.01

**Table 3-6 Molecular Mass of Chemicals Used** 

Table 3-7 Amount of CaCl <sub>2</sub> and	l NaHCO₃ for	0.3g/litre CaCO <sub>3</sub>
Solution		

Components	CaCl <sub>2</sub>	2NaHCO <sub>3</sub>	CaCO <sub>3</sub>
Molar mass	110.9054	168.002	100.089
Molar mass ratio (g/mol)	1.108	1.6785	1
Mass for 1 liter	0.3 g/l x 1.108 = 0.3324 g/l	0.3 g/l x 1.6785 = 0.5035 g/l	0.3 g/l

Mix one beaker with 500ml distilled water and calcium chloride in a 500ml beaker and stir until there are no floating particles. Do the same thing with the sodium bicarbonate powder. To make 1 litre of calcium carbonate solution with a concentration of 0.3 gram/litre, combine both the 500ml sodium bicarbonate

and calcium carbonate mixes in a 1000ml conical flask. Repeat the whole method of combining these two powders for each litre until the holding tank has 7 litres of calcium carbonate solution. There should be no floating particles in the bulk solution, which should be clean and colourless.

#### 3.10 EDTA Titration Materials Preparation

The quantity of Ca2+ ions in the bulk fouling solution is determined using EDTA titration. Before titration may begin, four main solutions are required. The titration procedures could be found in section **3.8**.

#### 3.11 0.01M EDTA Solution

To complex with the Ca++ in the bulk solution, EDTA (ethylene-diamine-tetraacetic acid) is utilised. Disodium dihydrogen EDTA, 3.722 gram, will be dissolved in distilled water and diluted in 1000ml distilled water.

Due to the acid's availability, ethylene-dinitrilo-tetra-acetic acid was employed instead of disodium dihydrogen EDTA in this investigation. Because ethylene-dinitrilo-tetra-acetic acid is insoluble in distilled water with a pH of 7.0, the pH of the solution will be raised with sodium hydroxide NaOH.

Instead, 300ml of distilled water will be combined with 2.9224 grams of ethylene-dinitrilo-tetra-acetic acid and 0.8 gram of sodium hydroxide. It will then be diluted to create a total volume of 1000ml of EDTA solution with a concentration of 0.01M.

Continuously agitate the solution until there are no floating particles and it is clear and colourless.

#### 3.12 Eriochrome Black T Solution

Eriochrome black T is a complicated indicator that turns a wine-red titration mixture blue. 15ml triethanolamine and 5ml 100% ethanol are combined with 0.2 gram solid Eriochrome black T solution. When not in use, fully combine all ingredients and store in the refrigerator.

#### 3.13 pH10 Ammonia Ammonium Chloride Buffer Solution

570 mL liquid ammonia NH3 and 70 g ammonium chloride NH4Cl are combined and diluted with distilled water to make a 1000 mL solution

#### 3.14 0.1M Magnesium Complex EDTA Preparation

In 500ml of distilled water, 37.2 grammes of EDTA (29.2 grammes of ethylenedinitrilotetraacetic acid + 8 grammes of sodium hydroxide) is mixed and dissolved. Add 24.65 grammes of magnesium sulphate to the solution after that. To make the colourless solution bright pink, add a few drops of phenolphthalein and a suitable amount of 2M sodium hydroxide. Dilute the solution with enough distilled water to make it 1000ml.

#### 3.15 Data Acquisition

A programmable logic controller (PLC) was installed, and the WinCC software was used to record the inlet and outlet temperatures of hot water passing through the pipe, the mean temperature of the tanks, the inlet and outlet of artificial solution temperatures passing through the annular pipe, the differential pressure between the annular pipe, and the flow 88 rates of the hot and solution lines. The RTD-100 sensors were used to measure all of the temperatures. The differential pressure and flow rates were also recorded by sending a 4-20 mA signal to the programme through the PLC. The application

was programmed to record every 10 minutes for up to 4320 minutes in recoding mode (S. N. Kazi et al., 2010).

This research will contain two components of experimentation, as indicated in previous chapters: the heat transfer test and the fouling test.

The heat transfer coefficient (hs) will be computed and compared using the following equation to detect the heat transfer for both the untreated and coated specimens:

$$h_s = \frac{q_c}{T_{surface} - T_{bulk}} \qquad \text{hs} = \text{Heat Transfer Coefficient}$$
(8)

Tsurface is the surface temperature, and Tbulk is the temperature of the bulk solution in the holding tank, where qc is the convective heat flux delivered, Tsurface is the surface temperature, and Tbulk is the temperature of the bulk solution in the holding tank.

The following Equation 9 & 10 is used to compute the Reynolds number:

#### **Equation 3-1 Reynolds Number Equations**

$$Re = \frac{\rho_f x \, U \, x \, D_h}{\mu_f} \tag{9}$$

$$R_f = \left(\frac{1}{U_{fouled}}\right) - \left(\frac{1}{U_{initial}}\right) \tag{10}$$

Where Ufouled and Uinitial are the total heat transfer coefficients for the fouled and initial clean conditions, respectively (Oon, Kazi et al. 2020). The

following Equation 11 may be used to compute the total heat transfer coefficients:

$$Q = U x A x \Delta T \tag{11}$$

Where Q is the heater's provided thermal energy, A is the area of the test specimen's outer surface, and T is the temperature difference between the inlet and output temperatures.

#### 3.16 Measurement and Characterization

The total quantity of calcium carbonate deposited on the heat exchanger's test section pipe was calculated using the dissolving salt technique. The test section pipe was removed from the heat exchanger after a 72-hour fouling test. The test portion was carefully removed throughout this part of the investigation to avoid scratching the surface and influencing the readings of the accumulated calcium carbonate. The calcium carbonate that had adhered to the test section surface in HCl was then diluted in 1L distilled water, cleaned with a soft brush, and the solution collected in a beaker. Before taking a sample for titration, make sure the solution is clear. The concentration of calcium carbonate crystalline deposition salt on the test section pipe was calculated using the EDTA-complexometric titration technique. The coupons were carefully removed from the test pipe in order to characterise the deposits. X-ray diffraction analysis (XRD) and scanning electron microscopy were used to examine the crystal morphology of the scale deposits (SEM). Energy dispersive spectroscopy was also used to verify the elemental analyses (EDS). To visually distinguish fouling deposits on various tested surfaces, optical pictures and photos were taken (J. W. Morse et al., 2007).

#### **CHAPTER 4: RESULTS & DISCUSSION**

#### 4.1 Thermophysical Properties of Synthetic Fibre

As indicated in Table 4.1, the density, thermal conductivity, viscosity, and specific heat capacity of the Nylon 6,6 fibre dispersion are assessed and summarized. For each concentration, the assessed thermophysical parameters are employed in the heat transmission and fouling resistance calculations.

Materials	Density	Thermal	Viscosity	Specific heat
	(kg/m <sup>3</sup> )	Conductivity	(mPa.s)	capacity
		(W/m.K)		(J/kg.K)
Water	995	0.611	0.829	4142
Nylon 0.0025 wt%	996.5348	0.412	0.602	4165
Nylon 0.0075 wt%	996.6769	0.413	0.603	4165
Nylon 0.0125 wt%	996.6967	0.413	0.603	4165
Nylon 0.05 wt%	997.7657	0.414	0.615	4165
Nylon 0.075 wt%	997.7711	0.414	0.616	4165
Nylon 0.1 wt%	997.8129	0.414	0.616	4165

**Table 4-1 Thermophysical Properties of Nylon Suspension** 

#### 4.2 **Distilled Water Run Experiment**

#### 4.2.1 Heat Transfer

The experimental Nusselt number was compared to proven correlations to confirm the design. As demonstrated in Figure 4.1, the computed experimental Nusselt number has a slight divergence when compared to a few conventional formulae. This demonstrates that the experimental test equipment was accurate and dependable. The results reveal that the experimental Nusselt number is closer to Gnielinski and Petukhov than the Gnielinski and Petukhov numbers. Gnielinski has a 3.4 percent volatility, whereas Petukhov has a 3.6 percent variance. The most opposing the experimental outcome were Maiga, Dittus Boelter, and Pak Cho. As a result, the Gnielinski correlation shows that the test equipment is well adjusted.



### Figure 4-1 Comparison of Nusselt Number for Experimental vs Theories

#### 4.3 Fibre Suspension in Heat Transfer Study

#### 4.3.1 Low Nylon Concentration Impact

Using various concentrations of nylon fibre samples, a series of experimental runs were conducted. In order to measure the heat transfer coefficient, the nylon content and velocity were modified correspondingly. Heat transfer coefficient versus velocity for three distinct low concentrations of nylon suspension at three different heat flux conditions is shown in Figures 4-2, 4-3, and 4-4. 0.0025, 0.0075, and 0.0125 wt. percent were the three low concentrations at a similar heat flux condition where the hot fluid temperature is maintained at three

average temperature of 50 °C, 60 °C, and 70 °C in velocities of 0.1m/s, 0.15m/s, 0.2m/s, 0.25m/s, 0.3m/s and 0.35m/s.



Figure 4-2 Low Concentration Nylon Impact at 50°C



Figure 4-3 Low Concentration Nylon Impact at 60°C



#### Figure 4-4 Low Concentration Nylon Impact at 70°C

All continuous heat flow has a same tendency. The study's low velocity range is 0.1 m/s to 0.2 m/s, while the high velocity range is 0.2 m/s to 0.35 m/s. When the findings were compared to water run, the heat transfer coefficients for all three low concentrations were lower than water (Gharehkhani et al., 2017). It can be shown that when the velocity of the fibre suspension flow rises, so does the heat transfer coefficient. This conclusion is in line with previous research that found that when fibre is suspended in water, the viscosity of the fluid changes, affecting turbulence eddies. This is in line with the role of fibres in improving heat transmission. At a maximum velocity of 0.35 m/s, the pattern seemed to be Nylon fibre. To guarantee that the interpreted results were legitimate, test runs and analysis were repeated several times.

#### 4.3.2 High Nylon Concentration Impact

The high concentration of nylon was investigated in order to learn more about the low concentration of nylon trend. For both low and high concentrations of nylon, the velocity range remained constant. Heat transfer coefficient versus velocity is shown in Figures 4-5, 4-6, and 4-7 for three distinct high concentrations of nylon suspension and three different heat flux conditions. 0.05, 0.075, and 0.1 wt. percent were the three high concentrations at a similar heat flux condition where the hot fluid temperature is maintained at three average temperature of 50 °C, 60 °C, and 70 °C in velocities of 0.1m/s, 0.15m/s, 0.2m/s, 0.25m/s, 0.3m/s and 0.35m/s.



Figure 4-5 High Concentration Nylon Impact at 50°C



Figure 4-6 High Concentration Nylon Impact at 60°C



Figure 4-7 High Concentration Nylon Impact at 70°C

#### 4.3.3 Summary on Nylon Concentration

The heat transfer coefficient is exactly related to the velocity of fibre suspension in annular flow, according to the results of various nylon concentrations. For velocity exceeding 0.2 m/s, the heat transfer coefficient is shown to be above water for larger concentrations of nylon. Although fibre has a lesser thermal conductivity than water, it can provide a dependable path for heat conduction, increasing the total heat transfer coefficient only over a particular range of velocity (S. N. Kazi et al., 2014c). By altering turbulent eddies, the lower thermal conductivity of fibre increases the heat transfer coefficient (Gharehkhani et al., 2017). The data patterns have been validated, and they coincide with earlier studies.

#### 4.3.4 Effect of Constant Heat Flux

The experimental runs were extended to investigate the influence of temperature on the annular flow of fibre suspensions, generally known as the constant heat flux effect. The optimal concentration for studying the effect of steady heat flow, according to the summary of effect of concentration on fibre suspension, is 0.1 wt. percent. Nusselt number as a function of velocity is shown in Figure 4-8 for 0.1 weight percent studied at a similar heat flux condition where the hot fluid temperature is constant at 60 °C in velocities of 0.1m/s, 0.15m/s, 0.2m/s, 0.25m/s, 0.3m/s and 0.35m/s.



Figure 4-8 Nusselt number as a function of velocity for 0.1 wt% of Nylon 6,6 for three different constant heat flux



Figure 4-9 Heat Transfer Coefficient as a function of velocity for 0.1 wt% of Nylon 6,6 for three different constant heat flux

The most important finding of this research is that temperature influences fibre suspension transport. The higher concentration fibre suspensions have a greater Nusselt number and heat transfer coefficient as the temperature rises. The flow of fibre suspensions across the annular regime is improved by raising the temperature. This is because, in compared to lower temperature heat dissipation, higher temperature heat dissipation causes fewer environmental losses. On top of that, the temperature effect played a role in energy transfer via turbulent eddies and fibre contact.

#### 4.4 Fouling Experiment

The fouling experiment is carried out for 72 hours starting 6.1.2022 (7.37pm) to 9.1.2022 (7.37pm) with the test rig in Fouling Lab. Hot water temperature is maintained at 60 degree Celsius whereas the bulk solution of Calcium Carbonate in cold water tank is maintained at 30 degree Celsius throughout the 72 hours run. The bulk solution is been prepared with a concentration of 0.3g/L of calcium carbonate. Hot water was evaporating quick due to its high temperature and distilled water were added from time to time to ensure the level doesn't goes below the heater coil as it might cause damage to the heater and temperature will be difficult to control when more room temperature distilled water was added to top up at the level. Fouling condition is been observed at the coupon for every 1 hour to experience the process of fouling form. Titration process is also been carried out for every 6 hours to compare the level of calcium carbonate concentration that is being fouled at the coupon and remaining concentration in the bulk solution tank.

#### 4.4.1 Fouling Resistance Without Additives

This fouling run is been conducted for 72 hours. There is distilled water in the hot water tank at 60 degree Celsius and calcium carbonate solution in cold water tank at 30 degree Celsius. Titration was carried out for every 4 hours to measure the concentration of remaining calcium carbonate in the cold water tank. The purpose of titration is to calculate amount of calcium carbonate has been deposited at the coupon for every 4 hours of interval. Titration sample is as shown in Figure 4-10.



# Figure 4-10 Sample of Titration to Calculate Concentration of Calcium Carbonate

Amount of EDTA solution required to turns the solution blue is recorded. Hard water is prepared based on the required amount of Sodium Bicarbonate and Sodium Chloride to be added back in the calcium carbonate bulk solution (in cold water tank).

# 4.4.2 Correlation of Coupon Weight Before vs After Experiment (Without Additives)

	Weight of Coupon
Additives	Without Nylon 6,6
Before Experiment (g)	7.1235
After Experiment (g)	7.4458
Weight of Deposition (g)	0.3223

 Table 4-2 Weight of Test Coupon Before vs After Experiment (Without Additives)

Based on Table 4-2 the weight of coupon before experiment was 7.1235 gram. The coupon is made up of stainless steel. After the 72 hours experiment, the mass of coupon is 7.4458 gram. From here, we see the difference of 0.3223 gram and it shows the amount of calcium carbonate deposited on it throughout the 72 hours experiment. There are many factors affecting the rate of fouling such as temperature of the suspension, coupon material type, velocity of flow, or concentration of suspension. Here in this experiment, we about to study the effect of concentration on the fouling resistance. In industries that apply heat exchangers system are very much concerned on this fouling resistance as it affects the heat exchange result if the fouling occurs to rapidly on the surface of heat exchangers. This requires frequent maintenance to be done which results in high-cost expenses.

#### 4.4.3 Fouling Resistance With Additives

This fouling run is been conducted for 72 hours. There are distilled water in the hot water tank at 60 degree Celsius and calcium carbonate solution with Nylon additives this time in cold water tank at 30 degree Celsius. The same titration was carried out for every 4 hours to measure the concentration of remaining calcium carbonate in the cold-water tank. Titration result data can be found as tabulated below:

No	Date	Time	Titration	Start	Titration	End	EDTA	Used
			Point (ml)		Point (ml)		(ml)	
1	6/1/2022	19:00	0		4.7		4.7	,
2	6/1/2022	23:00	4.7		6.1		1.4	
3	7/1/2022	3:00	6.1		11		4.9	)
4	7/1/2022	7:00	11		14.4		3.4	
5	7/1/2022	11:00	14.4		19.3		4.9	
6	7/1/2022	15:00	19.3		23.6		4.3	
7	7/1/2022	19:00	23.6		27.7		4.1	
8	7/1/2022	23:00	27.7		31.2		3.5	
9	8/1/2022	3:00	31.2		35.4		4.2	
10	8/1/2022	7:00	35.4		39.2		3.8	
11	8/1/2022	11:00	39.2		43.7		4.5	
12	8/1/2022	15:00	43.7		47.4		3.7	,
13	8/1/2022	19:00	47.4		52.1		4.7	,
14	8/1/2022	23:00	52.1		56.4		4.3	
15	9/1/2022	3:00	56.4		60.7		4.3	
16	9/1/2022	7:00	60.7		64.3		3.6	
17	9/1/2022	11:00	64.3		68.7		4.4	
18	9/1/2022	15:00	68.7		72.3		3.6	
19	9/1/2022	19:00	72.3		76.5		4.2	

Table 4-3 Titration Data for 72 Hours Experiment for with additives

4.4.4 Correlation of Coupon Weight Before vs After Experiment (With

Additives)

 Table 4-4 Weight of Test Coupon Before vs After Experiment (With Additives)

	Weight of Coupon
Additives	With Nylon 6,6
Before Experiment (g)	7.1235
After Experiment (g)	7.2589
Weight of Deposition (g)	0.1354

Based on Table 4-4, the weight of coupon before experiment was 7.1235 gram. After the 72 hours experiment, the mass of coupon is 7.2589 gram. From here, we see the difference of 0.1354 gram and it shows the amount of calcium carbonate deposited on it throughout the 72 hours experiment. It shows that the suspension with additives could increase the induction period of fouling. A better comparison of data is drafted in the graph in Figure 4-13.

#### 4.4.5 Summary of Fouling Resistance for With Additives vs Without Additives.



# Figure 4-11 Error Bar for Fouling Resistance of With Additives vs Without Additives

Figure 4-11 depicts the fouling resistance to the calcium carbonate solution as a function of time for various concentrations with and without additions. At zero concentrations of additives in the calcium carbonate solution, fouling resistance rises with time. The induction period is extremely brief. The resistance was increasing to a higher degree after 5 hours. The trend persisted for another 20 hours before gradually decreasing (reducing) and becoming stable. This occurred as a result of the removal of a portion of the deposition until it became stable. After adding the additives to the calcium carbonate solution, the fouling resistance altered the pattern of deposition, slowed the resistance at the start, and extended the induction time for fouling deposition. After 15 hours, the resistance of the additive with 0.1% wt Nylon concentration reduced owing to low deposition on the surface, which improved surface roughness and overall heat transfer coefficient, which was reflected by the retardation of fouling resistance. Later, the resistance increased and gradually stabilized, remaining below the fouling resistance in the absence of additives. Due to the induction period, same margins of error were recorded for fouling resistance for the first 5 hours of the experiment. The margin of error was then drastically decreased.

The slope of the curves demonstrates that the rate of fouling retardation decrease with the use of additives. On the other hand, when the amount of additives in the fouling liquid increased, the total deposition decreased due to a reduction in the efficiency of the attraction force from the nuclei at the test coupon towards the calcium carbonate crystals and foul on the surface.



4.4.6 Summary of Heat Transfer Coefficient (With Additives vs Without

#### Additives)

Figure 4-12 Error Bar for Overall Heat Transfer for With Additives & Without Additives

Figure 4-12 shows that the heat transfer coefficient for 72 hours of experiment. It is shown that the trend is litreally constant up to 32 hours and begins to drop until 45<sup>th</sup> hour. At this point, it depicts that the fouling has formed at the coupon and the whole hot water pipe surface which retarded the heat transfer efficiency and cause the process to be slower compared to the 1<sup>st</sup> 32 hours of the experiment. From the 45<sup>th</sup> hour onwards, the heat transfer trend seems to be constant as the surface of hot water pipe is reaching its maximum attraction force limit for calcium carbonate crystal to deposit on it. The trend will be more obvious to be analyse if it been run for longer period of hours which is expected for the heat transfer efficiency to continuously drop due to

thick layer of deposition on pipe surface which disallow heat transfer to occur efficiently.

From the graph, it can also be clearly observed that the bulk solution with Nylon 6,6 additives reaches a higher heat transfer coefficient compared to bulk solution without Nylon 6,6 additives. This proves that the presence of Nylon 6,6 additive in the solution could increase the induction time of calcium carbonate crystal deposition on the pipe surface by slowing the nuclei growth on hot water pipe surface which attracts CaCO<sub>3</sub> crystals. This is why the heat transfer is better compared to those without additives where the crystal deposition is happening quicker.

### 4.4.7 Summary of Calcium Carbonate Deposition Weight for With Additives vs Without Additives



# Figure 4-13 Chart of CaCO<sub>3</sub> Deposited on Coupon for With Additives vs Without Additives

From Figure 4-13 The weight of calcium carbonate that forms on the surface

of the heat exchanger test coupon. The test coupon is removed from the heated
pipe once the test is completed, and the weight is measured to compare to the weight before the test. Chart above indicates that 0.0462g of deposits were created on the test coupon with calcium carbonate solution without Nylon, while 0.0278g of deposits were formed on the test section with calcium carbonate solution with Nylon. This data and result clearly demonstrate that the presence of Nylon in the solution could reduce the salt ions attraction by retarding the growth of nuclei on the coupon surface and minimized the formation of deposits on the heat exchanger surface and that it may be employed as a fouling mitigation technology in industry.

### 4.4.8 Calculation of Titration Measurement

Titration calculat	tion				
Calibrated titration	on amount:				
	1 r	nl EDTA	0.545	mg Ca++	
	for concentre	ation of 0.3g/L:			
	5.5 r	nl EDTA	2.9975	mg Ca++	
	Concentratio	on used for experiment			
	300 r	mg/L			
To calculate amo	ount of Ca++				
1)	1.2 r	nl EDTA	0.654	mg Ca++	
2)	Current CaCO3 concentration measured:				
	(	Ca molar mass		40.075	
	C	CaCO3 molar mass		100.089	

	Current concentration:			CaCO3 molar mass x mea Ca molar mass		x measured amount Ca++		
	Therefore:							
	Current concentration			1.633	mg / 25m	il		
	CaCO3			65.34	mg / 1 liter		300	
Difference	of CaCO3= original conce	ntration - cui	rent conc	entration				
Difference	of CaCO3:	234.66	mg/liter					
Required r	nass to add (top up) into b	bulk solution						
Mass for e	ach component:							

	CaCl2	2NaHCO3	CaCO3	
molar mass (1g/mol)	1.108	1.679	1	g/L
for 0.3g/L	0.3324	0.5037	0.3	g/L
	0.2600	0.3940	0.2347	g/L (measured difference CaCO3)
required to add back	5.200160853	7.880027142	4.693285	g/20L

# Figure 4-14 Sample Calculation Method to Find Amount of CaCO<sub>3</sub> to be added back to the Bulk Solution in Cold Water Tank

As mentioned earlier, titration is done to calculate the concentration of calcium carbonate remaining in the cold water tank. Once the concentration is calculated, the amount of salt required to be added back to the cold water tank so that the concentration is maintained.

### 4.4.9 Morphology of Deposited CaCO<sub>3</sub> on Test Coupon



### Figure 4-15 SEM Images of Stainless-Steel Test Coupon Before Experiment

Figure 4-15 shows SEM images taken from fresh test coupon before experiment. All three pictures above are taken in different magnification which is 20um, 50um and 100um. From these images, it can be seen that the stainlesssteel test coupon is clear without any foreign particles deposition on the surface and it is totally prepared to be used for fouling deposition test. This images is taken to prove that no existing calcium carbonate crystal or other particles are deposited to the fresh test coupon before running the experiment and to ensure that the weight of test coupon recorded before the experiment is a pure coupon weight to be compared with the after experiment SEM images and weight result.



Figure 4-16 SEM Images of Stainless-Steel Test Coupon Before Experiment



Figure 4-17 Condition of CaCO<sub>3</sub> Fouling on Test Coupon After 72 Hours of Experiment

Figure 4-16 shows SEM images taken from calcium carbonate deposition on test coupon after running the 72 hours experiment without additives and with additives. The fouling portion is observed under a microscope to study the crystal structure size and crystal morphology. From here, we could discuss that the calcium carbonate crystal fouling formation is authenticated and obvious under the SEM image which shows that the data provided on fouling resistance and weight analysis are valid to prove comparison result between with and without additives.

#### 5.1 Conclusion

The aim of the research was to investigate how a specific synthetic fibre in an annular flow heat exchanger transfers heat and prevents fouling. This section discusses the general conclusions.

Changes in flowrate and concentration have been shown to have a significant influence on the heat transfer coefficient and fouling mitigation of fibre suspension in annular flow in previous research. The inclusion of nylon fibre resulted in an increase in heat transmission. Low fibre content was thought to increase the heat transfer coefficient. The breakeven point of low-concentration synthetic fibres in terms of heat transfer coefficient was above water for the velocity range of 0.2 m/s to 3.5 m/s at greater concentrations of nylon in the range of 0.05 wt. percent - 0.1 wt. percent. Heat transfer coefficient of nylon fibre concentrations of less than 0.05 wt.%, measured below the water curve but with a tiny divergence towards high velocity. The results of a research of continuous heat flux at 50°C, 60°C, and 70°C show that higher temperatures enhance annular flow regime, but only to a minimal scale.

To perform fouling and fouling mitigation studies, an experimental test rig was devised and built. The focus of this study was on calcium carbonate (CaCO3) fouling and the usage of polymeric fibre to reduce fouling. A rise in the concentration of fouling components in solution, a reduction of flow velocity, and an increase in the surface to bulk temperature differential are all seen in current studies on mineral (CaCO3) fouling on heated pipe surfaces. Due to the increased pushing force for mass movement, all of these factors improve fouling resistance. The application of zinc and tourmaline-based catalytic material slows the formation of the fouling deposit. The rate of additive efficacy progressively reduces with the rate of augmentation of additives in the solution, but the overall effect is greater with a higher proportion of additives in the fouling solution, as shown by the findings. In the absence of additives, scale deposition develops a tenacious deposition of dissolved salts (CaCO<sub>3</sub>) on the test section of the stainless-steel hot pipe, whereas in the presence of additives Nylon 6,6 in the solution, scale deposition of the stainless-steel hot pipe.

The addition of Nylon 6,6 additive to the cooling liquid might delay deposition and tenacity, improve heat exchanger performance, save maintenance costs, and extend the heat exchanger's continuous operation. Furthermore, the additive utilised in this case was functionalized by low-cost additions, which might reduce the costs of updating the heat exchanger system to be more efficient in the long run.

## 5.2 Recommendation

The research work presented in this proposal has added to our understanding of synthetic fibre suspension in annular flow. The following suggestions might be made in light of recent discoveries:

To further understand the benefits of fibre flow in annular flow, an investigation of the stream conduct of polymeric fibres suspended at greater speeds was recommended. Due to the limitations of the existing test rig, velocity greater than 0.35 m/s should be tested in order to better understand the influence of polymeric fibre suspension on heat transfer coefficient and fouling mitigation, as well as the impact of inspection on drag coefficient. Besides, extensive research into the fouling deposition mechanisms of various salts, such as Ca3(PO4)2, CaSiO3, MgSiO3, MgCO3, and combinations, as well as their mitigation using green additives, will bring new insights and aid in the fight against fouling in real-world scenarios in industry. By adding green additives to the aqueous fouling solution, the effect of fouling mitigation on non-metal surfaces may be examined in a similar way to metal surfaces. This might aid in the selection of heat exchanger tube coating materials. Finally, the developed LabVIEW system for monitoring and controlling the system is a great starting point for designing and fabricating an experimental system for fouling research. Future complicated fouling research, such as co-precipitation, tri-precipitation, or complex multi-phase flow fouling, should include full automation and accuracy enhancement.

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