JJMIE

Volume 19, Number 4, Dec. 2025
ISSN 1995-6665
Pages 829– 838
https://doi.org/10.59038/jjmie/190412
Editor-in-Chief: Prof. Faris M. AL-Oqla

Jordan Journal of Mechanical and Industrial Engineering

Numerical Study on the Influence of Flow Hydrodynamics and Tube Geometry on Heat Exchanger Fouling

Abdullah A. Alshorman

Al-Balqa' Applied University- Al-Huson University College - Mechanical Engineering Department, P.O.Box 50 - Al-Huson 19117- Irbid – Jordan

Received 23 July 2025 *Accepted 17 October 2025*

Abstract

Fouling in heat exchangers is a thermo-hydrodynamic slow process caused by the gradual accumulation of impurities, mineral salts, biological organisms, and deposits on the solid surfaces of the heat exchangers. This undesirable thermal behavior lowers the thermal effectiveness and minimizes the total thermal performance of the heat exchangers. Generally, several parameters contribute to fouling development, including the thermal and hydrodynamic properties of the working fluids, the type and design details of the heat exchanger, as well as the structural material and operating conditions.

This numerical study was conducted to gain a deeper understanding of fouling mechanisms and to control their progress. Primarily, this simulation investigation was planned and performed to formulate and study heat exchanger fouling based on the thermal properties of fluids, flow hydrodynamics, and geometrical effects using MATLAB coding. The results of this analytical study showed that the increase of most of the thermal properties of working fluids, like specific heat (C_p), thermal conductivity (K), and thermal diffusivity (α) will reduce the tendency for fouling at different fouling index ranges (FI). The lowest fouling index was for water at a range of (0.0065-0.0025) m^2 k/W, and at a moderate range of (0.0144-0.0038) m^2 k/W for Benzene, while the highest range was (3.75-1.66) m^2 k/W for carbon dioxide. On the other hand, the high values of the hydrodynamic properties like density (ρ) and dynamic viscosity (μ) enhance the tendency for fouling. Additionally, the gaseous and organic working fluids enable a high rate of fouling. Geometrically, the lowest fouling rate occurred with the elliptical tube for hot water at 12.12% against circular tube and by 66.58% versus square tube.

Keywords: Fouling, Fouling index, working fluids, heat exchangers, thermal effectiveness, hydrodynamic properties.

1. Introduction

Heat exchangers are an essential thermal-hydrodynamic systems for exchanging heat between two working fluids (hot fluid and cold fluid) separated by solid thermal mediums with realistic thermal properties and proper functional design. Moreover, these heat exchangers have different types, structural designs, geometrical dimensions, and thermal applications in several engineering and industrial fields.

Due to thermal and hydrodynamic interactions between the working fluids and the solid surfaces of the heat exchanger's piping and tubes, deposits known as fouling commonly form inside the tubes. This fouling results from the sedimentation of impurities and mineral salts in the fluids, variations in flow velocity within the tubes and fittings, and biological activity present in the working fluids [1, 2].

Fouling in heat exchangers is a common phenomenon that can potentially reduce the effectiveness and thermal performance of the exchangers. This decay is mainly due to increased thermal resistance inside heat exchangers by fouling [3,4]. Therefore, getting a deep understanding of fouling is essential to control its development rate and reduce the tendency of design and operational factors for fouling. Mostly, many parameters affect fouling progress, these include design parameters, mechanical and thermal properties of the working fluids, tubes materials, operational conditions and surrounding parameters. Accordingly, this analytical simulation study is executed to account for all of these parameters and their related impacts on fouling in heat exchangers. The investigation of these factors is crucial to managing fouling initiation and progress in wide range of industrial and engineering applications.

Most previous studies on fouling have focused on one or two individual parameters, examining their isolated effects without considering their combined influence. Furthermore, little attention has been given to the impact of tube geometry on fouling, particularly in conjunction with other contributing factors [5,6]. To address these gaps, the present analytical simulation study investigates the collective effects of multiple parameters on fouling formation in heat exchangers. The fouling process is modeled by incorporating the dimensional geometric

* Corresponding author e-mail: alshorman@bau.edu.jo.

parameters of the heat exchanger, along with the thermal and hydrodynamic properties of the working fluids, across three different tube geometries. The resulting fouling factor is then evaluated for its influence on heat exchanger performance, specifically through its relationship with the overall heat transfer coefficient, heat transfer rate, and the effectiveness of the heat exchanger [7,8].

2. Factors and Effective Parameters of Fouling

The formation of fouling in heat exchangers is controlled by several interrelated factors, including the heat exchanger's design and type, properties and flow conditions of the working fluids, operating temperatures and pressures, material characteristics of heat transfer surfaces, preventive and periodic maintenance schedules, and microstructure of solid material surface. Effective control, monitoring, and operation approaches are also important for minimizing fouling and certifying long-term thermal and mechanical performance of heat exchanger[9,10,11]. In this simulation study, the combined effects of various thermal, hydrodynamic and geometrical, factors are modeled and analyzed to assess their influence on the initiation and progress of fouling.

3. Method and Procedures

3.1. Methodology and Mathematical Formulation

The basic equations that describe the thermodynamics model of the system are explainedas following according the main effective parameters of fouling and its associated factors [12, 13, 14, 15].

3.2. Model assumptions and considerations

The following assumptions are made during the development of the mathematical model, based on relevant scientific and technical considerations, to simplify the modeling process and facilitate mathematical analysis for this initial one-dimensional version model:

1. One-dimensional model
2. Steady-state operation
3. The style of the system is a double pipe heat exchanger or shell and tube heat exchanger
4. The outer surface of the shell is insulated
5. The inner and outer fouling layers are symmetrical in material and thickness
6. Counter-flow arrangement for hot fluid and cold fluid inside the heat exchanger

Figure (1) shows the various layers of the studied system with fouling layer within the heat exchanger tubes. In this counter flow arrangement, the hot fluid passed inside the inner tube while the cold one passed inside the outer shell. The bright brown layer represents the fouling in both sides of the inner tube.

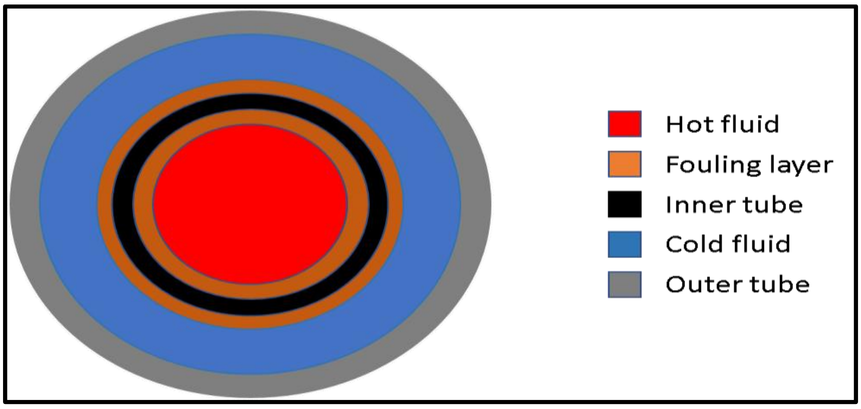


Figure 1. Schematic diagram of the heat exchanger tubes and fouling layers and thickness

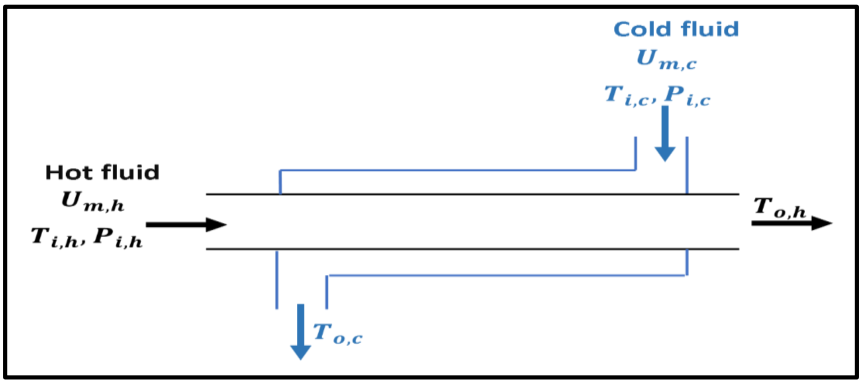


Figure 2. Counter flow arrangement for hot and cold fluids with their defined parameters of temperatures, pressures and overall heat transfer coefficients

Figure (2) shows the counter flow arrangement for hot and cold fluids in the heat exchanger with their defined parameters of temperatures, pressures and overall heat transfer coefficients.

Referring to Figure (3), the inner and outer heat transfer surface area for the system could be determined based on the geometry and dimensions of the heat exchanger tubes. Here, D_i and t_i are the inner tube diameter and thickness, while D_o and t_o are the outer tube diameter and thickness respectively and they can be symbolized as follows:

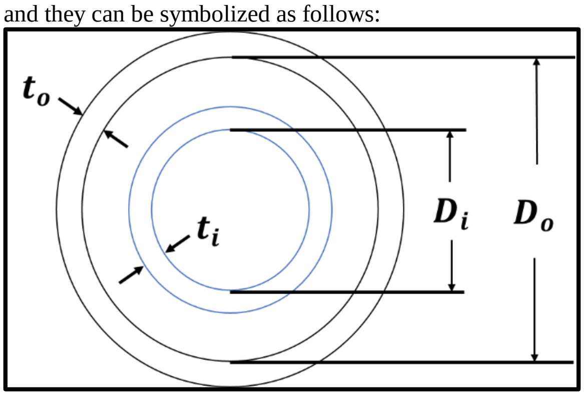


Figure 3. Cross-sectional view of the system, D_i is the inside diameter, D_o is the outside diameter, t_i is the thickness of inside tube and t_o is the thickness of outside tub

4. The heat rate of the heat exchanger or heat exchanger outcome(Q)

The heat rate of heat exchanger (Q) is the amount of useful heat transfer from the hot working fluid to cold working fluid within the heat exchanger in the unit of (W) according to the equations (1).

$$Q = \mathrm{U}\ \mathrm{A}\ \Delta T_{LMTD} \quad (1)$$

Where U is the overall heat transfer coefficient in the unit of (W/m^2K) as explained in equations (2) and (7 & 8), A is the surface area of heat transfer in (m^2) as demonstrated in equation (6) where D_o is the diameter of the cold fluid pipe as shown in figure (2), and ΔT_{LMTD} is the logarithmic mean temperature difference in (K) or (°C) as explained in equation (3).

$$\mathrm{U} = \mathrm{Q/A}\ \ \Delta T_{LMTD} \quad (2)$$

$$\Delta T_{LMTD} = \frac{\Delta T_1 - \Delta T_2}{Ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \quad (3)$$

Where ΔT_1 is the temperature difference between the inlet temperature of hot fluid (T_{hi}) and the outlet temperature of the cold fluid (T_{co}) at the inlet of the heat exchanger as explained in equation (4), while, ΔT_2 is the temperature difference between the outlet temperature of hot fluid (T_{ho}) and the inlet temperature of the cold fluid (T_{ci}) at the outlet of the heat exchanger as explained in equation (5), and (A) is the surface area of heat transfer and (L) is the heat exchanger length according to equation (6).

$$\Delta T_1 = T_{hi} - T_{co} \quad (4)$$

$$\Delta T_2 = T_{ho} - T_{ci} \quad (5)$$

$$A = 2\pi\ D_o L \quad (6)$$

Also, the heat transfer rate (Q) could be evaluated for both hot and cold working fluids (Q_c and Q_h) using equations (7 and 8)

$$Qc = \dot{m}_h cp_h (T_{h,i} - T_{h,o}) \quad (7)$$

$$Qh = \dot{m}_c cp_c (T_{c,o} - T_{c,i}) \quad (8)$$

Where ($\dot{m}_h$) and ($\dot{m}_c$) are the mass flow rates of hot and cold fluids respectively in (kg/s), (C_p) is the specific heat coefficient in (J/kg K), ($T_{h,i} - T_{h,o}$) and ($T_{c,o} - T_{c,i}$) are the temperature differences of both hot and cold fluid, respectively.

5. Fouling formation and fouling Index (FI)

Fouling factor is the related added thermal resistance to the heat exchanger because of gradual chronicle fouling deposits on both inside and outside surfaces of the tubes of the heat exchanger (R_{di} and R_{do}) [16, 17]. The increase of this fouling factor will lower the overall heat transfer coefficient (U) and hence badly affect the heat exchanging rate of the heat exchanger (Q) and lower its effectiveness (Ɛ). The thermal resistance of fouling (R_{fl}) means extra thickness of the heat exchanger tube and hence negatively affected the heat exchanging inside the heat exchanger [18, 19]. This fouling thermal resistance ($R_{th\text{-}f}$) could be expressed according to the equation (9), while the fouling factor (R_{di}) is related to the thermal resistance of fouling (R_{th-f}) as explained in equation (10), and the fouling index (FI) equal the fouling factor (R_{di}) according to equations (11)and (15). Here (t_f) is the tube wall thickness after fouling, (k_f) is the thermal conductivity and (A_f) is the surface area of the same tube, while (t), (k) and (A) are those of clean tube before fouling.

$$\mathrm{R_{th-f}} = (\mathrm{t_f}/\mathrm{k_f}\mathrm{A_f}) = \quad 1/\mathrm{U_f A_f} \quad (9)$$

$$\mathrm{R_{di}} = (\mathrm{R_{th-f}}\mathrm{A_f}) = \ (\mathrm{t_f}/\mathrm{k_f}\mathrm{A_f})\ \mathrm{A_f} \quad (10)$$

$$\mathrm{JF} = \mathrm{R_{di}} = 1l\ \mathrm{U_f} – 1/\mathrm{U} = \mathrm{A_f}/\mathrm{R_{th-f}}\ - \mathrm{A}/\mathrm{R_{th}} = (\mathrm{t_f}/\mathrm{k_f}) - (\mathrm{t}/\mathrm{k}) \quad (11)$$

6. Clean and dirty heat transfer coefficient (Uclean and Udirty)

The overall heat transfer coefficient (U_{clean}) is the normal value of the heat transfer coefficient in the units of (W/m^2 K) before fouling builds up when the heat exchanger is new at the beginning of the operation, this coefficient is expressed according to the equation (12). Here. h_i and h_o are the convection heat transfer coefficients in (W/m^2 K) for both hot and cold fluids respectively. On the other hand, the dirty heat transfer coefficient U_{dirty} is the value of the overall heat transfer coefficient after fouling occurred in the same units of (U_{clean}). Moreover, the dirty overall coefficient (U_{dirty}) due to inside and outside fouling are expressed according to equations (13) and (14) respectively [20, 21].

$$U_{clean} = \left(\frac{1}{h_i} + \frac{1}{h_o}\right)^{-1} \quad (12)$$

$$\frac{1}{U_{dirty}} = \frac{1}{U_{clean}} + \mathrm{R_{di}} + \mathrm{R_{do}} \text{ (For inside and outside fouling)} \quad (13)$$

$$\frac{1}{U_{dirty}} = \frac{1}{U_{clean}} + \mathrm{R_{di}} \text{(For inside fouling only)} \quad (14)$$

Based on the above analysis and according to equations (9-14) the fouling index (FI) could be expressed as shown in equation (15). As a result of fouling, the thermal outcome of the heat exchanger is lowered from a higher rate (Q_{clean}) to a lower rate ($Q_{fouling}$) as explained in equations (16 and 17). Consequently, the effectiveness of the heat exchanger is reduced from clean effectiveness (ε_{clean}) to a lower one due to fouling ($\varepsilon_{fouling}$) as explained in equations (18 and 19).

$$FI = R_d = \frac{1}{U_{dirty}} - \frac{1}{U_{clean}} = A_f / R_{th-f} - A / R_{th} = (t_f/k_f) - (t/k) \quad (15)$$

$$Q_{clean} = U_{clean}\, A\, \Delta T_{LMTD} \quad (16)$$

$$Q_{fouling} = U_{dirty}\, A\, \Delta T_{LMTD} \quad (17)$$

$$\varepsilon_{clean} = Q_{clean}/Q_{max} \quad (18)$$

$$\varepsilon_{fouling} = Q_{fouling}/Q_{max} \quad (19)$$

The maximum possible heat rate of the heat exchanger (Q_{max}) is represented in equation (20), where $(\dot{m}\ cp)_{min}$ is the minimum thermal capacity of one fluid among the two working fluids which one has the smallest value and then the other has the largest one as demonstrated in equation (21). Moreover, T_{hi} is the inlet temperature of the hot fluid, while T_{ci} is the inlet temperature of the cold fluid for the heat exchanger.

$$Q_{max} = (\dot{m}\ cp)_{min}(T_{hi} - T_{ci}) \quad (20)$$

$$(\dot{m}\ cp)_{min} = C_{min} = \text{Minimum thermal capacity for one fluid} \quad (21)$$

Basically, the fouling factor or fouling index (FI) is the scaling factor that accounts for the effect of chronic fouling in the heat exchanger due to the deposit of minerals, salts, impurities, and scales on its solid surfaces of heat exchanger [20, 21].

7. Concept and logic of simulation

The developed mathematical model of fouling in heat exchangers designates several influential parameters that govern fouling formation. These include the type of working fluids, the geometry and structural design of the heat exchanger, the construction materials and their thermal and physicochemical properties, as well as the operation conditions such as temperature and pressure of working fluids within the heat exchanger [22, 23, 24, 25]. The formatting steps of fouling effects may be logically arranged as follows:

1. The new heat exchanger normally started working without any fouling and is working with a clean overall heat transfer coefficient (U_{clean}), clean heat transfer rate (Q_{clean}), and maximum effectiveness (ε_{clean})
2. After a few months of working, fouling starts to initiate and form scale and deposits inside the heat exchanger with fouling factor (R_d)
3. The fouling scales increase the thickness of the tube surfaces and hence increase the thermal resistance within the heat exchanger tubes(R_{th})
4. Fouling strongly affects the thermal resistance of the heat exchange surfaces inside the heat exchanger and hence the overall heat transfer coefficient
5. The change in thermal resistance of the tubes will severely affect the convection heat transfer coefficient within the heat exchanger (h) and as a result, the overall heat transfer coefficient (U) will be changed from (U_{clean}) to ($U_{dirty,}$)
6. The change in the value of the convection heat transfer coefficient within the heat exchanger (h) will affect the value of Nusselt number (Nu), where Nu= h D/k_f, D is tube diameter and k_f is the thermal conductivity of the working fluid [26].
7. The clean overall heat transfer coefficient (U_{clean}) will be affected by fouling and minimized to be a dirty overall heat transfer coefficient ($U_{dirty,}$)
8. Fouling also critically affects both the surface area and cross-section areas of the tubes inside the heat exchanger, and this will sizably affect the mass flow rate of the working fluid ($\dot{m}$)within the heat exchanger [24]. The change in fluid mass flow rate will affect the Reynolds number (Re) of the working fluid under consideration [25], where Re= ρVD/μ=4 $\dot{m}$/πDμ, here ρ is the fluid density, V is flow velocity, μ is fluid dynamic viscosity [27].
9. Comparatively, the dirty overall heat transfer coefficient ($U_{dirty,}$) is less than the clean overall heat transfer coefficient (U_{clean}) at a rate proportional to the rate of fouling and fouling factor (R_d) as explained in equation (13&14) [28].
10. Due to the lowering of the overall heat transfer coefficient (U), and the mass flow rate area (A), the total heat exchange rate (Q) and the effectiveness of the heat exchanger (ε) will decline accordingly [29].
11. Based on the above functional analysis, it is essential to control fouling formation in heat exchangers to minimize its impact, thereby enhancing heat exchanger effectiveness and achieving higherthermal outcome.

All relevant parameters are incorporated to investigate the impact of fouling on the thermal performance of heat exchangers through both mathematical and simulation models. The simulation model was developed analytically using the parametric equations of the mathematical model and implemented in MATLAB® software. The simulation workflow is illustrated in Figure (4), and the ranges of numerical values of parameters are listed in table (1). This model is then used to analyze the influence of various thermal, hydrodynamic, and design parameters on the fouling formation rate, as discussed in the following analysis section.

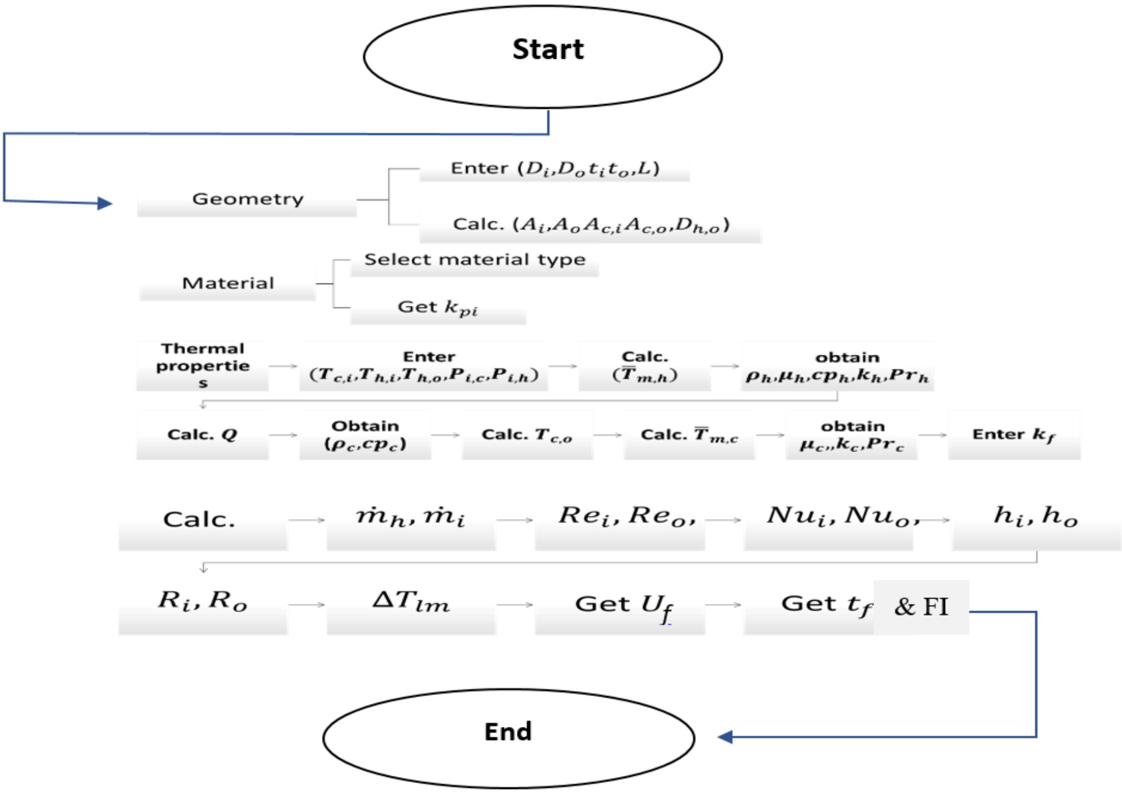


Figure 4. Simulation flow chart of effective parameters for fouling in heat exchanger

Table 1. Ranges of Numerical Valuesof Simulated Effective Parameters

No.	Parameters	SI Units	Numerical values Range	Note
1	Heat exchanger length (L)	m	0.5-5	
2	Inside diameter of tube (ID)	m	0.01-0.07	
3	Outside dimeter of tube (OD)	m	0.08-0.10	
4	Cold fluid temperature T_c	ºC, K	10-40	
5	Hot fluid temperature T_c	ºC, K	65-125	
6	Fluid density (ρ)	Kg/m^3	1.20-1000	**
7	Fluid dynamic viscosity (μ)	Pa-s	$1.8x10^{-5}$-$1.3x10^{-3}$	**
8	Fluid thermal diffusivity (α)	m^2/s	$11x10^{-6}$-$90\ x10^{-6}$	**
9	Fluid specific heat (C_p)	J/kg K	1000-4190	**
10	Fluid thermal conductivity (k)	W/m K	0.025-0.7	**
11	Prandtl number (Pr)	Dimensionless	0.6-7	**
	According to the type of working fluid			

8. Results and Discussion

The effect of various parameters on fouling formation in heat exchangers was analyzed to assess their roles and relative contributions. These parameters include the thermomechanical properties of the working fluids, operational conditions such as the inlet temperatures of the hot and cold working fluids, and the types of fluids used. The thermomechanical properties considered in the study are specific heat capacity (Cp), thermal conductivity (k), thermal diffusivity (α), Prandtl number (Pr), where Pr = ν/α (momentum diffusivity divided by thermal diffusivity), fluid density (ρ), and dynamic viscosity (μ).

8.1. Effects of Thermomechanical Properties of Working Fluids on Fouling Index (FI)

8.1.1. Impact of Thermal Properties - Specific Heat, Thermal Conductivity, Thermal Diffusivity, and Prandtl Numberon Fouling Index

The influence of thermal and mechanical properties of working fluids on the fouling index (FI) in heat exchangers was examined, and the simulation results are presented in Figures (5) to (15). The properties considered include specific heat capacity (Cp), thermal conductivity (k), thermal diffusivity (α), Prandtl number (Pr), fluid density (ρ), and dynamic viscosity (μ). Moreover, the impact of the inlet temperatures of the cold and hot fluids (Tci and Thi) was studied for two types of working fluids: water and air, through three heat exchanger tube geometries: circular, elliptical, and square, as illustrated in Figures (12) to (15).

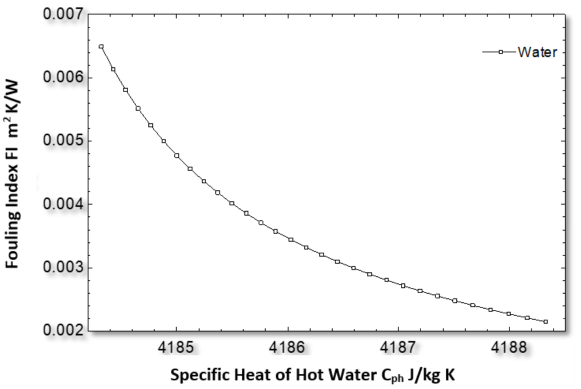


Figure 5. Effectsof the specific heat of water(C_{ph})on the fouling index (FI) in heat exchanger

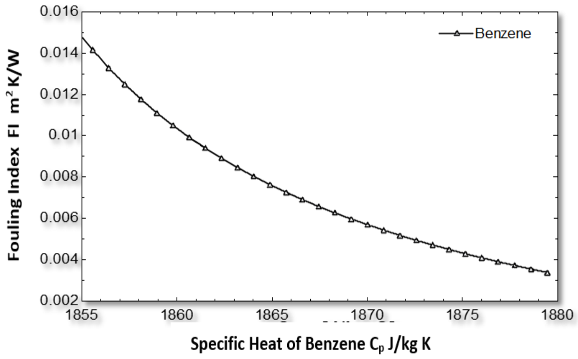


Figure 6 (A). Impact of the specific heat of benzene fouling index (FI) in heat exchanger

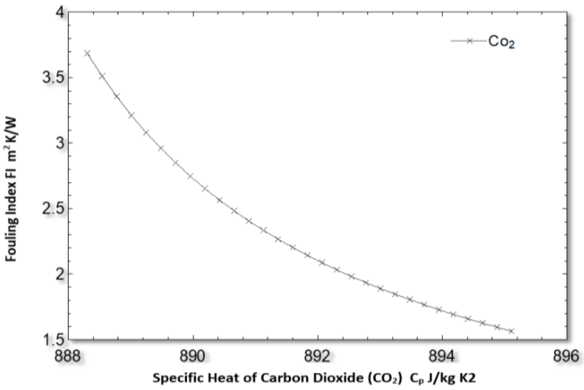


Figure 6 (B). Influence of the specific heat of carbon onon the (C_{ph}) on the fouling index (FI) in heat exchanger

Figures (5)and (6)show the Effects of the specific heat of water, benzene, and carbon dioxide on the fouling index in the heat exchanger respectively, it could be noted that the increase of the fluid's specific heat lowers the fouling index in inverse relation as explained in the three figures. This behavior could be explained by the role of specific heat increase in the enhancement of thermal potential and heat transfer rate (equations 7 and 8) of working fluids which minimize the tendency of sedimentation rate of dissolved mineral salts in the working fluids, and hence lower the chance for fouling formation within the tubes of heat exchangers. However, the highest fouling index is associated with carbon dioxide at an FI range of (3.85-1.55) m^2 K/W,then benzene at an FI range of (0.0168 - 0.0022) m^2 K/W, while the lowest fouling index is related to water with a range of (0.0065-0.002) m^2 K/W at the same operating conditions of the heat exchanger. These different ranges of fouling index are due to the physiochemical structures and behaviors in addition to the thermal properties of the working fluids. Generally, organic material has a higher tendency for fouling than inorganic one, also the gaseous working fluid has a higher ability to produce fouling than liquid one as shown in Figures (5 and 6).

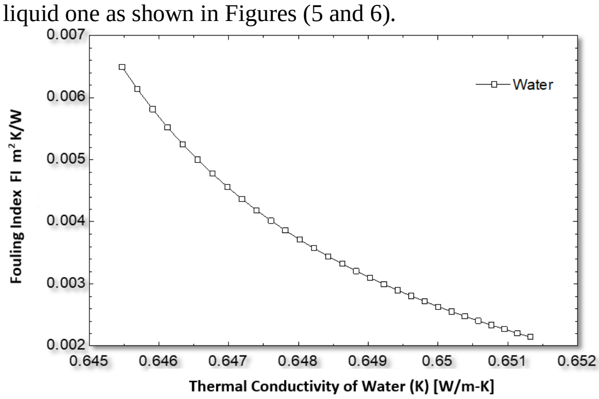


Figure 7. Effects of the thermal conductivity of the water (k)on the fouling index (Fi)

The effect of thermal conductivity (K) of hot fluid (water) has the same trend as that for specific heat (C_p) as shown in Figure (7) but with a steeper drop in the fouling index as the thermal conductivity increases, while the rise of specific heat has an asymptotic reduction in the fouling index for higher values of (C_p). The thermal conductivity (k) of both solids and liquids increases with temperature, and this increase will enhance the heat transfer rate between the hot and cold fluid of the heat exchanger, therefore the propensity for fouling will be reduced. These results indicate the effect of thermal conductivity (k) has a slightly higher rate on reducing the fouling index than that of specific heat (C_p) for the same working fluids.

The thermal diffusivity (α) is an important parameter that determines and controls the thermal attitude and activity of materials to transfer heat through any thermal applications, like heat exchanger processes. In specific, thermal diffusivity (α)can be defined as the ratio between the thermal conductivity of the material (k) to the product of the material density (ρ) and its specific heat (C_p), (i.e., $\alpha = k / \rho C_p$). Also, this parameter indicates the ability of a material to diffuse heat to the surroundings. Accordingly, higher temperature leads to higher thermal conductivity for the working fluid as the temperature rise will increase both thermal conductivity and specific heat of the working fluid, with a fluid density reduction. This is, in turn, affects the thermal diffusivity, and so the fouling index behaves similarly to that of the thermal conductivity and specific heat [30] as shown in Figure (8).

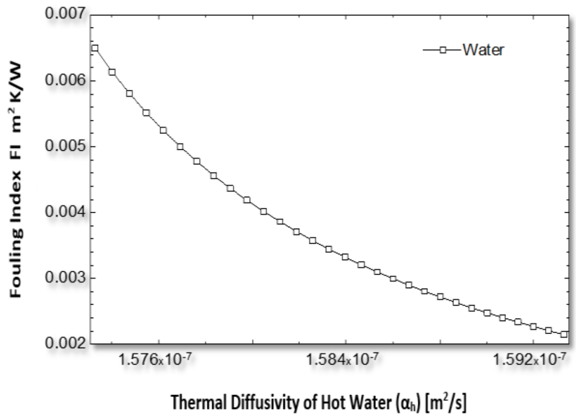


Figure 8. Impact of the thermal diffusivity of hot water (α_h) on the fouling index (FI)

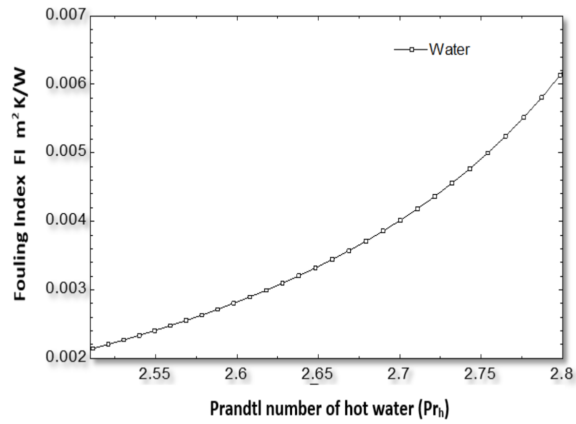


Figure 9. Influence of the Prandtl number (Pr) of the hot water on the fouling index (FI)

As another indication of the thermal behavior of the working fluids, the Prandtl number (Pr) stands to indicate the ratio between the viscous diffusivity (ν) and the thermal diffusivity (α) as Pr= ν/α. The effect of this number on the fouling index is investigated for hot water as a hot working fluid in the heat exchanger and the results are presented in Figure (9). The results show that the Prandtl number has an opposite effect on the fouling index, and it has an inverse behavior to that of thermal diffusivity as shown in the figure (9). This could be clarified as the temperature increases the thermal diffusivity increases as a result, while the kinematic viscosity () reduces, and these both results minimize the chance for fouling to occur. Also, the increase in the value of the Prandtl number enhances the value of the Nusselt number (Nu) which enhances the convection heat transfer and hence the working fluid ability for fouling. Here Nu = h D/k_f, where h is the convection heat transfer coefficient of working fluid, D is tube diameter and k_f is the thermal conductivity of the working fluid.

8.2. Effects of Mechanical Properties: Effects of Fluids Density and Viscosity on Fouling Index

Figures (10) and (11) represent the effects of hot fluid density (ρ) and viscosity (μ) on the fouling index respectively. Both effects have the same direction as the increase in both values of density and viscosity enhances the fouling index because both parameters has an inverse relation to the temperature rise for liquids. Also, the increase of viscosity enhances the adverse viscous effect of fluid which retard the flow velocity and enable for a higher chance of fouling as shown in Figure (8). Furthermore, the increase in density occurs as the fluid temperature decreases, also. This increases the viscosity and thus leads to the progress of the inertia of working fluid and slightly slows down the flow motion rate [30], therefore the fouling index increases. The effect of fluid viscosity is more dominant than that of fluid density in the fouling formation, as the viscous effect is related to opposing shear stress, which enables a higher possibility of fouling.

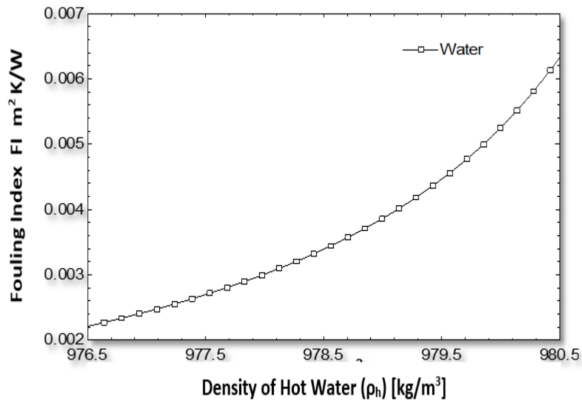


Figure 10. Effect of the density of the hot water (ρ_h) on the fouling index (FI)

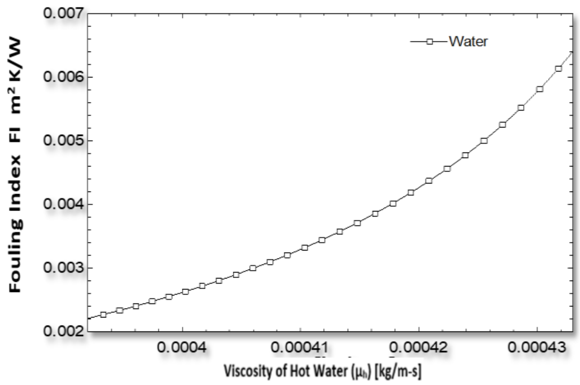


Figure 11. Impact of the viscosity of hot water (μ) on the fouling index (FI)

8.3. Effects of Operating Temperature and Cross-Sectional Area of Heat Exchanger Tubes on Fouling Index

The effects of inlet temperatures of both cold and hot fluids (T_{ci} and T_{hi}) on fouling index under three different tubes of circular, elliptical, and square cross-sectional area as elucidated in Figures (9) and (10) for water and through Figures (11) to (12) for air.

Figure (12) represents the effect of the water temperature increase as a hot fluid inside the heat exchanger on the fouling index. It is noted that a higher inlet temperature of hot water leads to a lower fouling index. The increase in inlet temperature (Thi) leads to a rise in specific heat (Cp) and thermal conductivity (k), also providing a lower viscosity of the working fluids. All of these factors minimize the tendency of falling and then lowering the fouling index (FI) as shown in Figure(12). However, the same result was obtained through the increase of the cold water as shown in Figure (13), but with a higher fouling index range for cold water, as it has a lower inlet temperature than the hot water for all cross-sectional area types of heat exchanger tubes, as illustrated in both figures (12) and (13).

Furthermore, figures (12) and (13) elucidated that the minimum fouling index is related to the elliptical tube at a fouling index range of (0.0052-0.0025) m^2 K/W, then the circular one at a fouling index range of (0.0065-0.0035) m^2 K/W,while the highest fouling index rang of (0.017 -0.006) m^2 K/Woccurs for the square tubesfor hot water and (0.025-0,010) m^2 K/W for hot water. On the other hand, higher fouling index ranges could be noted for the three types of tubes for cold water as explained in Figure (10)

This could be explained by knowing that for the same cross-sectional area, the equivalent diameter of the elliptical shape is higher than for both circular and square shapes. A higher equivalent diameter means higher Reynold's number and lower friction factor (as could be noted in Moody chart), and hence lower head losses and less pressure drop through the heat exchanger [31]. These factors lead to minimizing the fouling rate for elliptical tubes, and they are suggested for use based on this point.

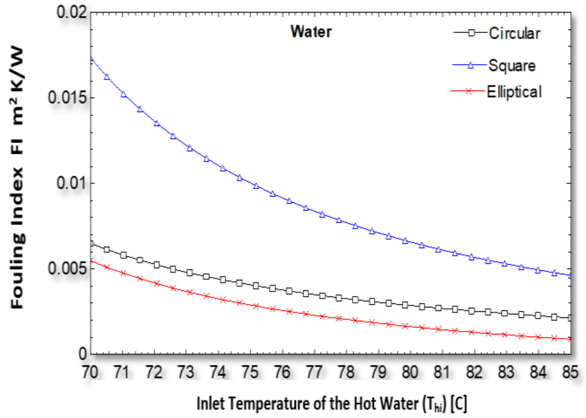


Figure 12. Influence of inlet temperature of the hot water (T_{hi}) on the fouling index (FI) for circular, elliptical, and square cross-sectional area of heat exchanger tubes

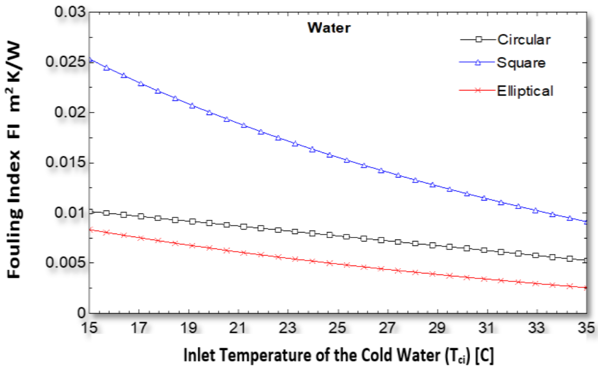


Figure 13. Effects of inlet temperature of the cold water (T_{ci}) on the fouling index (FI) for circular, elliptical, and square cross-sectional area of heat exchanger tubes

As the fluid is replaced from water to air while the other parameters kept the same, the effect of the temperature increase also leads to a lower fouling index as shown in figures (14) and (15). For the same input velocity, the mass flow rate for water is much higher than for air due to the lower density of air. Also, the specific heat of water is higher than of air. These are the main properties that are responsible for the high fouling index for air compared with water. Also, the suspended materials in a gaseous medium (air) is easier to fall and accumulate to provide fouling in the tubes. The cohesion forces of water is much more than those of air, and the viscosity of gases (air) increases with temperature rise, while the opposite occurs for liquids (water), and this explains the higher fouling rates of air than those of water for both cold and hot temperatures as can be noted through Figures (12-15).

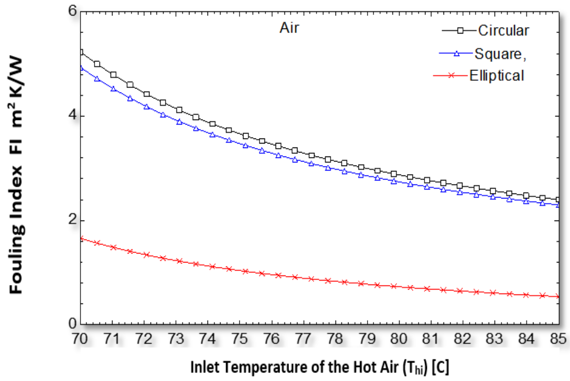


Figure 14. Impact of inlet temperature of the hot air (T_{hi}) on the fouling index (FI) for circular, elliptical, and square cross-sectional area of heat exchanger tubes

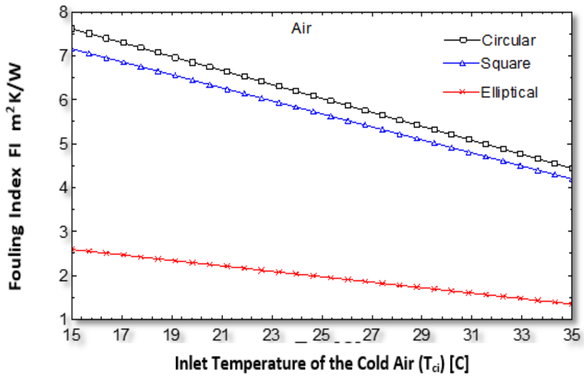
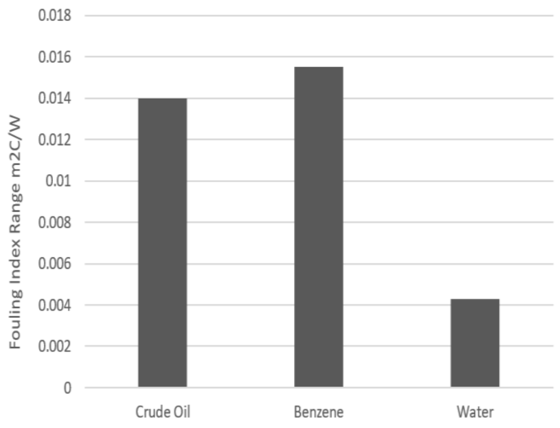


Figure 15. Influence of inlet temperature of the cold air (T_{ci}) on the fouling index (FI) for circular, elliptical, and square cross-sectionalareas of heat exchanger tubes

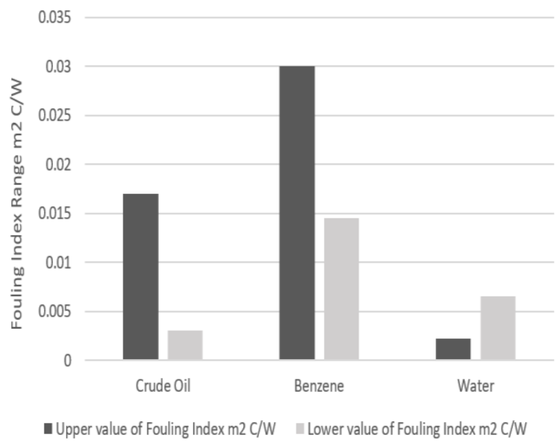
Moreover, Figures (14) and (15) show that the lowest fouling index range is associated with elliptical tubes, while a reasonably higher fouling range is related to circular and square tubes at relatively near values for air as working fluid. The fouling index range for elliptical tubes is (1.8-0.8)m^2 K/W, and (5.4-2.8)m^2 K/W for circular tubes, while (5.2-2.6)m^2 K/W for square tubes for hot air as shown in Figure (15). Nevertheless, the fouling ranges are higher for cold air as explained in Figure (14). Purposely, these fouling ranges are much more than those of water, so it is better to use water as a working fluid rather than air because of their diverse relative ability for fouling, and due to their different thermal and mechanical properties that affect their tendency for fouling.

9. Validation of Simulation Model

The present simulation model was used to study fouling approach for several working fluids, which include cold and hot water, air, benzene and carbon dioxide. The fouling index range for all these fluids are determined and presented as above. As a validation for this simulation, the results of this model are compared with published experimental results by Ikram K. et al, 2024 (19). The simulation fouling index ranges in ($m^{2o}C/W$) for benzene and water are linked to that of crude oil, which is experimentally determined. The simulation fouling index range of benzene was (0.0145-0.03= 0.0155) $m^{2o}C/W$, while that of water was (0.0022-0.0065= 0.0043) $m^{2o}C/W$ and the experimental fouling index range of crude oil was (0.003-0.017= 0.014) $m^{2o}C/W$. Figure (16) shows the comparisons for fouling ranges of the three fluids in figure 1(6-A), and for both upper and lower limits of fouling range in figure 1(6-B). Obviously, the model results for benzene and crude oil are closed to each other as both fluids are organic and they have nearly close thermal properties. This indicates the ability of this simulation model to draw precise predictions and effective simulation. Moreover, figure (16) shows that water exhibits a lower fouling index range compared to organic fluids due to its comparatively lower density and viscosity, as well as its relatively lower tendency for fouling. This supports the real validity of the model.



(A)



(B)

Figure 16. Validation of simulation results for benzene and water by experimental data of crude oil by Ikram K. et al, 2024 [19]

10. Conclusions

A parametric simulation study was conducted to investigate the effects of thermomechanical properties of working fluids, operating temperatures, phase of the working fluid, and tube sectional-area changes on fouling in heat exchangers, using circular, elliptical, and square tubes. Many valuable results were produced and presented to reveal the best method to minimize and control the fouling in heat exchangers and to enhance their thermal performance in industrial and engineering applications. Consequently, numerous conclusions can be drawn from these new findings. Firstly, the higher thermal properties and temperatures of working fluids enable for lower tendency for fouling. The fouling index for hot water was less than that of benzene by 99.81% and lower than that of carbon dioxide by 61.11% due to their various specific heats and thermal conductivity, as temperature gain enhances specific heat, thermal conductivity, and thermal diffusivity of working fluids The rise in temperatures of working fluid has lowered the fouling index by 40% for both square and circular tubes, while it was 36.58% for elliptical tubes. Also, the increase in operating temperature reduces both the density and viscosity of fluids, and this minimizes the chance for fouling by 64.51% and 67.65% respectively. This suggests to useof working fluids of relatively high specific heat, high thermal diffusivity, low viscosity, and low Prandtl number. Secondly, liquids working fluids like water yield a lower fouling rate than gaseous fluids like air. Thirdly, the geometrical shape of the tubes inside the heat exchanger strongly affects the fouling rate for both liquids and gaseous fluids. The lowest fouling rate occurred with elliptical tubes for hot water at 12.12% against circular tube and by 66.58% versus square tube. While the case of hot air, the dropping of fouling rate for elliptical tube was more at a percentage of 66.66% beside circular tubes and 63.38% against square tubes. However the highest fouling rate was associated with square tubes for cold water at a fouling index range of (0.025-0.012) m^2 K/W, and at (7.8-5.2) m^2 K/W for cold air in circular tubes. These new findings strongly recommend that elliptical tubes should be technically implanted in the heat exchanger industry and other related thermal applications due to their low relative ability to provide fouling. This study has covered many factors and parameters of fouling, but it could be extended to investigate the transient nonsymmetrical fouling for 2D and 3D conditions, also, the interactions and tendency of other working fluids for fouling and other tubes materials may be inspected.

Declaration of conflicting interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Abdullah A. Alshormanhttps://orcid.org/0000-0001-9672-3139

Citation diversity

The author agrees and supports the application of the citation diversity in this scientific work

References

[1] M. A. Kartal, Contamination in Heat Exchangers: Types, Energy Effects and Prevention Methods, IgMin Research In Engineeering, July 03, 2(7), 2024, pp. 503-507,

[2] DOI: 10.61927/igmin209; Available at: igmin.link/p209

[3] J. Sansana et al., Hybrid Approach for Advanced Monitoring and Forecasting of Fouling with Application to an Ethylene Oxide Plant, Ind. Eng. Chem. Res. 63, 2024, pp. 10666−10676, https://doi.org/10.1021/acs.iecr.4c00298,

[4] B. Akindade et al., Investigation of the Effects of Fouling And Pitting Corrosion on The Efficiency of Plate Heat Exchangers, JREAS, Vol. 09, Issue 03, July 2024

[5] S. K. Ogbonnaya, and O. Ajayi,Fouling Phenomenon And Its Effect On Heat Exchanger: A Review, Frontiers in Heat and Mass Transfer (FHMT), 9, 31, 2017, DOI: 10.5098/hmt.9.31

[6] Zaza A. et al., Fouling Mitigation on Different Heat Exchanging Surfaces Materials Used in the Hybrid Cooling Tower Test Facility, AIP Conference Proceedings 2126, 080007, 2019, https://doi.org/10.1063/1.5117602 2126

[7] Zou K. et al., Study on dynamic measurement of fouling thermal resistance in a boiler, IOP Conf. Series: Materials Science and Engineering 721, 2020 012013, doi:10.1088/1757-899X/721/1/012013

[8] W. Xiaoa et al., Heat Exchanger Reliability Analysis Based on Fouling Growth Model by Fault Tree Analysis, Chemical Engineering Transactions, 76, 2019, pp, 265-270, DOI:10.3303/CET1976045

[9] Jradi R., Marvillet C., and Jeday M. R., Estimation and sensitivity analysis of fouling resistance in phosphoric acid/steam heat exchanger using artificial neural networks and regression methods, Scientific Reports, 13:17889, 2023 https://doi.org/10.1038/s41598-023-44516-6

[10] T. Kah Houet al., Industrial Heat Exchanger: Operation and Maintenancet o Minimize Fouling and Corrosion, Heat Exchangers– Advanced Features and Applications, 2017, pp. 193-207, ,http://dx.doi.org/10.5772/66274

[11] Ebieto, C.E and Eke G.B., Performance Analysis of Shell and Tube Heat Exchangers: A case study, Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS), 3(5), 2012, pp, 899-903.

[12] Wallhäußer E., Hussein M. A., and Becker T., Clean or not clean - Detecting fouling in heat exchangers, AMA Conferences 2013 - SENSOR 2013, OPTO 2013, IRS 2 2013, DOI 10.5162/sensor2013/A5.4

[13] Incropera, F., DeWitt D., Bergman T. , Lavine A. , Fundamentals of Heat and Mass Transfer, John Wiley & Sons, Inc., 6th edition, 2007, USA

[14] Janna, W. S., Design of Thermal Systems, PWS Publishing Company, 2nd edition, 2002, USA

[15] Hicks, T.G., Hicks, S. D., and Leto, J., Standard Handbook of Engineering Calculations, 3rd Edition, McGraw-Hill, Inc., 1995, USA

[16] V. Vasauskas, and Baskutis S., Failures and fouling analysis in heat exchangers, MECHANIKA. Nr.5(61), 2006

[17] Chudý D., Jegla Z., Perspective Ways of Heat Transfer Enhancement For Heat Exchangers in Fouling Conditions, 30th International Conference ENGINEERING MECHANICS 2024, Milovy, Czech Republic, May 14 – 16, 2024

[18] Aselmeyer F. et al., An Experimental Approach to Overcome the Fouling Issue in Micro Heat Exchangers, Chem. Ing. Tech., 96, No. 10, , 2024, pp, 1394–1403

[19] DOI: 10.1002/cite.202400012

[20] D. Pretoro., F. D'Iglio, and F. Manenti. Optimal Cleaning Cycle Scheduling under Uncertain Conditions- A Flexibility Analysis on Heat Exchanger Fouling, Processes, 9, 93, 2021https://doi.org/10.3390/pr9010093

[21] Ikram K. et al., Comparative analysis of fouling resistance prediction in shell and tube heat exchangers using advanced machine learning techniques, Research on Engineering Structures & Materials 10(1),2024, pp, 253-270,

[22] Weber C. et al., Analysis of different fouling predictive models in a heat exchanger from experimental data, The 29th International Conference on Efficiency Cost Optimization, Simulation And Environmental Impact of Energy System, June 19-23, Slovenia, 2016

[23] J. Wang et al., Prediction Model of Fouling Thickness of Heat ExchangerBased on TA-LSTM Structure, Processes, 11, 2594, 2023, https://doi.org/10.3390/pr11092594

[24] S. Emani, et. al., Crude Oil Fouling in Heat Exchangers: A Study on Effects of Influencing Forces, E3S Web of Conferences, 287, 03003, PP. 1-6, 2021, https://doi.org/10.1051/e3sconf/202128703003

[25] Bevas C., et al., Industrial scale fouling of heat exchangers in isocyanate

[26] Production, Surface and Interface Analysis;56, 2024, pp, 308–318, DOI: 10.1002/sia.7292

[27] Bell I. H., et al., Experimental Analysis of The Effects of Practical Fouling Heat Exchanger Heat Transfer And Air Side Pressure Drop for A Hybrid Coolar, International Conference on Heat Exchanger Fouling and Cleaning VIII, June 14-19, 2009, Austria

[28] N. Hussami, H. Al-Haj Ibrahim, and A. Safwat, Modelling of fouling in heat exchangers using the Artificial Neural Network Approach, International journal of Chemistry, Mathematics and Physics (IJCMP) [Vol-2, Issue-5, Sept-Oct, 2018, pp. 33-52, https://dx.doi.org/10.22161/ijcmp.2.5.1

[29] S. Sundaret al., Fouling Modeling and Prediction Approach for Heat Exchangers using Deep Learning, International Journal of Heat and Mass Transfer, Volume 159, October 2020, 120112

[30] Budiati T., and Biyanto T. R., Optimization of Design Heat Exchanger to Reduce

[31] Fouling Resistance in Milk Pasteurization, IOP Conf. Series: Earth and Environmental Science 207 (2018) 012004, IOP Conf. Series: Earth and Environmental Science 207 2018, 012004

[32] J. Loyola-Fuentes, M. Jobson, and R. Smith, Estimation of Fouling Model Parameters for Shell-side and Tube-side of Crude Oil Heat Exchangers Using Data Reconciliation and Parameter Estimation, Industrial & Engineering Chemistry Research, 2019, https://doi.org/10.1021/acs.iecr.9b00457

[33] E. Diaz-Bejaranoet al., Modeling and Prediction of Shell-Side Fouling in Shell-and-Tube Heat Exchangers, HEAT TRANSFER ENGINEERING, VOL. 40, NO. 11, 2019, pp. 845–861.

[34] Hou T. K., et al., Industrial Heat Exchanger: Operation and Maintenance to Minimize Fouling and Corrosion, Heat Exchangers– Advanced Features and Applications, INTECH 2017

[35] A. Alshorman, L. A. Al-Samrraie and K, A. Alrawashdeh, Analysis of Effect of Piping Geometrical Shape on Major Head Losses, Jordanian Journal of Engineering and Chemical Industries (JJECI),Vol.5 No.3, 12, 2022