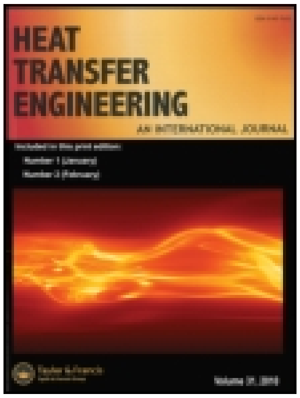

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Experimental Study of Fouling Resistance in Twisted Tube Heat Exchanger

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This paper discusses fouling of a twisted tube heat exchanger under different conditions of fluid velocity and heat input. The fluid velocity was varied from 0.5 to 2.0 m/s, whereas the heat input to the heat exchanger was varied from 200 to 800 W. The experimental results show that for low fluid velocity of 0.5 m/s, the fouling resistance showed noticeable variation with respect to heat input, whereas for high velocity ranges, that is, 1.0–2 m/s, the variation in fouling resistance is less. The fouling in twisted tube steadily increases with time for different values of heat input from 1000 min onward for fluid velocity in the range from 1.0 to 2.0 m/s. It is also observed that fouling resistance curves overlap for various values of heat input. During the initial 1000 min of the test duration, the maximum fouling in a twisted tube heat exchanger decreases with increase in fluid velocity from 1.0 to 2.0 m/s. This behavior of the fouling rate can be attributed to the fact that at higher fluid velocity, flow becomes turbulent, and this in turn flushes the fouling particles. The time-series correlations for the fouling resistance are found to be logarithmic in nature.

INTRODUCTION

Heat-exchanger fouling causes a major economic drain on industries today. In most industrialized countries these losses amount to around 0.25 to 0.30% of the gross national product. Costs associated with exchanger fouling are reflected in over-sizing of the heat exchangers, leading to not only the incremental capital and installation costs but also the operation, maintenance, and downtime costs, adding up to a staggering 2.5 to 3.0 times the initial purchase price of heat exchangers. More than 35–40% of heat exchangers employed in global heat transfer processes are of the shell-and-tube type. This is primarily due to the robust construction geometry as well as ease of maintenance and upgrades possible with shell-and-tube heat exchangers.

Fouling of heat-exchanger tubes happens due to several mechanisms, such as particulate, corrosion, chemical reaction, etc. Fouling tends to increase over time. According to a hypothesis presented by Taborek et al. [1] and later confirmed by Hasson in his review article [2], the scale grows linearly with time for deposits consisting of pure salts. On the other hand, scaling of a variety of salts, each exhibiting different crystalline formations, results in an asymptotic fouling-time curve. Hasson et al. [3] elucidated the controlling rate mechanisms in the deposition of $CaCO_3$ scale in a heat exchanger. Various studies have been conducted on $CaCO_3$ fouling in tubes and heat exchangers [4–24]. Scale formation of $CaCO_3$ on tube walls was studied by Andritsos et al. [12] in a once-through flow system under isothermal conditions. The effect of thermal-hydraulic parameters on the induction time of $CaCO_3$ scaling and models to predict the growth of $CaCO_3$ at different locations of the heat exchanger was studied by Budair et al. [22]. Khan et al. [24] studied the effect of parameters like fluid velocity, tube diameter, and tube surface temperature on the scaling growth. Furthermore, the effect of $CaCO_3$ concentration was also studied. The variation of scale growth along the length of the heat exchanger was also presented. Tubman [25] investigated the potential for fouling in plain and augmented tubes in cooling-tower applications. In his work, three primary factors that affect fouling potential were examined: internal tube geometry, water velocity, and water quality.

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Previous studies considered fouling of plain tube heat exchangers. The twisted tube heat exchanger is a new technology designed to guide the shell-side flow into a swirl pattern in order to increase the heat transfer rate and reduce the fouling rate. Twisted tube heat exchangers were developed by Brown Fintube [26, 27]. Zukauskas et al. [28] showed that the distribution of the heat transfer coefficient in a bundle of twisted tubes in cross-flow is more uniform than in a bundle of smooth tubes. Also, there is no overheating in points of contact between the tubes. The thermohydraulic performance of bundles of twisted tubes is significantly affected by the arrangement of the tubes within the bundle, but variation of the relative tube twist pitch from 6.1 to 12.2 does not significantly affect the heat transfer coefficient of the bundle. The average coefficient of heat transfer for bundles of twisted tubes is 10 to 40% higher than that for smooth tube bundles. Dzybenko and Dreitser [29] conducted experiments to compare heat transfer data for bundles with different numbers of tubes using a flow model with the concept of the characteristic wall layer thickness. Also, they compared heat transfer data at different Reynolds numbers (5000, 10,000, and 100,000) for bundles with different numbers of tubes, using a flow model with allowance for the transverse component of the velocity. Brodov et al. [30] investigated the enhancement provided by replacing smooth heat exchanger tubes with helically twisted tubes. They found 10 to 70% improvement in the condensation heat transfer coefficient, depending on the operating conditions and tube geometry. Butterworth et al. [31] described a twisted tube heat exchanger that is inherently able to overcome thermal and pressure-drop limitations, in addition to providing the further advantages of tube-side enhancement and good tube support to reduced susceptibility to vibration.

Recently, several studies related to twisted tube heat exchangers have been reported [32–36]. Zhang et al. [32] examined four different types of structured twisted tube heat exchangers. The results of the study showed that the twisted tube geometry size and the fluid's Reynolds number have significant effect on the heat transfer and flow friction properties in both the tube side and the shell side of twisted tube heat exchangers. Al-Hadhrami et al. [36] found that considerable benefits in terms of energy and cost savings can be realized through the application of twisted tube heat-exchanger technology.

The purpose of this research is to study the fouling resistance in twisted tube heat exchanger by varying the fluid velocity and heat input under controlled laboratory conditions. The experiments were conducted on a specially designed apparatus for twisted tube heat exchanger studies. The details of the experimental setup are described in detail in the following section.

DESCRIPTION OF THE EXPERIMENTAL SETUP

The experimental setup consists of different components which are shown in Figure 1. The working fluid used in the experimental work was "raw water" (see Table 1 for chemical analysis) that comes from a water well in Dhahran, Saudi Arabia. The reservoir tank is filled with water until it reaches a certain level, controlled by the use of a float valve. The capacity of the reservoir tank is approximately 1 cubic meter. Water is passed to the centrifugal pump through a polyvinyl chloride (PVC) piping system when the valve in the downstream tank is opened. The PVC piping, approximately 1 inch inner diameter, is connected to all the components in a test loop. Water is passed through a digital flow meter to measure the flow rate before entering the pump. The pump circulates the water through the rest of the test loop components by exerting high pressure, and the pressure is observed by a pressure gauge. The raw water is passed through a filter to screen large-sized particles before flowing through the heat exchanger. The piping system splits feed into two parts before connecting to the heat exchanger. One part is used for calibration to check the flow rate manually. If no calibration is done, the valve before the heat exchanger is kept in an open state while the other valve is closed. The water enters the twisted tube housed in the heat exchanger unit. The downstream electronic valve in the heat exchanger unit controls the velocity inside the twisted tube. The water is discharged to a drain through the electronic valve.

Table 1 Quality characterization (in ppm or mg/l) of water samples

Element	Concentration at test tube inlet	Concentration at test tube outlet	Difference in concentration	Percent variation (%)
Boron	0.572	0.572	0	0.0
Barium	0.028	0.028	0	0.0
Calcium	350	335	–15	–4.3
Copper	0.02	0.022	0.002	10.0
Iron	0.036	0.054	0.018	50.0
Potassium	45.4	45.1	–0.3	–0.7
Lithium	0.15	0.15	0	0.0
Magnesium	106	101	–5	–4.7
Sodium	695	677	–18	–2.6
Sulfur	234	231	–3	–1.3
Silicon	8.54	8.47	–0.07	–0.8
Strontium	8.84	8.44	–0.4	–4.5
Zinc	0.004	0.004	0	0.0
Chloride	1520	1600	80	5.3
Sulfate	755	784	29	3.8
PH	7.51	7.53	0.02	0.3
Conductivity (mS/cm)	5.2	5.2	0	0.0
Total alkalinity (as $CaCO_3$)	150	160	10	6.7
Total dissolved solids	3600	3690	90	2.5
Total suspended solids	12	18	6	50.0

The control panel is used to monitor fouling. It is a microprocessor-based data acquisition system designed to control, monitor, and report all parameters necessary to perform heat transfer analysis. As deposits (scaling, microbial slime, and sediments) accumulate, the tube surface becomes thermally insulated, and the change in thermal resistance is electronically reported. Changes in thermal resistance due to corrosion and corrosion products may also be detected.

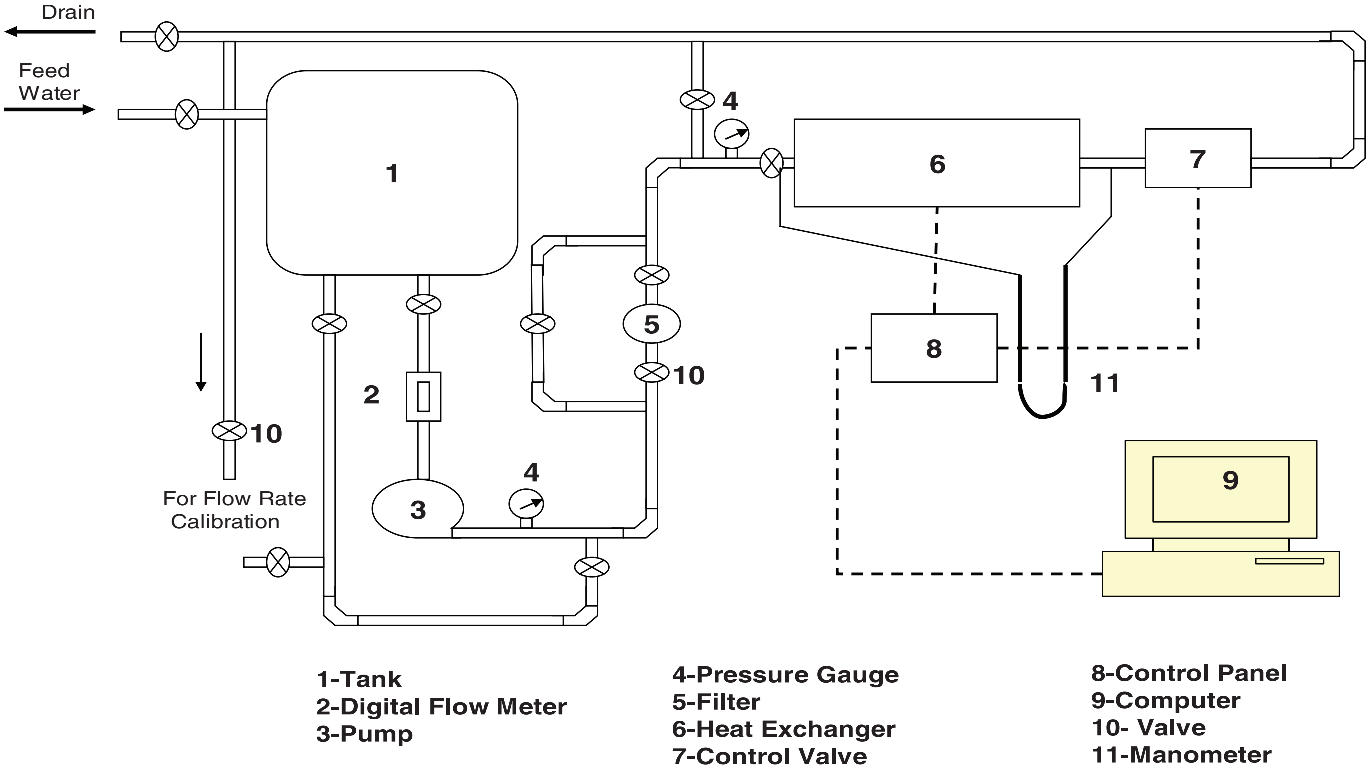

Figure 1 Schematic diagram of the experimental setup for testing twisted tube heat exchanger. (Color figure available online.)

Figure 2 shows in detail the components of the heat exchanger unit. The unit is designed to be robust and easy to install and operate. The engineering concept of this unit is to install a pipe with two cylindrical aluminum blocks that are attached perfectly to its outer surface. A T-type thermocouple is connected to the inlet block cylinder to measure the inlet fluid temperature. The heater block cylinder is bounded with a flexible constant heat flux heater element made of acrylic rubber. A heater block temperature sensor is imbedded inside the heater block to measure the block temperature. The twisted tube with two blocks is insulated by fibreglass insulation inside a steel box. This experimental setup has flexibility to test different tube sizes for fouling.

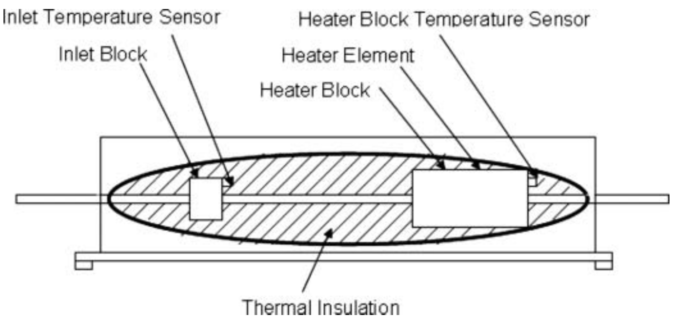

Figure 2 Heat exchanger unit.

The twisted tube geometry is elliptically shaped and the dimensions of the heat exchanger unit are shown in Figure 3. The temperature probes are attached on the inlet and heater aluminum blocks. The temperature measured in the block was assumed to be the same as the surface temperature of twisted tube since the Biot number is less than 0.1. The temperature probe was installed outside the tube because the flow would have been interrupted if it was installed inside the twisted tube. The inlet and heater blocks were fabricated locally. Figure 4 shows the cast aluminum blocks on the twisted tube surface. The outside geometry of the twisted tube was not uniform. Aluminum casting was used to make sure that there was full contact among the tube surface, heater and inlet blocks. This is to ensure the proper heat transfer to the tube surface.

During the course of the experiment, it was ensured that there was enough water supply and the tank was filled with water. Also, all the necessary valves for operating the system were checked carefully. The flow of water was regulated through valves for circulation and to maintain a desired velocity. The computer was switched on and all the connections (made between heat exchanger, flow meter, and computer) were properly checked prior to running the experiment.

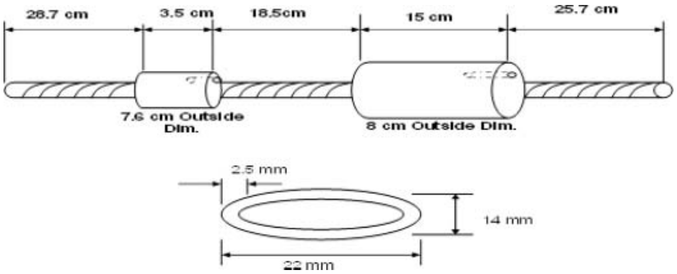

Figure 3 Dimensions of the twisted tube.

Tube cleaning procedure. The tube was disassembled and cleaned after each experiment. The cleaning of the interior of the twisted tube was carried out using chemical and mechanical means. The chemical cleaning involved the use of a chemical solution to remove the scale. The tube was rinsed thoroughly by filling it with chemical solution until the tubes became clean. Mechanical cleaning involved the use of a soft sponge and water after the chemical cleaning. After chemical and mechanical cleaning, the tube was flushed with water several times to ensure that no fouling particles remained inside the tube. This was important and necessary to avoid damaging of the electronic control valve.

Water sample analysis. Water samples were collected at the test-tube inlet and at outlet for quality characterization. The results of the analyses are shown in Table 1. The instruments used for the analyses were inductively coupled plasma atomic emission spectroscopy (ICP-AES) for metals calibration with three levels of mixed standard, ion chromatography for chloride and sulfate, and potentiometric titration for alkalinity. Total dissolved solids and total suspended solids were determined gravimetrically. It can be seen from Table 1 that the concentration of some elements increased while some decreased and others remained the same. Concentration of calcium and sodium decreased. This implies that the elements accumulated in the twisted tube. On the other hand, chloride, dissolved solids, and sulfate showed the opposite trend.

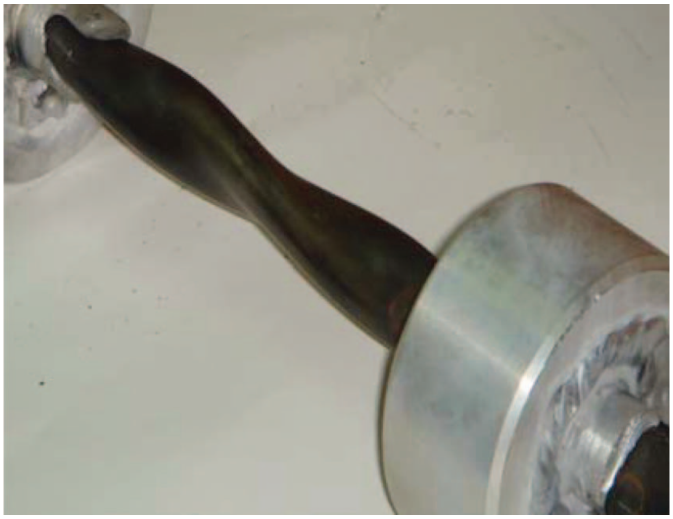

Figure 4 Photograph of the twisted tube with aluminum inlet block. (Color figure available online.)

METHODOLOGY FOR FOULING RESISTANCE CALCULATION

This section explains the general principles involved in the calculation of the parameters and the interpretation of the data collected. The assumption has been made that the water or fluid with similar characteristics is circulating in the system.

In a fouling monitoring system, a uniform heat flux was applied to the twisted tube, carrying the fluid, through an electric heating element. The heat input, the tube wall temperature, fluid velocity, water and block temperatures, and thermal resistance (R) were measured. The relationships among these parameters were considered with the assumption of no heat losses.

Conduction Thermal Resistance Calculation

The geometry and physical relationships of the elements within the heat exchanger are shown in Figure 3. Initially or under clean tube condition, there is no fouling in the tube. Therefore, the tube conduction thermal resistance can be calculated by the following equation:

$$R_{Cond} = R_{Total,i} - R_{Conv,i} \tag{1}$$

where

$$R_{Total,i} = \frac{A(T_{block,i} - T_{water,i})}{q} \tag{2}$$

The initial convection thermal resistance ($R_{Conv,i}$) is developed from an empirical relationship of the convective heat transfer coefficient, which is a derivation of the Colburn equation [28] and given by the following equation:

$$R_{Conv,i} = \frac{D_i}{0.023 * \mathrm{Re}^{0.8} * \mathrm{Pr}^{0.4}\, k_{water}} \tag{3}$$

Wall Surface Temperature Calculation

Wall surface temperature (T_{wall}) is defined as the temperature of the inside wall of the tube (beneath any fouling layer that may develop), and is calculated by the relationship:

$$T_{wall} = T_{block} - \left(R_{Cond} * \frac{q}{A} \right) \tag{4}$$

where R_{Cond} can be calculated from Eq. (1).

Table 2 Heat input and fluid velocity for different experimental cases.

Case number	Applied heat (W)	Velocity (m/s)	Period (days)	Repetition
1	200	2	7	3 times
2	400	2	7	3 times
3	600	2	7	2 times
4	800	2	7	2 times
5	200	1.5	7	2 times
6	400	1.5	7	2 times
7	600	1.5	7	2 times
8	800	1.5	7	2 times
9	200	1	7	2 times
10	400	1	7	2 times
11	600	1	7	2 times
12	800	1	7	2 times
13	200	0.5	7	2 times
14	400	0.5	7	2 times
15	600	0.5	7	2 times
16	800	0.5	7	3 times

Fouling Resistance Calculation

By analogy with electrical conduction, there are three resistances in series as shown in Figure 5 for the existing heat exchanger system. Since there is one fluid side and during the course of the use of the heat exchanger twisted tube, there is fouling layer buildup on the surface of the twisted tube.

Therefore, the fouling resistance is given by the following equation:

$$R_f = R_{Total} - R_{Cond} - R_{Conv} \tag{5}$$

where

$$R_{Total} = \frac{A(T_{block} - T_{water})}{q} \tag{6}$$

Alternatively, R_f can also be obtained from the following relation by using Eqs. (2) and (6):

$$R_f = R_{Total} - \mathrm{R}_{Total,i} \tag{7}$$

The fouling resistance is dynamic in nature. As the fouling layer buildup progresses with time, the fouling resistance also increases. So, in other words, the fouling resistance depends on the period of use of the heat exchanger.

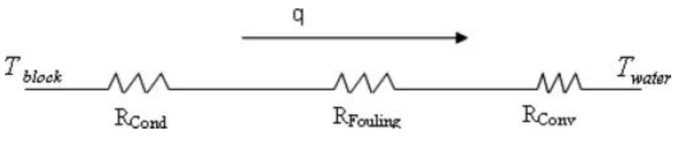

Figure 5 Thermal resistances for the existing twisted tube heat exchanger system.

Uncertainty Analysis

The fouling resistance (considering Eq. 7) is a function of

$$R_f = f(A, q, T_{block,i}, T_{water,i}, T_{block}, T_{water})$$

The standard uncertainty in the fouling resistance, neglecting the covariance, is calculated using the following equation:

$$(U_{c,R_f})^2 = \left(\frac{\partial R_f}{\partial A} u_A\right)^2 + \left(\frac{\partial R_f}{\partial q} u_q\right)^2 + \left(\frac{\partial R_f}{\partial T_{block,i}} u_{T_{block,i}}\right)^2 + \left(\frac{\partial R_f}{\partial T_{water,i}} u_{T_{water,i}}\right)^2 + \left(\frac{\partial R_f}{\partial T_{block}} u_{T_{block}}\right)^2 + \left(\frac{\partial R_f}{\partial T_{water}} u_{T_{water}}\right)^2 \tag{8}$$

Uncertainty propagation for the dependent variable in terms of the measured values is calculated using Engineering Equation Solver (EES) software [37]. The measured variables x_1, x_2, etc. have a random variability that is referred to as the uncertainty; this uncertainty is displayed as $a \pm u_x$. The input to EES for calculating the uncertainty of a dependent variable is the magnitude (a) of the measured variable (x) and the uncertainty (u_x) in each measured variable.

The sample uncertainty results obtained using EES display the partial derivative of the calculated variable with respect to each measured variable and the percentage of the total uncertainty in the calculated variable resulting from the uncertainty in each measured variable.

The estimated uncertainty in fouling resistance has been found to vary by ±8.2%.

RESULTS AND DISCUSSION

For this study, the results of the experiments for the twisted tube heat exchanger for 16 different cases are reported in Table 2. Each experiment was conducted for a period of 1 week and repeated two or three times as shown in the table.

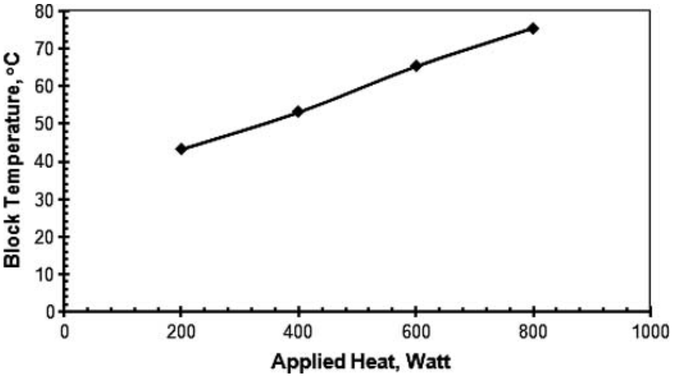

Figure 6 Block temperature variation with applied heat.

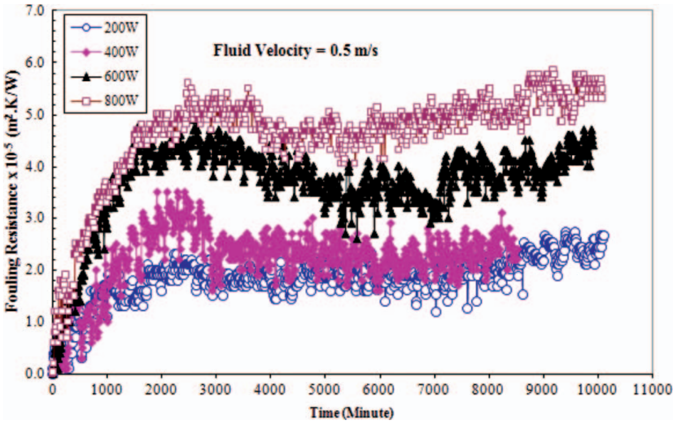

Figure 7 Fouling resistance for different heat input at fluid velocity of 0.5 m/s. (Color figure available online.)

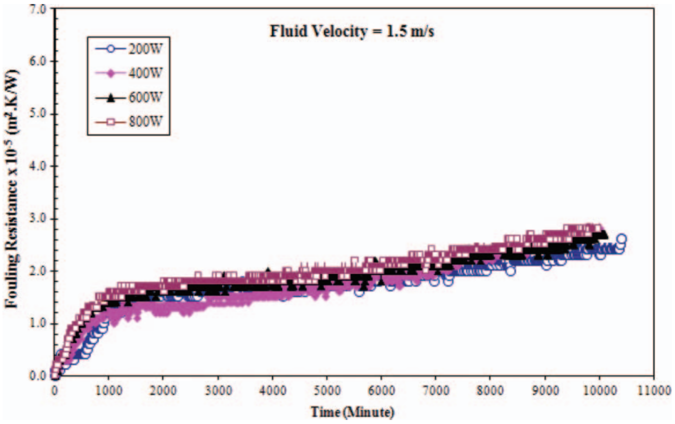

Figure 9 Fouling resistance for different heat input at fluid velocity of 1.5 m/s. (Color figure available online.)

Fouling resistance was studied as a function of time. Fouling behavior for different heat transfer rates and velocities is discussed.

Figure 6 shows the heater block temperature for different heat inputs. As is evident from the figure, the heater block temperature varies linearly with applied heat. The block temperature varied in the range of 43.3 to 75.4°C for heat input from 200 to 800 W.

Figures 7 to 10 show the fouling resistance for various fluid velocities (0.5 to 2.0 m/s) and various heat inputs (200 to 800 W). These data were collected over a period of one week for each experiment.

Figure 7 shows the variation of fouling resistance for different values of heat input for fluid velocity of 0.5 m/s. It is evident from the figure that the fouling resistance is a function of the heat applied to the fluid. Initially, for heat input of 200 W, the fouling resistance increases and reaches a maximum value at around 2500 min; then there is slight dip in value, and after that it remains constant during the rest of the test period. The pattern of fouling resistance in the twisted tube heat exchangers during the test period indicates that up to a certain period of time the scale thickness increases and there is slight removal of scale for a short duration. As the time progresses, the fouling resistance remains constant, which is an indication of permanent buildup of a scale layer on the internal surface of the twisted tube heat exchanger. However, a different pattern in fouling resistance is observed after the dip in the resistance at 2000 min for higher values of heat input as compared to that of the pattern for heat input of 200 W. It can be observed from Figure 7 that the fouling resistance steadily increases with time for higher values of heat input from 6000 min onward. This shows that the scale buildup steadily continues with time for heat input greater than 200 W.

The fouling resistance for various values of heat input for inlet fluid velocities from 1.0 to 2.0 m/s are shown in Figures 8 to 10. For all values of heat input, fouling resistance increases steadily with time for the cases considered. The patterns for fouling resistance in these cases are different than that observed for a fluid velocity of 0.5 m/s. In these cases, no dip in thermal resistance is observed like that noticed in the previous case where fluid velocity was 0.5 m/s.

It is also observed that fouling resistance curves are overlapping for various values of heat input for fluid velocities greater than 0.5 m/s. This indicates that the change in value of heat input does not have an appreciable affect on fouling rate after 1000

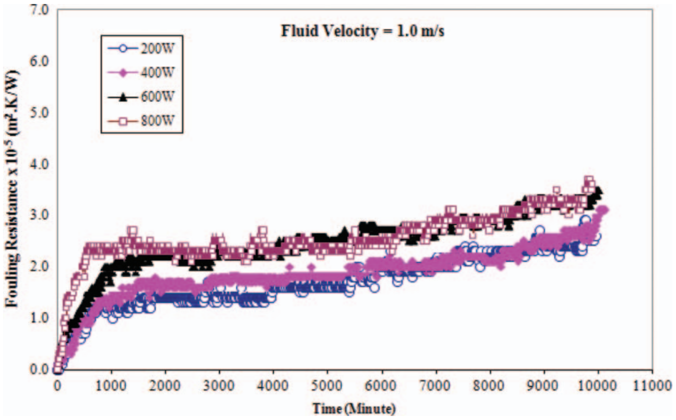

Figure 8 Fouling resistance for different heat input at fluid velocity of 1.0 m/s. (Color figure available online.)

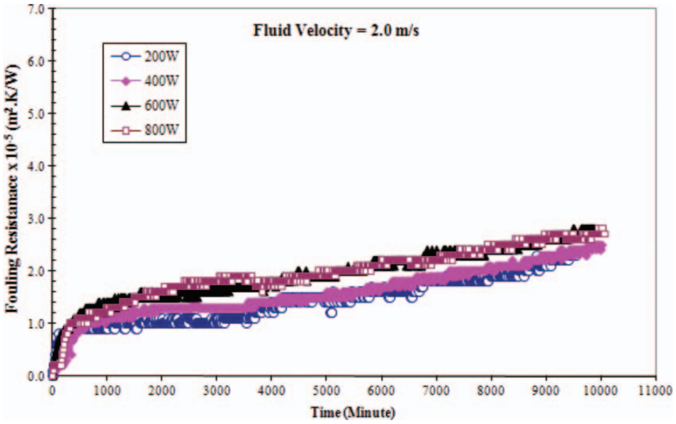

Figure 10 Fouling resistance for different heat input at fluid velocity of 2.0 m/s. (Color figure available online.)

Table 3 Time-series correlation of fouling resistance (R_f) in twisted tube heat exchanger for 200 and 400 W heat input

	Heat Input			
	200 W		400 W	
Velocity, m/s	R_f (t) × 10^{-5} m^2-K/W	*R*-squared	R_f (t) × 10^{-5} m^2-K/W	*R*-squared
0.5	$0.3494 \times \ln t - 1.0149$	0.657	$0.3873 \times \ln t - 0.9137$	0.3836
1.0	$0.4726 \times \ln t - 2.1603$	0.8446	$0.4693 \times \ln t - 1.9782$	0.8693
1.5	$0.4852 \times \ln t - 2.2587$	0.9109	$0.5237 \times \ln t - 2.5539$	0.8289
2.0	$0.3724 \times \ln t - 1.6094$	0.7347	$0.4440 \times \ln t - 2.0569$	0.8345

Table 4 Time-series correlation of fouling resistance (R_f) in twisted tube heat exchanger for 600 and 800 W heat input

	Heat Input			
	600 W		800 W	
Velocity, m/s	R_f (t) × 10^{-5} m^2-K/W	*R*-squared	R_f (t) × 10^{-5} m^2-K/W	*R*-squared
0.5	$0.5261 \times \ln t - 0.6186$	0.4204	$0.8447 \times \ln t - 2.3204$	0.778
1.0	$0.5743 \times \ln t - 2.2259$	0.9173	$0.4164 \times \ln t - 0.8700$	0.7159
1.5	$0.4517 \times \ln t - 1.8058$	0.9007	$0.4750 \times \ln t - 1.9045$	0.9019
2.0	$0.4663 \times \ln t - 1.8811$	0.8704	$0.5047 \times \ln t - 2.2042$	0.9195

min for fluid velocity from 1.0 to 2.0 m/s. Note that initially up to 1000 min duration, the maximum fouling resistance decreases with increase in fluid velocity. This behavior of fouling rate can be attributed to the fact that at a high fluid velocity, flow becomes turbulent, and this in turn flushes the fouling particles.

The continuous rise in the fouling resistance at higher flow velocities may be explained by the fact that a deposit layer will continue to grow until it gets to a critical thickness. A critical thickness would have been achieved much more quickly at low flow velocity and hence there is an asymptotic trend

The fouling resistance in the twisted tube heat exchanger was time-series correlated for different heat input and fluid velocity. The correlations obtained for the fouling resistance are shown in Tables 3 and 4. The time-series correlations for the fouling resistance are found to be logarithmic in nature. Except two cases, the *R*-squared for the correlation is well above 0.6 for most of the experimental cases.

CONCLUSIONS

In this experimental work, investigations were carried out to study the fouling resistance in the twisted tube heat exchanger under different conditions of fluid velocity and heat input. The fluid velocity was varied from 0.5 to 2.0 m/s, whereas the heat input to the heat exchanger was varied from 200 to 800 W.

The experimental results show that for low fluid velocity of 0.5 m/s, the fouling resistance had noticeable variation with respect to heat input. However, for the high velocity range 1.–2 m/s, the fouling resistance showed less variation, especially at high heat input. The fouling resistance steadily increases with time for higher values of heat input from 1000 min onward for fluid velocity from 1.0 to 2.0 m/s. It is also observed that fouling resistance curves are overlapping for various values of heat input. It is worthwhile to note that initially up to 1000 min test duration, the maximum fouling resistance decreases with increase in fluid velocity. This behavior of fouling rate can be attributed to the fact that at a high fluid velocity, flow becomes turbulent and this in turn flushes the fouling particles. The fouling resistance in the twisted tube heat exchanger was also time-series correlated for different heat input and fluid velocity. The time-series correlations for fouling resistance are found to be logarithmic in nature.

NOMENCLATURE

A	tube outside surface area of the heater block (m^2)
D_i	inner diameter of pipe (m)
k	thermal conductivity (W/m-K)
q	applied heat (W)
R_{Cond}	conduction thermal resistance (m^2-K/W)
R_{Conv}	convection thermal resistance (m^2-K/W)
R_f	fouling thermal resistance (m^2-K/W)
R_{Total}	total thermal resistance (m^2-K/W)
Re	Reynolds number
Pr	Prandtl number
T_{block}	block temperature (°C)
T_{wall}	tube wall surface temperature (°C)
T_{water}	water temperature (°C)
U_c	uncertainty in fouling resistance, %
u_x	uncertainty in each measured variable x, %

Subscripts

i	initial
t	time (min)

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