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Fouling Performance of A Horizontal Corrugated Tube due to Air Injection

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ABSTRACT

In the present study, the fouling performance of a circumferentially corrugated tube was probed due to the air injection. The molasses of sugar beet was considered as the working fluid. The tube was considered to be under constant heat flux. Also, the flow rate of the molasses of sugar beet was considered to be constant. Five different flow rates of the airstream were considered to check the effect of airflow rate. The flow rate of working fluid was kept at the constant flow rate of 2 L/min. The tests were conducted for 5000s (84 minutes). For a better understanding of the nature of the flow, the structure of two-phase steam was recorded via a Canon SX540 Camera. The results presented that the air injection in the corrugated tube will completely change the structure of the working fluid which will bring a very turbulent structure for the working fluid. The thermal results presented that during the testing time, the air injection will keep the heat transfer coefficient about 120% higher than a single-phase stream. The mass evaluation results revealed that the air injection could decrease the weight of fouled substance up to 75%.

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1. INTRODUCTION

The fouling phenomenon is known as the most important problem in industrial systems and the production processes [1, 2]. The fouling phenomenon in thermal systems not only brings up many maintenance costs but also, reduces the thermal efficiency of the systems which leads to a reduction of the efficiency of the whole system [3]. In recent decades, corrugated tubes are proposed as the ultimate solution to be used in thermal systems since they have better thermal performance and their anti-fouling nature in comparison with the smooth tubes [3, 4]. The ejection phenomena and the throttling effect of the corrugations lead to more stability of the small pieces of the fouling substances and weaken the effect of gravity on these parcels. On the other hand, the corrugations interrupt the development of the boundary layer and increase the turbulence intensity of the mainstream which leads to the improvement of heat transfer and increases the stability of the parcels within the flow stream [5-7]. Furthermore, in recent years, the application of air injection is proposed as a very effective method for heat transfer improvement within thermal systems [8, 9]. However, very rare studies have probed the simultaneous effect of air injection and corrugation on the fouling and thermal performance of a thermal system. In the following, a summary of the studies on using both corrugated tubes, air injection, and the fouling phenomenon is provided.

Li et al. [10] investigated the effect of H-type fines on the thermo-hydraulic and fouling performance of a tube heat exchanger. Their results presented that H-type fins with three pairs of grooves could reduce the fouling rate up to 23.7%. Trafczynski et al. [11] evaluated the fouling performance of a heat exchanger and proposed applicable suggestions to better schedule the operation of the heat exchanger. The effect of Sodium carboxymethyl cellulose (SCMC) on the fouling performance of a heat transfer surface was investigated by Xu et al. [12]. Through their study; they probed the effect of different parameters of solution mass flow rate, solution inlet temperature, and solution viscosity. Chapela et al. [13] probed a transient model of thermal performance and fouling phenomena of a biomass shell boiler. Tang et al.

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[14] proposed the honeycomb circular tube bundles as a new design for the fouling reduction within a shell and multitude heat exchanger. Furthermore, they developed new correlations for Nusselt number, friction factor, and fouling thermal resistance. Their results revealed that the predicted results from the correlations had only a 4% deviation from the results of numerical simulations. Zhao et al. [15] investigated the thermal performance and fouling properties of an evaporating falling film through a vertical tube. Through their study, they compared the effect of the porous surface with a plain tube. Their results revealed that although the thermal performance of a tube with a porous surface was a little worse than the plain tube the fouling rate of the tube with a porous surface was one-tenth of the that associated with the plain tube. Wang et al. [16] investigated the fouling properties of a finned tube heat exchanger. Through their study, the effect of different tubes and arrangements were evaluated. Their finding presented that double H-type fins could slightly reduce fouling. The fouling performance of an enhanced tube utilized in a cooling tower was probed by Shen et al. [17]. They developed a model for predicting the fouling residence which presented a maximum error of 0.0645. In another study, Wang et al. [18] compared the thermal and fouling performance of a plain tube with a helically ribbed tubes. They investigated Reynolds number was considered to be 16000. Their results presented a better fouling performance for ribbed tubes when compared to plain tube. Son et al. [19] used the air injection as an anti-fouling method for a plate type microfiltration membrane. Through their study, they investigated the effect of continues and periodic air injection algorithms. Their results revealed a very effective influence of periodic air injection on the reduction of fouling through the considered membrane. Sinaga et al. [20] conducted an experimental investigation and probed the effect of air injection on the thermal performance of a double tube heat exchanger. They mentioned that the air injection increases the turbulence intensity of the overall stream which would lead in better thermal and fouling performance of the heat exchangers.

In the present study, the simultaneous effect of using circumferential corrugation and air injection on the thermal and fouling performance of a straight heat exchanger are evaluated and compared with a plain tube heat exchanger. From the above-provided literature and based on the authors' knowledge, almost no investigation had considered the effect of the two aforementioned factors. Indeed, the available papers in literature are divided into two main groups. The first group examines, only the THERMAL performance of corrugated tubes in the presence of NONE-boiling gas liquid two phase flow and there was almost **NO** investigation on the Fouling performance of the corrugated tube together with NONE-boiling two phase flow**.** Besides, the second group reported the effect of boiling gas liquid two phase flow on the thermal and fouling performance of the corrugated tube in the presence of boiling two-phase flow. Indeed, the nature and application of boiling two phase flow and None-boiling two phase flow is completely different. This makes the necessity of investigation on the fouling performance of none-boiling two phase flow inside the corrugated tubes. Furthermore, the available papers on thermal performance of none-boiling two phase flow inside the corrugated tubes have focused on steady flow, whereas the nature of streams that deal with fouling phenomena is unsteady which should be addressed even in more future papers. Thus, it would be of great importance for thermal engineers to probe the effect of both air injection and circumferential corrugation on the fouling performance of a straight tube.

2. EXPERIMENTAL METHODOLOGY AND PROCEDURE

Figure 1 presents the schematic of the test rig provided for caring out the considered tests. The air injection method utilized in this study was previously used by different researchers [5, 21, 22]. The advantage of this injection method is that since it is located outside the heat exchange unit, it could be utilized for the existing thermal systems in industrial applications. From Figure 1, it could be realized that the test rig has consisted of two main parts. The first one was the air supply part which was consisted of a compressor, two valves, and one air flow rate measuring Rotameter. The second one is the working fluid supply system which was comprised of a lotion tank (which was used for storing the molasses of sugar beet), two control valves, and one lotion flow rate measuring Rotameter.

The air was injected into the lotion stream through the mixing well. Then the two-phase stream had been passed through the test section. Passing through the test section, the lotion gained thermal energy from the heated walls of the corrugated tube. The thermal energy was produced via heater wires that were wrapped around the tube at the whole length of the test section. At the final stage and after passing the test section, the two-phase lotion was directed into a heat exchanger to lose its thermal energy and to find the initial temperature. Then, this two-phase stream was again directed into the lotion tanks. Through the lotion tank, the air was divided from the molasses of sugar beet due to the buoyancy effect.

For the data recording, two evaluation methods were conducted. First weight variation analyses and second heat transfer coefficient evaluation. The heat transfer coefficient evaluation is an indirect method for understanding the thermal resistance variation due to the fouling phenomena. For measuring the heat transfer coefficient, the surface temperatures of the corrugated and helical tubes were measured. Also, the inlet and outlet temperature of the lotion was measured too. It is worth mentioning that the inlet temperatures of the air stream and working fluid (molasses of sugar beet) were kept almost constant and were about 12℃ ±0.5 and 14℃ ±0.5, respectively. Also, the mass weighting evaluation was performed by a scale (Model: Bama 111) which had an accuracy of ±0.1 g. the temperature recording system was a 12 Channel digital data logger (Model: Lutron 4208SD) which had coupled with K type thermocouples. The aforementioned system provides an accuracy of ±0.5°C for measuring the temperature. It is worth mentioning that the running test time was considered to be 5000s (about 84minute). Indeed, there was no clear concept or restriction on defining testing time through the literature. However the authors followed the published research work by Peyghambarzadeh et al. [23] and tried to determine the testing time in the range of what they have considered.

Table 1 present the different cases considered in the present study simultaneous with the geometrical properties of both plain and corrugated tube.

It is noteworthy that the uncertainty analysis was performed based on the method proposed by Moffat [24]. This method was previously used by numerous researchers [5, 7, 20, 25, 26]. The uncertainty for heat transfer coefficient and weight were found to be a maximum of 8.65% and 5%, respectively.

3. PARAMETER DEFINITION

The time-dependent heat transfer coefficient was defined as follows:

The total thermal energy gained by the working fluid could be measured via the following equation. At which the $\dot{m}$, C_p, T_{out} and T_{in} denote the mass flow rate, specific heat capacity, the outlet temperature of the working fluid, and the inlet temperature of the working fluid respectively.

To define the properties of multiphase flows, different theories were developed, however, each of these could provide the proper results in a certain range of air and gas flow rates. In lower values of gas flow rate, the two-phase stream properties associated with thermal behavior could be assumed to be equal to the liquid phase. This is since the mass flow rate and the Cp of the air flow rate are significantly less than the water flow rate. It should be noted that many experts [27–30] have stated that this effect is negligible. Through the present investigation, the maximum fraction between the air mass flow rate and water mass flow rates was 0.0053 which denotes that the total energy gained by the air stream is so less than that of the water stream. Consequently, the effect of the definition type of Cp of the gas stream could be neglected [30-33].

$$Q(t) = \dot{m}(t)C_p(T_{out}(t) - T_{in}(t)) \tag{1}$$

For finding the convective heat transfer coefficient, the above calculated thermal energy should be equal to that gained via the convective method. Which results in a calculation of the heat transfer coefficient in the following type.

$$h(t) = \frac{Q(t)}{A(\bar{T}_w(t) - T_b(t))} \tag{2}$$

As mentioned before mass analyses were performed in this study. For the better presentation of results, the following parameters were defined in this study.

In this study, the difference in the initial weight of the tube and the weight of the tube at the end of each test is defined as β and is defined as follows:

$$\beta = W_{t=5000}(t) - W_i \tag{3}$$

At the above equation the $W_{t=5000}(t)$ is the weight of tubes at the end of run time and the W_i is the initial weight of the tube. In the results section the β_p and β_c are defined as the weight difference of plain tube and corrugated tube, respectively.

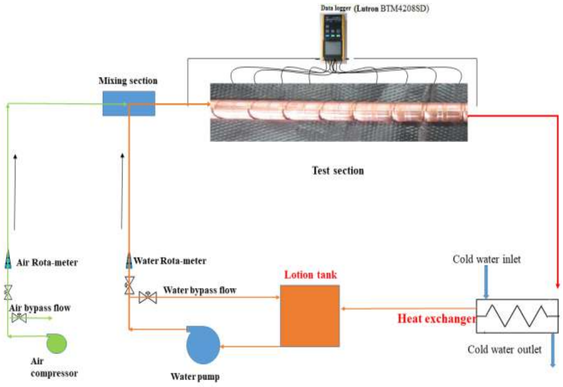


Figure 1. Presentation of a schematic view of the test rig

TABLE 1. Various cases are considered in the present study

Tube type	Water flow rate (L/min)	Airflow rate (L/min)	Thermal energy (W)	Airflow inlet temperature (℃)	Liquid flow inlet temperature (℃)
Plain	2	0,1,2,3,4,5	1000	12	14
Corrugated	2	0,1,2,3,4,5	1000	12	14

Also, the weight difference percentage is defined as follows:

$$\alpha = \frac{W_{t=5000}(t)-W_i}{W_i} \times 100 \tag{4}$$

4. RESULTS AND DISCUSSIONS

4. 1. Thermal Analysis In this section, the time-dependent heat transfer coefficient of the both plain tube and corrugated tube are provided in case of both air injection and single-phase flow. In Figure 2, the time-dependent heat transfer coefficient of the plain tube and corrugated tube in the case of single-phase flow is presented. The flow rate of the liquid phase (V_L) was kept constant and it was equal to 4 L/min. From Figure 2, it could be realized that through the corrugated tube, the heat transfer coefficient is more than that related to the smooth tube through the run time. Since all the parameters were equal between the smooth and corrugated tubes, the difference in the heat transfer coefficient is related to the fouling resistance of the two tubes which was due to higher turbulence intensity of flow inside the corrugated tube. Actually, the smooth tubes gain more fouled substance on their walls and this causes to increment of the fouling resistance of the tube which leads to a reduction of heat transfer coefficient. However, for the corrugated tube, the corrugated walls increases the turbulence intensity of the liquid stream which results in longer remaining of the fouling parcels through the liquid stream and prevent the fouling of the parcels through the working fluid. In fact, the corrugations provide two throttling and ejection effects at the entrance and existence of the corrugated regions. This causes a fluctuation in the pressure drop and changes the directions of the movement of the parcels through the working fluid. All these together prevent the creation of a fouling layer through the tube and reduce its' thickness which leads to the increment of heat transfer coefficient.

Figure 3 presents the variation of the time-dependent heat transfer coefficient in the case of air injection. As mentioned before the liquid flow rate was kept constant and was equal to 4 L /min; however, five different airflow rates (Va) of 1, 2, 3, 4, and 5 L /min were considered to check the effect of air injection flow rate. As could be realized from Figure 3, the air injection has increased the heat transfer coefficient through the running time. Also, by the increment of air injection rate, the increment of the airflow rate has significantly increased. Indeed, the air injection causes the creation of air bubbles/ slugs within the liquid phase. The coincidence between the air bubbles and liquid phase causes to increment of the turbulence intensity of the flow stream and results in more stability of the fouling parcels within the flow stream. Consequently, the fouling layer develops at a more slow rate and the heat transfer coefficient remains at high values. By the increment of air injection flow rate, the air bubbles get bigger resulting in a more powerful coincidence with the solid body of the tube walls and the working fluid parcels. By the increment of the reaction between the air bubbles and working fluid parcels the stability of the fouling parcels within the working fluid increases. On the other hand, the movement of the air slugs on the top of the tube (horizontal orientation of tube is considered in this paper) sweeps the fouling layer and prevents it from getting developed. Consequently, the heat transfer coefficient achieves higher values.

Figure 4 presents the variation of heat transfer coefficient for the cases with air injection through the corrugated tube. From Figure 4, it could be realized that the influence of air injection of the performance enhancement through the corrugated tube is more than that in the smooth tube. Indeed, through the corrugated tube, the coincidences of the bubbles with grooved walls cause the creation of vortexes within the liquid phase. These vortexes prevent the accumulation of parcels on the heated walls of the tube which enhances the fouling performance and increases the heat transfer coefficient.

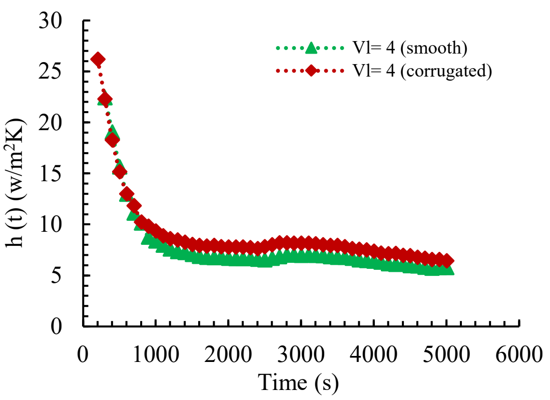


Figure 2. Variation of heat transfer coefficient vs time for single-phase stream

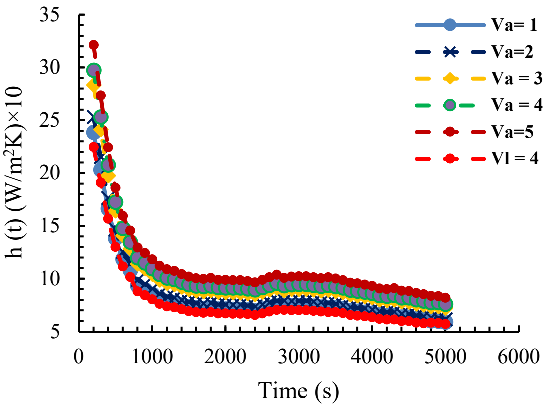


Figure 3. Variation of heat transfer coefficient vs time for two-phase and single phase flows within smooth tube

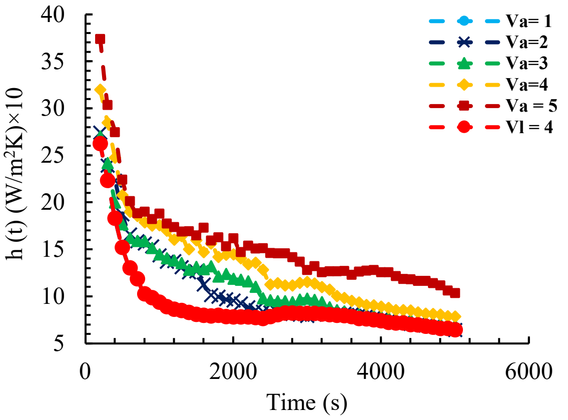


Figure 4. Variation of heat transfer coefficient vs time for two-phase and single phase flows within corrugated tube

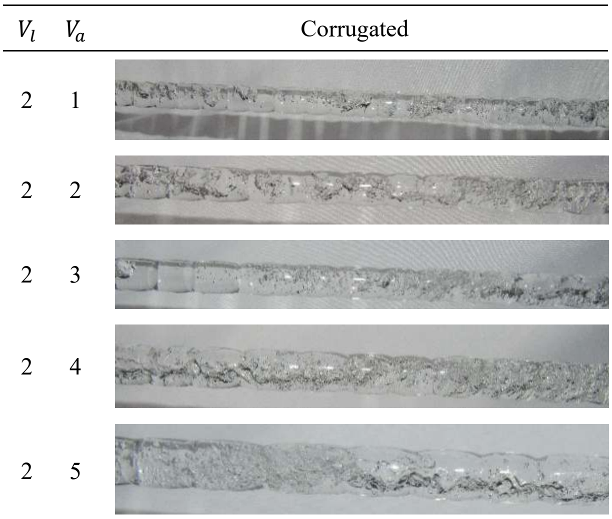


Figure 5. Flow structures due to air injection through the corrugated tube

By comparing Figures 3 and 4, it could be realized that the curves associated with Figure 3 are more smooth than those related to Figure 4 (corrugated tube). It is due to the very turbulent nature of the flow inside the corrugated tube. To understand this, the flow structure of the gas/liquid two-phase flow through the corrugated tube was probed within a glass-made corrugated tube. Through the glass-made corrugated tube, all the hydraulic properties of the flow stream were identical to that in the real heated test section. Figure 5 presents the flow structure of the gas/liquid two-phase flow within the corrugated tube. It is worth mentioning that for capturing the presented flow structures, a Canon SX 540 camera was used which had a shutter speed of 1/2000s. Also, it should be noted that for investigating the flow structure, water was used instead of molasses of sugar beet. It is because due to the darkness of the molasses of sugar beet, capturing the appropriate photos was impossible. However, it should be noted that due to the appropriate viscosity of molasses of sugar beet in comparison with water, the flow structures of these two combinations of gas and liquid could be assumed to be almost identical [34, 35].

From Figure 5, it could be seen that as the air gets injected into the corrugated tube, the air slugs and air bubbles together become created. The interface of air slugs with the water phase is very wavy within the corrugated tube. However, the interface of air slugs with the water phase within the smooth tube has consisted of a very smooth line. It is seen that by the increment of air injection flow rate, numerous tiny bubbles are created in the flow. It could be seen that by the increment of the number of the tiny bubble the dispersion form of the bubbles also changes. Indeed, in the low air injection flow rates, the bubbles move at the upper half of the tube whereas in the higher flow rates the bubble disperse at the whole cross-section of the tube. This way of dispersion significantly affects the accumulation of the fouling parcels and prevents the creation of a fouling layer. Consequently, the fouling resistance remains in minor values and the heat transfer coefficient becomes in higher values than that in single-phase flow.

4. 2. Weight Variation Analysis

Figure 6 A and B, presents the mass variation results for the plain tube and corrugated tube, respectively. It could be seen that the maximum accumulated mass of fouling substance was related to the cases without air injection at both the plain tube and corrugated tube. It could be easily found

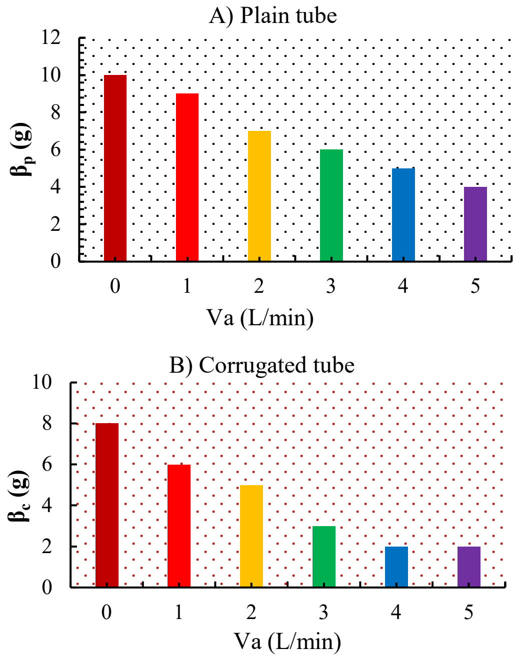
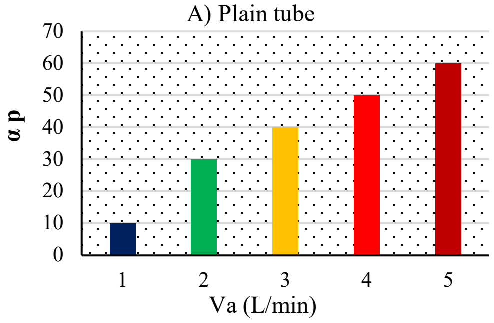


Figure 6. Mass variation results, A) plain tube, B) corrugated tube

that by the increment of air injection flow rate, the mass variation results diminish, denoting this point that the augmentation of the air injection flow rate reduces the accumulated weight of the fouling substances. The maximum mass variation was about 10 g and was related to the plain tube at a single-phase stream. Also, the minimum mass variation results are related to corrugated tube and values of 2g which was related to the two-phase flow with an airflow rate of L /min.

Figure 7 A and B, presents the percentage variation of the mass weight results associated with a plain tube and corrugated tube, respectively. It could be easily understood that the maximum percentage variation of weight variation results is associated with corrugated tubes and presents an about 75% enhancement in the accumulation of fouled particles in comparison to the single-phase flow. A very important point that should be mentioned is that the mass variation results associated with an airflow rate of 4 and 5 L /min are almost identical in the corrugated tube. Indeed, by the increment of air injection flow rate through the corrugated tube, the flow structure totally changes and a fully bubbly flow could be seen in the airflow rates of 4 and 5 L /min. In these airflow rates, the dispersion of air bubbles is placed through all the cross-sections of the corrugated tube. This type of dispersion, significantly increases the turbulence intensity of the flow stream and causes the fouling particles to remain through the flow and prevents them from getting accumulated on the walls of the corrugated tube. The same value of percentage variation of weight variation results indicates that through the corrugated tube, the airflow rate of 4 L /min could be assumed as an optimized value for the enhancement of fouling performance of the corrugated tubes.

A) Plain tube



B) Corrugated tube

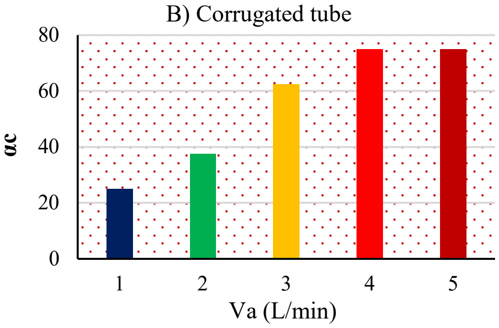


Figure 7. Percentage variation results, A) plain tube, B) corrugated tube

5. CONCLUSIONS

Through this investigation, the thermal and fouling performance of plain tubes and the corrugated tube is compared and evaluated. The tubes were under constant heat flux and the molasses of sugar beet was considered as the working fluid. The tests were implemented for 5000s (84minute). For a better understanding of the nature of the flow, the structure of the two-phase stream was recorded via a Canon SX540 Camera within a glass-made tube. The main findings of the present paper were as following:

- The corrugated tube has more heat transfer coefficient over time compared to the plain tube.
- The flow structure within the corrugated tube is more complex than that in the plain tube.
- The dispersion of the bubbles in the corrugated tube is more even than that in a plain tube.
- The corrugated tube has significantly better fouling performance than the plain tube.
- It was found that the increment of air injection flow rate leads to a reduction of fouling accumulation on the walls of the tube.
- The maximum reduction in the fouling accumulation for the corrugated tube was found to be 75%.

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Persian Abstract

چکیده

در مطالعه حاضر، عملکرد رسوب گذاری یک لوله مارپیچ تحت تزریق هوا مورد بررسی قرار گرفت. ملاس چغندرقند به عنوان مایع کارکردی در نظر گرفته شد. لوله تحت شار حرارتی ثابت در نظر گرفته شد. همچنین میزان جریان ملاس چغندرقند بصورت ثابت در نظر گرفته شد. پنج نرخ جریان مختلف جریان هوا برای بررسی تأثیر سرعت جریان هوا در نظر گرفته شد. میزان جریان سیال کارکردی بر روی سرعت ثابت ۲ لیتر در دقیقه ثابت گردید. آزمایش‌ها به مدت زمان ٥٠٠٠ ثانیه (٨٤ دقیقه) انجام شدند. برای درک بهتر ماهیت جریان، ساختار بخار دو فاز از طریق دوربین Canon SX540 ثبت گردید. نتایج ارائه شده نشان می دهد که تزریق هوا در لوله مارپیچ ساختار سیال کارکردی را کاملاً تغییر می دهد که ساختاری بسیار آشفته برای سیال کارکردی نتیجه می دهد. نتایج حرارتی نشان داد که در طول زمان آزمایش، تزریق هوا ضریب انتقال حرارت را در حدود ۱۲۰ درصد بیشتر از جریان تک فاز نگه می دارد. نتایج ارزیابی توده نشان داد که تزریق هوا می‌تواند وزن ماده رسوب شده را تا ۷۵ درصد کاهش دهد.