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Investigating the Impact of Air Injection on the Thermal Performance of Helical Tube with Varying Helix Diameters: Downward Flow

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ABSTRACT

In this experimental investigation, the heat transfer and pressure drop of helical tubes with various helical diameters have been studied considering air injections. The tube was rested in vertical form and was put under the constant heat flux. The flow had a downward form and the air was injected into the water stream outside the helical tube. According to the findings, air injection has a notable impact on the heat transfer coefficient of each helical tube. The results showed that employing air bubbles could increase the Nusselt Number by up to 14 %. To make an acceptable comparison among all states, the Cost Benefit Ratio (C.B.R.) factor was evaluated. The results showed that the pipes with bigger diameters had the best C.B.R. factor values. It means that the air injection in the tubes with larger diameters was more beneficial than in the tubes with smaller helix diameters. The best value was attained for the helix diameter of 18 cm and the VF of 0.33 with a C.B.R. factor of 0.84. Also, the worst value was 1.18 for a helix diameter of 10 cm.

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1. Introduction

In general, pipes of any kind are of special importance in the industry. A group of tubes known as helical tubes is used in compact heat exchangers, refrigerants, and evaporators in the food and pharmaceutical industries to increase the efficiency of systems. Therefore, examining and determining their optimal performance conditions are of special importance [1-3]. In this regard, many experimental and numerical studies have been performed under different conditions to evaluate the optimal conditions for this equipment. Various studies have considered

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passive techniques to enhance the efficiency of helical tubes. Khorasani et al. [4] investigated the effects of air injection into the shell of a heat exchanger with a winding tube and a horizontal shell. At the bottom of the heat exchanger shell, they employed an advanced air injection device for a more complete examination. In another research, Khorasani et al. [5] used helical wires with different pitches and wire diameters for improving the thermal efficiency of helical tubes. The results demonstrated that the size of wire diameter and pitch had a significant effect on the Nu number and friction factor. Pourhedayat et al. [6] provided empirical correlations for predicting the exergy loss, friction factor and Nusselt number of the helical tube with wire spring inserts. In another investigation, Chen et al. [7] numerically investigated the effect of circular corrugations on the thermal performance of the helical tubes. Their findings present the significant influence of the existence of circular corrugations on the thermal and frictional performance of the helical tube. Furthermore, they conducted evaluations on the economic benefits of the presence of circular corrugations. Their results revealed that the presence of helical corrugations could provide 9 % higher net profit per unit transferred heat load when compared with the smooth tube. Xie et al. [8] experimentally investigated the application of twisted tape turbulators on the thermal performance of the helical tube which was put within a hot reservoir. Their findings presented that the presence of twisted tapes would provide up to 66 % of augmentation in the Nu number values. Abdzadeh et al. [9] reported that the application of air/water two phase flow inside a horizontal helical tube would bring up to 20 % of increment in the heat transfer coefficient. They reported that the Volume fraction VF and form and shape of the bubbles are the most important parameters affecting the thermal performance of the helical tube.

Some researchers, like Styrikovich et al. [10] who investigated the temperature distribution of the steam-water during the longitude of the helicoidal pipes, focused on the effects of the coil diameter, pressure, mass flow rate, and heat flux on the dryout characteristics in helically coiled tubes. They showed that the dryout temperature profile in the proposed tubes was smoother than that in straight ones. Chung et al. [11, 12] studied and found the most effective parameters among the coil diameter, pressure, and mass flow. Xu et al. [11] experimentally studied the dryout characteristics in helically coiled tubes covering a wide range of system and geometric parameters. They proposed an analytical model in their work. Cao et al. [12] numerically worked on different micro-fin helical coil tubes to investigate the flow features. They used an artificial neural network model to predict the parameters. Lei and Bao [13] experimentally studied a helicoidal pipe. They found the heat transfer correlations of RP-3. Yuan et al. [14] proposed a new type of micro-fins helically coiled tubes. They developed a calculation model. Also, they analyzed the effects of five structural parameters on the total cost and effectiveness of the helically coiled tube heat exchangers. In their work, an adaptive multi-objective differential evolution algorithm was implemented.

The helical tubes are widely used in industrial applications such as HVAC systems, oil refinery systems, drug production systems, and heat exchangers. Almost, all of the mentioned applications include the main objective of this study which is to show how air injection affects the performance of helical tubes. So far, limited research has been conducted to investigate the effect of the air injection on the thermal performance of helical pipes with a downward flow. Hence, providing experimental results in this field could be valuable.

2. Experimental setup

The present experimental sample was constructed according to Moradi et al.'s [15] work. A pump guided water from a filled tank. Two valves were employed to adjust the volumetric flow rate. To determine the volumetric flow rate, a rotameter (KHL-08A01M-V mode) was also utilized. To generate airflow, a compressor was employed. Firstly, two streams (air and water) were mixed in a mixer then were fed to the test section. The test segment consisted of a helicoidal pipe that was equipped with a continuous heat flux. Figure 1 shows the geometrical parameters of the helix. The heater wires, having 1200 W maximum power capacity, were wrapped around the helix and generated a consistent heat flux. To ensure a permanent thermal energy, a 2 KW dimmer was utilized to modulate and measure the applied electric voltage. Furthermore, it should be noted that to decrease the heat loss, the helical tube was coated with a layer of glass wool with a thickness of around 1.5 cm. A digital manometer and a data logger recorded the pressure drop and temperature respectively. The pressure drop measuring probes were placed at the helical tube's entrance and outflow (points 1 and 2). It's worth noting that to measure the surface temperature, K-type thermocouples were used at each rotation of the helix.

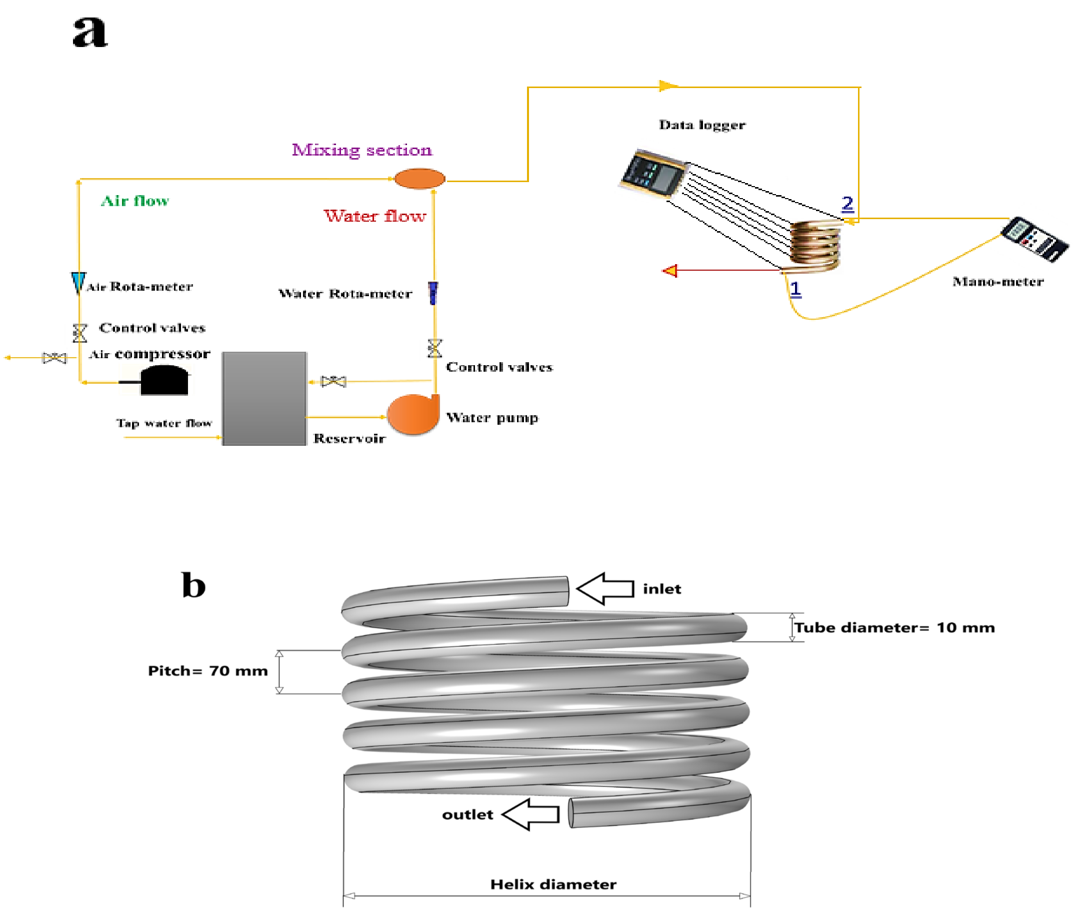


Figure 1. Schematic of the a) test section b) helix.

Herein, various helix diameters were studied. Table 1 shows the different case studies in this research. The helix had three distinct diameters: 10, 14, and 18 cm. However, the helix turn numbers were not constant at all cases (since this affects the length of the tube whereas the lengths of all coiled tubes were equal) and only the pitch of the coil was constant.

Also, air and water were combined at different flow rates. It should be noted that four distinct water flow rates and five distinct airflow rates were examined. The water temperature and air intake were kept practically constant. The entrance temperatures for water and airflow were around 12 ± 1 °C and 17 ± 0.5 °C respectively. The outlet temperature was recorded after the flow had achieved a thermally stable state (about 35 minutes). It's worth noting that the flow was always downward.

Table 1

Definition of the test condition.

Helix diameter (cm)	Water flow rate (Lit/min)	Airflow rate (Lit/min)	Flow orientation	Air inlet temperature (°C)	Water inlet temperature (°C)	Total exerted thermal energy (W)
10	2,4,6,8	1,2,3,4,5	downward	17 ± 0.5	12 ± 1	1200
14	2,4,6,8	1,2,3,4,5	downward	17 ± 0.5	12 ± 1	1200
18	2,4,6,8	1,2,3,4,5	downward	17 ± 0.5	12 ± 1	1200

3. Description of parameters

In this work, two important parameters including the Nu number and pressure drop are examined. Also, to obtain the optimal efficiency points for the real use, a performance criterion is applied to these parameters. The heat transfer coefficient is estimated by evaluating the flow's entrance and exit temperatures, and the tube's wall temperature [15, 16]. Utilizing Equation (1), the total thermal energy can be obtained from the fluid flow:

$$q = \dot{m}_w C_{p.w}(T_{out} - T_{in}) \quad (1)$$

where T_{in} and T_{out} are the temperatures of the flow stream at the inlet and outlet respectively. The working fluid's mass flow rate is $\dot{m}_w$, while the working fluid's specific heat capacity is $C_{p.w}$. It's worth noting that the fluid's film temperature is employed to attain the thermophysical properties of working fluids as follows:

$$T_f = \frac{T_b + \overline{T}_w}{2} \quad (2)$$

$\overline{T}_w$ is the tube's mean wall temperature, and T_b is the working fluid's bulk temperature in the equation above. The following equations are used to compute the aforementioned parameters.

$$\overline{T}_w = \frac{\sum_{i=1}^{i=10} T_{w,i}}{10} \quad (3)$$

$$T_b = \frac{T_{in} + T_{out}}{2} \quad (4)$$

The mixing portion and the test section's entry were separated by roughly 1 m, allowing the two flows to achieve a thermally stable condition. It should be mentioned that the amount of the thermal energy supplied by the air stream that can be transmitted to the water streams (in terms of the possible temperature difference) is extremely small, and the temperature difference at the water streams is negligible [17-19].

The heat transfer through the helical tube is via the convective mechanism. The following equation is employed to obtain the convection heat transfer coefficient.

$$\bar{h} = \frac{q}{A(\bar{T}_w - T_b)} \quad (5)$$

Finally, the Nusselt number (Nu) could be calculated by the below equation.

$$Nu = \frac{\bar{h}D_h}{K_f} \quad (6)$$

At which the Dh is the hydraulic diameter and the K_f was the conductive thermal coefficient of the working fluid.

Furthermore, the following equation is utilized to measure the pressure drop.

$$\Delta P = P_2 - P_1 \quad (6)$$

It is noteworthy, because of the existence of air bubbles in the mainstream, the manometer experienced fluctuations. So an average value of high and low pressure drop values (recorded in a 10 min period) is used. Also, the results are presented in terms of the volume fraction which is defined as below:

$$VF = \frac{Qa}{Qa + Qw} \quad (7)$$

Through which the terms Q_a and Qw are defined as the volumetric flow rate of air and the water flow rate.

4. Results and discussion

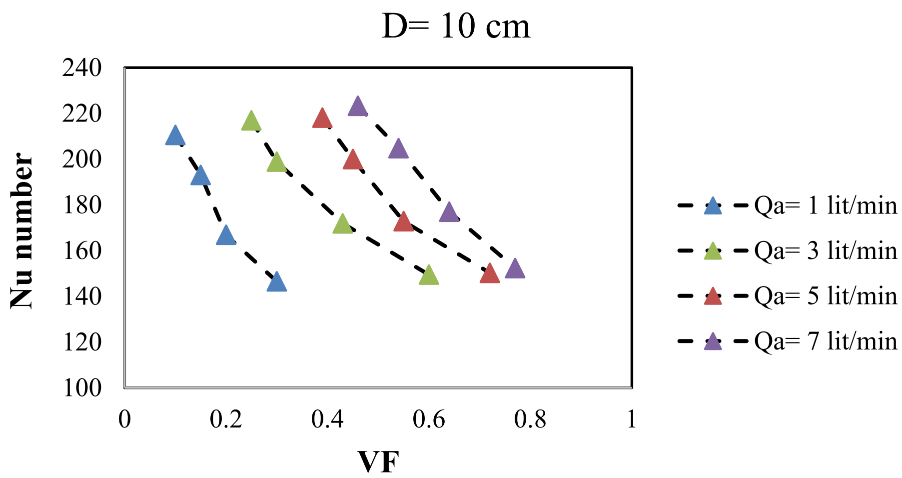
4.1. Heat transfer features

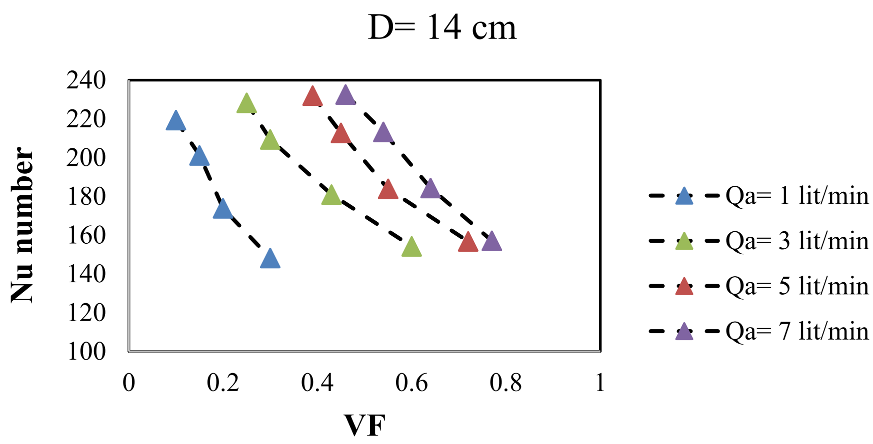
In fluid dynamics, the Nusselt number (Nu) is the ratio of the convective to conductive heat transfer at a boundary in a fluid. Convection includes both advection (fluid motion) and diffusion (conduction). The conductive component is measured under the same conditions as the convective but for a hypothetically motionless fluid. This number is a dimensionless number, closely related to the fluid's Reynolds number. This parameter is considered as a suitable criterion to study the heat transfer features, especially in helically coiled tubes.

Figure 2, shows the variation of the Nu number for different flow rates and helix diameter. It is obvious that by the increment of the volume fraction the values of the Nu number have decreased. In fact, by reducing the water flow rate, the intensity of the secondary flows experiences a reduction and this causes a decrease in the turbulence intensity. So, the boundary layer mixing phenomenon diminishes, and the heat transfer coefficient decreases. Besides, it was found that by the increment of the airflow rate the Nu number values increase. Indeed, when the airflow rate rises, the turbulence intensity goes up. The bubbles actually swap the boundary layer and prevent it from growing up. For as much as the heat transfer mode is the conduction in the boundary layer, as the thickness of the viscous layer remains in small sizes, the thermal resistance of the layer reduces so that the heat transfer rate enhances. Also, it is shown that the more helix diameter, the less Nu number. Indeed, when the helix diameter is decreased, the working fluid has less path to sweep and therefore leaves the tube immediately and consequently it has less time to transfer heat.

4.2. Fluid flow features

This part of the present work shows the results for pressure. Figure 3 represents the variation of pressure drop values in terms of volume fraction (VF) for helical tubes with different helix diameters. It is observed that by increasing the volume fraction, the values of the pressure drop were decreased. It's found that when the airflow rate goes up, so does the pressure drop. The improvement of the VF for a constant airflow rate is equivalent to the decrease of the water flow rate, as shown in equation 7. The decrease of pressure drop values by increasing VF is based on a reduction in water flow rates. Indeed, the less the water flow rate, the fewer coincidences, and consequently, the less the pressure loss. This phenomenon also decreases the turbulent intensity. Comparing the values of the pressure drop for all helix diameters, it is seen that by the enhancement in the diameter size the pressure drop values increase notably. The reason behind this behavior is based on the behaviors of the centrifugal forces. Indeed, the centrifugal forces experience a reduction in the higher helix diameter resulting in the lower frictional effect of swirling flows on the main stream. On the other hand, the force of gravity in coincidence with the buoyant force (which is applied on the air bubble and acts in the opposite direction of the gravity) causes the increment of the pressure drop. This force is higher in a helix with a bigger diameter. The higher pressure drops through the tubes with helix diameters of 10, 14, and 18 cm were about 352.27, 370.09, and 402.35 m bar. It is noteworthy that the presented total pressure drop values in Figure 2 were the average of the minimum and maximum of the pressure drops which were seen through the 5 minutes of a testing period. This period was considered to ensure that the flow has reached its repeatable condition.





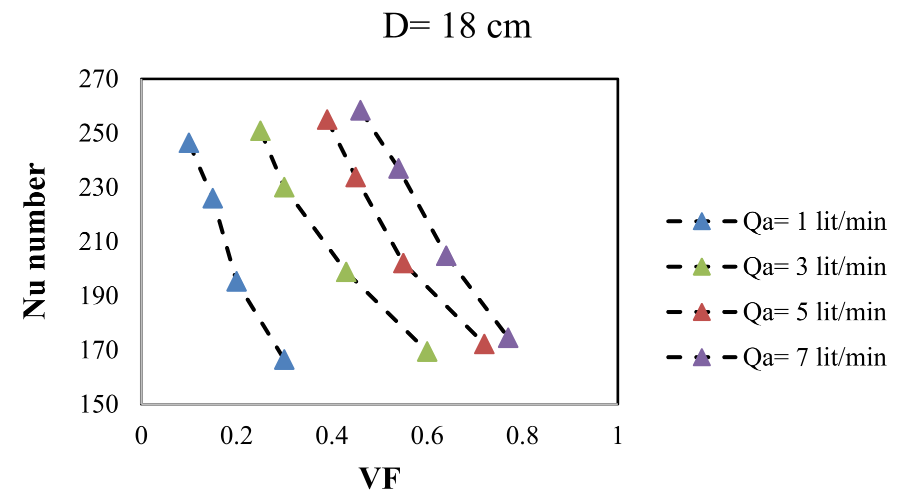
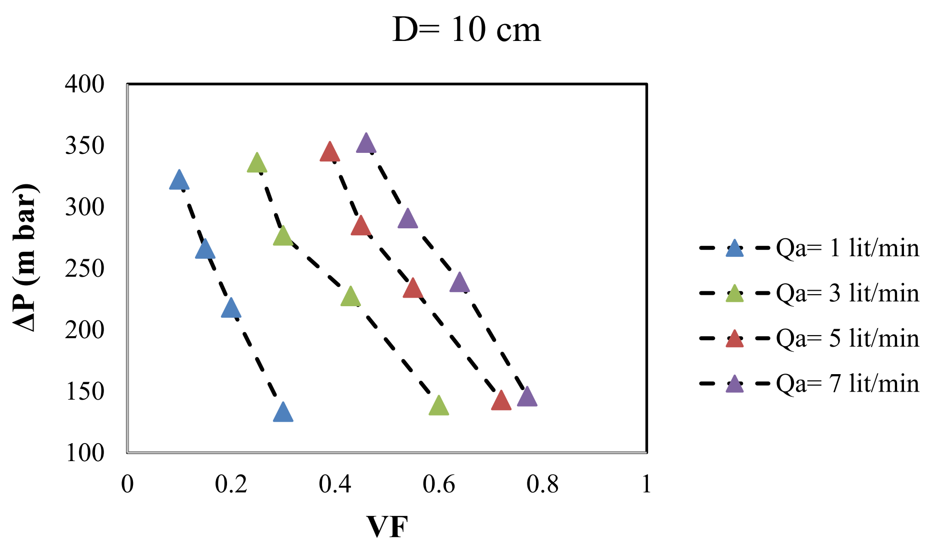
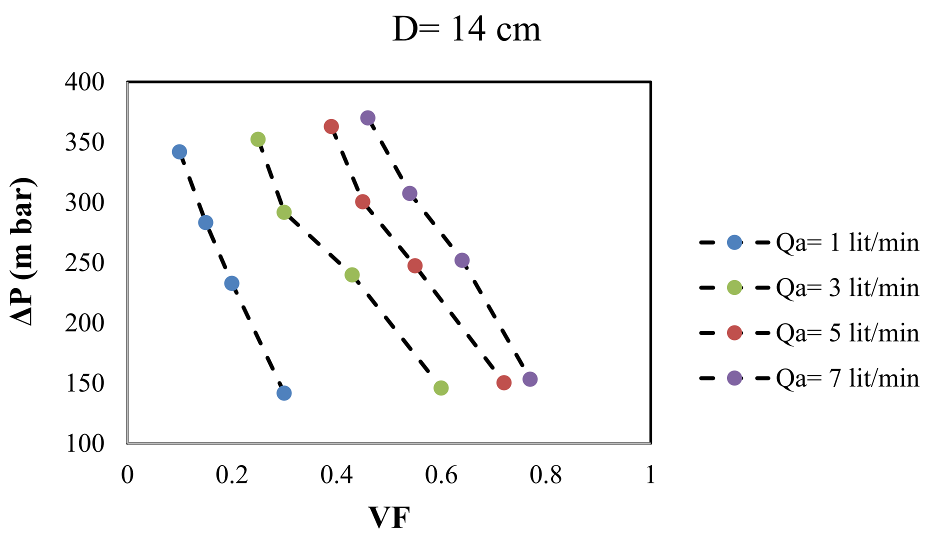


Figure 2. Comparison of Nu numbers for different flow rates and volume fractions.





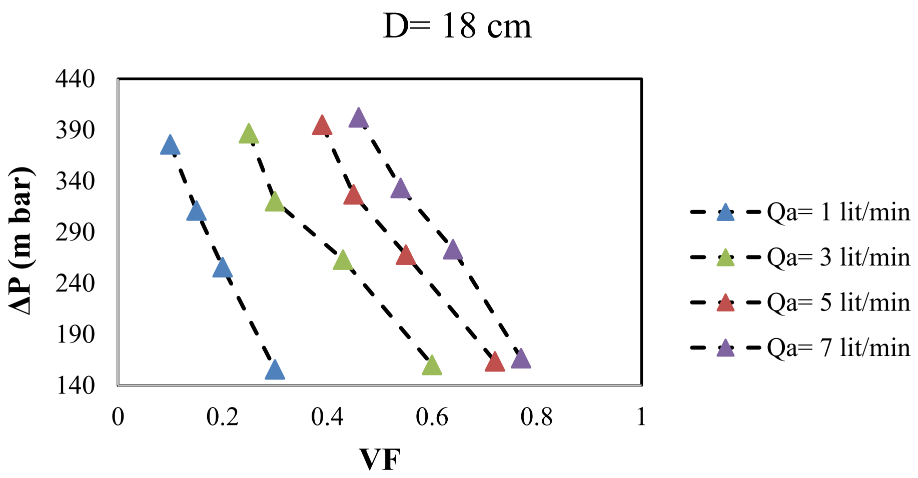


Figure 3. Comparison of pressure drops for different flow rates and volume fractions.

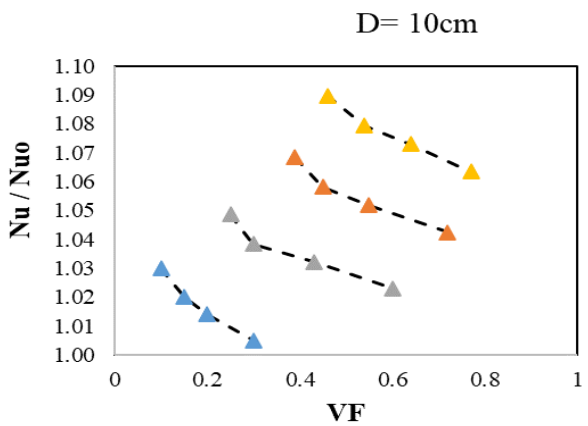
4.3. Assessment of the Cost Benefit Ratio (C.B.R.) factor

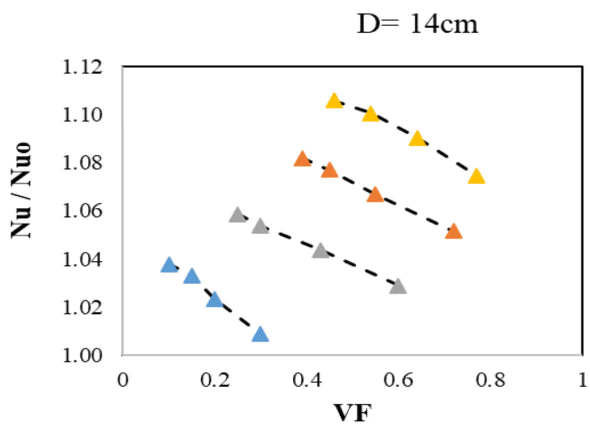
The Cost Benefit Ratio (C.B.R.) factor was defined based on Equation 8 which represents the ratio of the percentage of the pressure drop fluctuation to the ratio of the percentage of the Nu number variation [20].

$$\text{C.B.R.} = \frac{\%(\frac{\Delta P_i}{\Delta P_0})}{\%(\frac{Nu_i}{Nu_0})} \qquad (8)$$

For this aim, firstly $\frac{Nu_i}{Nu_0}$ and $\frac{\Delta P_i}{\Delta P_0}$ were needed. It is worth noting that the "o" index indicates the state without bubble injection and the "i" index indicates the state with bubble injection. Figures 4 and 5 display these factors respectively.

Figure 4 represents that the Nu number ratio is somehow always greater than one and increases by increasing the air injection flow rate. Indeed, injecting air bubbles promotes turbulent factors by increasing local Reynolds number and making coincidences. These coincidences are defined between bubbles, bubbles and water parts, and bubbles and solid walls. The collision between air bubbles and solid walls disrupts the boundary layer, which increases the heat transfer rate. Also, according to Figure 5, it can be found that the maximum pressure drop ratio has the value of 1.25. The pressure drop ratio almost decreases as the volume fraction rises.





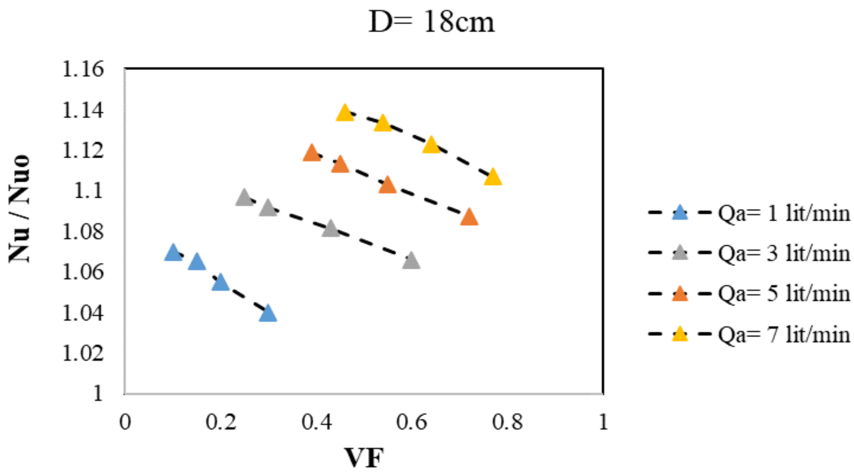


Figure 4. Nusselt number ratio versus the volume fraction for different flow rates and the helix diameter.

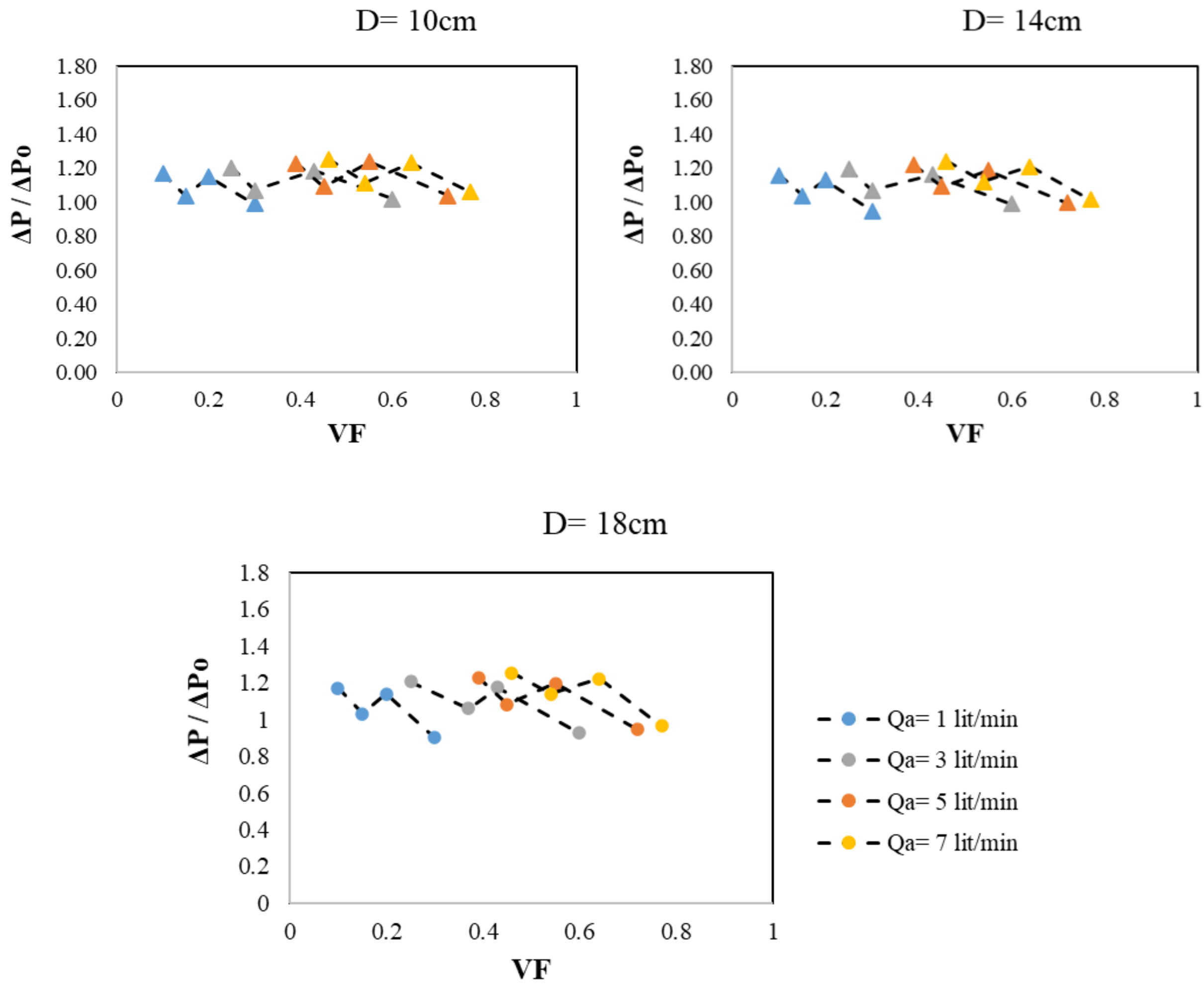


Figure 5. Pressure drop ratio versus the volume fraction for different flow rates and the helix diameter.

It should be noticed that the C.B.R. values under one demonstrate that the considered method leads to more heat transfer enhancement than the pressure drop increment. The behavior of the C.B.R. values is displayed in Figure 6. It is obvious that the graph trend is so similar to that of the pressure drop. The results show that pipes with bigger diameters have the highest values of the C.B.R. factor. It means that air injection in the tubes with larger diameters was more beneficial than in the tubes with smaller helix diameters. The best value was attained for the helix diameter of 18 cm and VF of 0.33 with a C.B.R. factor of 0.84. Also, the worst value was 1.18 for a helix diameter of 10 cm.

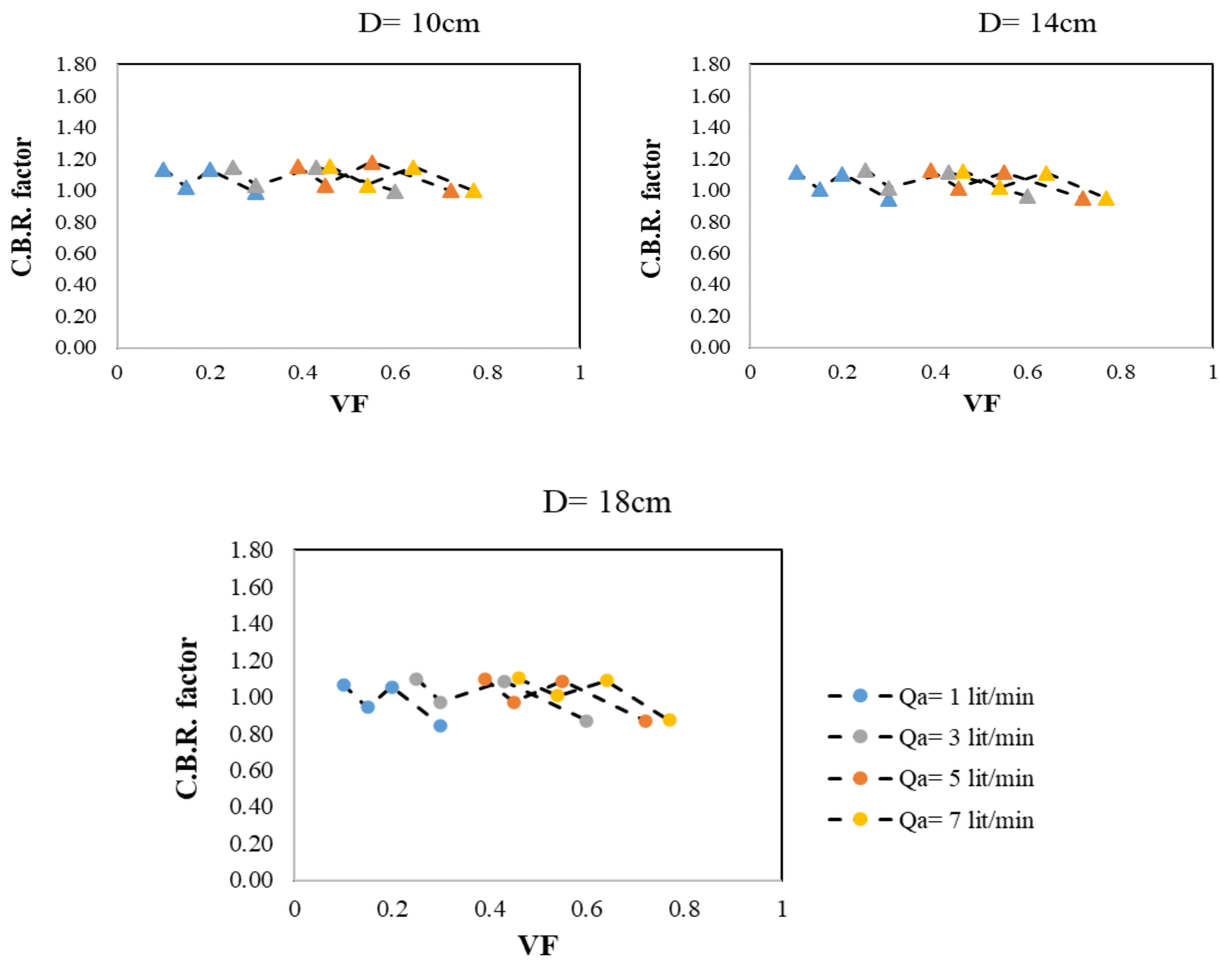


Figure 6. C.B.R. factor versus the volume fraction for different flow rates and the helix diameter.

5. Conclusions

The present study was an experimental investigation for the effect of air injection on the productivity of the helical tubes. Herein, some parameters such as volume fractions and helix diameters were studied. The mainstream was considered downward and the walls of the tubes were under a constant heat flux of 1200 W. Three different helix diameters of 10, 14, and 18 cm were fabricated to study the effect of the Helix diameter. Also, the VF was in the range of 0.11 to 0.77. The achieved results are shown as follows:

- By the increment of the volume fraction, the values of the Nu number have decreased.
- The results revealed that the augmentation of the airflow rate increases the values of the Nu number Because the turbulence

intensity goes up when the airflow rate rises. The bubbles actually swap the boundary layer and prevent it from growing up.

- It was concluded that by the increment of the helix diameter, the Nu number increases.
- It was observed that by increasing the volume fraction, the values of the pressure drop were decreased.
- It's found that when the airflow rate goes up, so does the pressure drop.
- Comparing the values of the pressure drop values for all helix diameters it was seen that by the enhancement in the diameter size the pressure drop value increased notably. However, the centrifugal forces experience a reduction in the higher helix diameter, the force of gravity helps the flow to move through the tube rapidly in the downward stream so the pressure drop depends on the friction force. This force is higher in a helix with a bigger diameter. The higher pressure drops through the tubes with helix diameters of 10, 14, and 18 cm were about 352.27, 370.09, and 402.35 m bar.
- The results showed that the pipes with bigger diameters had the highest values of the C.B.R. factor. It means that air injection in the tubes with larger diameters was more beneficial than in the tubes with smaller helix diameters. The highest value was attained for the helix diameter of 18 cm and VF of 0.33 with a C.B.R. factor of 0.84. Also, the lowest value was 1.18 for a helix diameter of 10 cm.

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