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Air Injection Impact on Thermal Performance of Vertical Tube with Helical Corrugations: Upward Flow

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A B S T R A C T

In this experimental work, the 2-phase air-water non-boiling ascending fluid flow in a vertical tube with helical corrugations has been investigated. The results showed that the head loss values decreased with an increase of the volume fraction. Also, by comparing the head loss values for each corrugation pitch, it can be observed that as the corrugation pitch goes down, the head loss values significantly increase. As a result, the intensity of vapors increases perpendicular to the main flow of water, which leads to an increase in the intensity of disturbance in the flow, and then the head loss increases. The Nusselt number goes down when the volume fraction experiences an increment. Looking at the figures related to Nusselt number, it is easy to see that the curves are drawn for a constant air flow rate. Consequently, an increase in volume fraction (VF) is equal to a decrease in the water flow rate. By reducing the water flow rate, the intensity of the main flow is reduced the intensity of turbulence is also reduced and the heat transfer coefficient is reduced. As a result, the amount of heat transfer has increased due to air injection. It should be noted that pipes with the largest corrugation pitch had the best Cost-benefit ratio (C.B.R.) factor values (which means the lowest value). This means that air injection in larger corrugation pitch tubes was more beneficial than in smaller corrugation pitch tubes.

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INTRODUCTION

The flow inside the pipes is one of the most important fluid flows, which is widely used in most sectors of various industries. Most heat exchangers use the same equipment. As mentioned earlier, increasing the rate of heat transfer in heat transfer phenomena is one of the key goals of researchers and engineers. Many energy and exergetic studies have been carried out in connection with the mentioned topic. Investigating techniques for increasing heat transfer in vertical pipes increases thermal efficiency and reduces heat losses in energy systems where these equipment are used [1]. Among the techniques for increasing thermal efficiency, passive methods have received more attention since they do not require an external activator. Turbulators like twisted strips, fins, discs, metal porous foams, and screws are used to increase the velocity gradient and turbulence in the vicinity of the walls and are used as a tool to improve heat transfer [2, 3]. A numerical simulation was performed by Huang et al. [4] on the absorber tubes of a solar collector. Absorber tubes were considered to be deep depressions. They showed that the use of hollow pipes can improve the thermal performance of the system. Bellos et al. [5] investigated the enhancement of heat transfer in the energy system using tubes with corrugated walls. They showed that the modified geometry of the wall as well as the 2-phase flow of nanofluids increased the thermal efficiency by about 4.55.

Extensive studies showed that grooved pipes have become an interesting case for experts and designers since they have improved thermal efficiency and anti-fouling

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configuration. These pipes are used as an alternative for smooth simple tubes in several industrial uses like gas or oil purification plants, the process of chemical engineering, food preparation procedures, manufacturing application, and so on [6–8]. It is worth considering here that in most of these industrial applications, it is possible to refer to a form of several phases, the flow in which the gas or liquid 2-phase flow is more considerable. In addition, new research has suggested the gas or liquid 2-phase flow as a non-passive technique for increasing heat transfer can be proposed by Mahdi Heyhat et al. [9] and Khorasani et al. [10]. Because of the various configurations of gas or liquid 2-phase flow compared to one-phase flows, the thermal efficiency of 2-phase flows is improved. Scientists have checked the features of these species in the smooth pipes. Because the characteristics of gas or liquid 2-phase flow vary with changes in the 2-phase ratio, tube shape, and flow direction, the investigation on determining the influence of the mentioned parameters will be of considerable value. Kim and Ghajar [11] carried out experimental research to investigate the flow layouts and frictional thermal features of gas or liquid 2-phase flow in a straight pipe. They mentioned that adding a gas phase to a liquid flow increases the action and reaction, which leads to a kind of turbulence and mixing, leading to an increase in the heat transfer rate. Kim and Ghajar [12] developed an empirical equation to predict the 2-phase flow coefficient in a straight pipe for heat transfer. In their work, they aimed to provide a correlation to be able to estimate the heat exchange coefficient over the entire range of patterns of flows in a straight pipe. Also, new correction factors to correct the previously suggested correlations were presented. An experimental and numerical study conducted by Lopez et al. [13]. They investigated the features of gas-liquid 2-phase flow in straight tubes. Meanwhile, Thaker and Banerjee [14] studied the smooth pipe. They suggested new correlations to predict flow features. Abazari Bahnemiri et al. [15] investigated the effects of nanoparticles and variations in tube diameter on heat transfer coefficients in spiral shells and tube heat exchangers. The CFD analysis, as well as the model of the aforementioned heat exchanger, was performed by coding in MATLAB for two systems including forced convection heat transfer and cryogenic cooling in single-phase fluid flow. Umayal Sundari et al. [16] worked on solar collector tubes. They experimentally studied boiling phenomena in these tubes. They studied the impacts of various factors on the system efficiency. In another work, Bagheri et al. [17] stated that the study of boiling as a new field is suitable for various research and industrial needs, including heat treatment in nuclear power plants, refrigeration equipment, rocket equipment, electric refrigeration, batteries, etc. Sidewall steam and air at the same temperature were analyzed in three dimensions. To do this, they first looked at the temperature prediction of the type of boiling in the form of nuclear boiling. In Liu et al. [18] work, the evaporation properties of inactive droplets on a hydrophobic surface in non-boiling mode at a constant temperature were studied. The results showed that droplet evaporation time has a positive relationship with initial surface size and hydrophobicity, but a negative relationship with surface temperature during droplet evaporation on a hydrophobic surface. Luo et al. [19] reported that understanding the mechanisms of heat transfer in non-boiling areas under seismic conditions is limited in the existing literature. Their study filled this gap by numerically investigating the heat transfer behavior of spray cooling in jointless regions under vibration using the Lagrangian-Euler method. To validate the computational fluid dynamics (CFD) model, spray heat transfer measurements were performed with a vibrating hot surface tester.

According to the presented materials, it seems that research and development in the field of using grooved pipes and using 2-phase flow to improve heat transfer and increase efficiency is one of the main topics of interest to scientists in the field of optimal use of energy and increasing efficiency. While 2-phase currents are used in common industries such as textile industries, agricultural industries, and industrial products, they also have special applications in industries such as power generation and electric energy. Therefore, studying the development of the use of grooved pipes and the 2-phase flow of water and air can be important and necessary. According to the studies carried out so far in the field of heat transfer of 2-phase flow of water and air in a grooved pipe, no experimental, numerical, or analytical study has been done, from this point of view, there are no valid experimental results for the use of those interested.

EXPERIMENTAL SETUP

To implement this project, an experimental system will be designed and implemented as described below. Then, the studied cases will be examined using the primary data obtained from the laboratory system. The general system used for testing is shown in Figure 1. The laboratory system consists of 2 or three main parts. The first part is related to the flow of water. City water after being filled in a chamber is pumped to the tank of a circulator pump. It is used in order to precisely adjust the placement. Then, a bypass is used to measure the flow rate of water from 2 flow-regulating valves, one in the main direction and the other in the direction of the water rotameter for the flow rate.

In the second part, the airflow is provided by a compressor, and after being regulated by 2 air valves, it enters the mixing chamber. The volume flow rate of air is measured by an air rotameter. The third part is related to the testing chamber. The testing chamber consists of a grooved copper tube that is subjected to constant thermal flux. Heat flux is applied to the tube by wire heaters that are rotated around the tube. To ensure the stability of the thermal flux, a dimmer is used to regulate the applied voltage. In order to check the heat transfer coefficient and the entropic behavior of the 2-phase flow, the temperature of the pipe surface, the temperature of the fluid at the inlet and outlet, and also the ambient temperature are measured by thermal thermocouples. To reduce heat loss, a layer of glass wool is used as insulation. It is worth mentioning that the laboratory data are recorded after the system reaches a thermally stable state.

It should be noted that the airflow will be supplied by a compressor with a power of 1.2 horsepower. The flow rate of the air entering the testing chamber will be measured by a rotameric flow meter (model KHL-08A01M-V). As shown in Figure 1, the 2 streams of water and air are then mixed in a mixing chamber. Figure 2 shows the overview of the mixing chamber. As shown in Figure 2, the end of the tube carrying the airflow is closed, to inject the airflow, 20 holes with a diameter of 0.3 mm will be created in 2 rows of 10 at the end of the tube. These 2 rows will have an angle of 180 degrees. After exiting these holes, the airflow will mix with the water flow and form a non-boiling 2-phase flow of water and air. The air-water mixture flow then passes through a 0.7-meter pipe, which is considered for the thermal balance of the air-water flow (it is assumed that the air-water flow may have a temperature difference at the beginning, this distance is equal to this. It is considered that all the heat transfer in the testing chamber is from the heat produced by the thermal element and the heat exchange between the 2 fluids is negligible) into the testing chamber. It is necessary to explain that to check the changes in the forced convection heat transfer coefficient, the inlet and outlet temperature of the water-air mixture and the pipe surface temperature will be measured. The temperature of the mixture will be measured by K-type penetrating sensors (designed for liquid flow), and the surface temperature by K-type surface sensors (designed to measure surface temperature). A Lutron brand 12-channel data logger (Lutron-BTM4208-SD) will also be used to record and display temperatures (temperature sensors are connected to the data logger). To check the amount of head loss, a Lutron brand digital head loss gauge (Lutron-PM9100) is used. 2 head loss detection sensors will be installed at the beginning of the tube and the end of it.

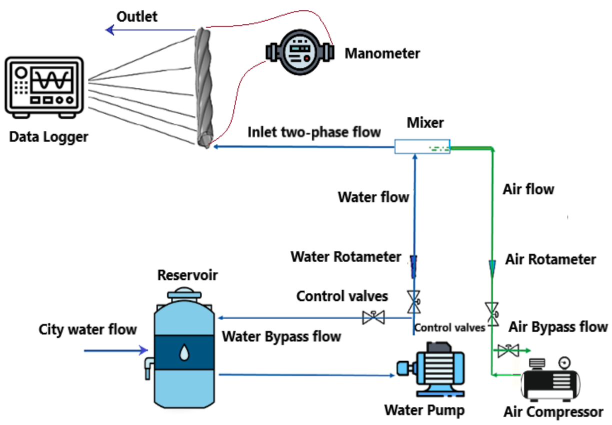

Figure 1. Proposed test section schematic

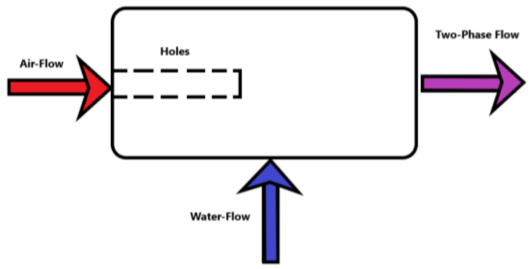

Figure 2. Mixing chamber

The present study is designed in such a way that for the upward flow (in this case, the buoyancy force on the bubble and the inertial force of the liquid flow act in the same direction) and the effect of air and water flows (mixing ratio, which has a direct effect on the flow pattern) has, the changes in the flow determine the effect of the inertial force of the flow) and the effect of the changes in the corrugation pitch in the formation of the flow pattern and heat transfer will be investigated. Table 1 briefly shows how to investigate the effect of the mentioned parameters on the thermal behavior and flow pattern of the helical pipe. It is worth mentioning that in this study, air bubbles will be injected into the water flow to form a 2-phase flow. A glass tube will be used to observe the flow in each step in order to check the flow regime. A Canon SX 530 model camera is used to view the stream and record images. To check the thermal behavior, a copper tube, which will be equal to the glass samples in terms of geometrical characteristics, is subjected to a constant thermal flux (the amount of thermal flux will be less than the critical flux required for boiling to ensure the non-boiling current) be) will be placed.

DEFINITIONS FOR USED PARAMETERS

Two main parameters composing Nu number and head loss, are tested in this study. A performance criterion is

Table 1. Initial conditions

Helical corrugation pitch (cm)	Water flow rate (Lit/min)	Airflow rate (Lit/min)	Flow orientation	Heat flux (W)
1	2,4,6,8	1,3,5,7	upward	1200
1.5	2,4,6,8	1,3,5,7	upward	1200
2	2,4,6,8	1,3,5,7	upward	1200

applied to these parameters to obtain the optimal efficiency points for real usage. Assessing the temperatures of the flow's entrance and exit, and the pipe wall temperature, the heat transfer coefficient is estimated. Using Equation (1), the total thermal energy may be harvested from the fluid flow:

$$q = \dot{m}\, C_P(T_{out} - T_{in}) \tag{1}$$

Having fluid motion leads to a convective form of heat transfer. To obtain the convection heat transfer coefficient, the following equation is used:

$$\bar{h}_{NST} = \frac{q}{A\,(\overline{T_w} - T_b)} \tag{2}$$

Also, Nusselt number (Nu) may be computed by the below equation:

$$Nu = \frac{\bar{h}D}{k_f} \tag{3}$$

where D is the diameter and k_f is the conductive thermal coefficient of the working fluid. C.B.R parameter or cost-benefit ratio is a suitable parameter to check the performance of any heat transfer enhancement method. This parameter is defined as follows:

$$C.B.R = \frac{\%(\frac{\Delta P_i}{\Delta P_0})}{\%(\frac{Nu_i}{Nu_0})} \tag{4}$$

It should be acknowledged that this study has limitations. In the first step, these restrictions are related to the construction of grooves inside the pipe which required a relatively precise and complex process. Another limitation was the adjustment of flow rate and pressure in the study, the smallest mistake in these two parameters strongly affected the results.

Two-phase flow is much more complicated than single-phase flow. Transactions between liquid and gas flow inside the pipe make it difficult to model these types of flows employing modeling software or mathematical models. Two-phase flow depends on many parameters, including the nature of the gas fluid, the nature of the liquid fluid, and the pipe material.

The total mass flow rate transferred in the pipe ($\dot{m}$) is equal to the sum of the gas fluid mass flow rate ($\dot{m}_G$) and the liquid fluid mass flow rate ($\dot{m}_L$).

$$\dot{m} = \dot{m}_G + \dot{m}_L \tag{5}$$

The porosity coefficient (α) is the ratio of the surface covered by gas to the surface covered by the total flow of gas and liquid and is determined as follows.

$$\alpha = \frac{A_G}{A} \tag{6}$$

RESULTS

Error analysis

Usually, in engineering sciences, physics, and chemistry, "Observational Error" or "Measurement Error" is considered to mean the difference between the measured value and the actual value. But in statistics, the error is not considered just a mistake in measurement. Changes and errors in the measurement of random phenomena are in their nature. Otherwise, we would not consider such events as coincidences. In laboratory work, error sources can be divided into two main groups:

- Systematic errors: Errors that are not caused by accident and depend on the measurement tools or the measurement process are called systematic errors. In this way, the systematic error lies in the essence of the measurement method or system.
- Random errors: If we repeat the measurement operation several times, the error resulting from this operation is called a random error. Because the conditions and factors affecting the measurement cause inconsistency in recording the correct value for a quantity.

The number of suggested experiments in the CCD plan is 20 for independent input parameters, of which the final 5 experiments are repeated. The purpose of conducting repetitive tests is to prevent human error and to check reproducibility when conducting tests. Based on the data obtained in the 16th to 20th iterations of the tests for the power, the random error is given in Figure 3. It should be noted that the error has been calculated as a percentage of relative error as follows:

$$error\% = \frac{|C.B.R._{16-20} - C.B.R._{15}|}{C.B.R._{15}} \times 100 \tag{7}$$

Fluid flow features

This section of the paper analyzes the hydraulic performance of the combination of air and water flows inside spiral tubes. Figure 3 shows the changes in pressure loss values according to volume fraction (VF) for pipes with various spiral corrugation pitches. It may be observed that the pressure loss values decrease with the increase in volume fraction. The amount of volume fraction is calculated from Equation (8).

$$VF = \frac{Q_g}{Q_g + Q_l} \tag{8}$$

It is worth noting that the reduction of pressure loss values with the reduction of VF is based on the reduction of the water flow rate, which is visible. It is important to know that reducing the speed of water flow reduces the impact between air bubbles and liquid water packets, as well as the head loss. An increase in the speed of the airflow equals an increase in the size of the bubbles and a stronger collision between the bubbles and the water elements. By comparing the head loss values for each corrugation pitch, it may be observed that as the corrugation pitch goes down, the head loss values go up significantly. This is due to the increased circulation of water in the pipe. As a result, the intensity of vapors increases perpendicular to the main flow of water, which leads to an increase in the intensity of disturbance in the flow, and then the head loss increases. It should be noted that the total pressure loss values presented in Figure 4 are the mean values for minimum and maximum head losses observed during a 5-minute test period. This period was considered to ensure that the flow has reached its reproducible conditions. It should be mentioned that the head loss through combined gas and liquid flows has an oscillating behavior so the results are presented as average values.

In Figure 5, the head loss ratio is extracted for three corrugation pitches. The ratio of head loss is defined as a 2-phase head loss (ΔPi) and a single-phase head loss (ΔP0). It can be seen that the head loss ratio decreases with the increase in volume fraction.

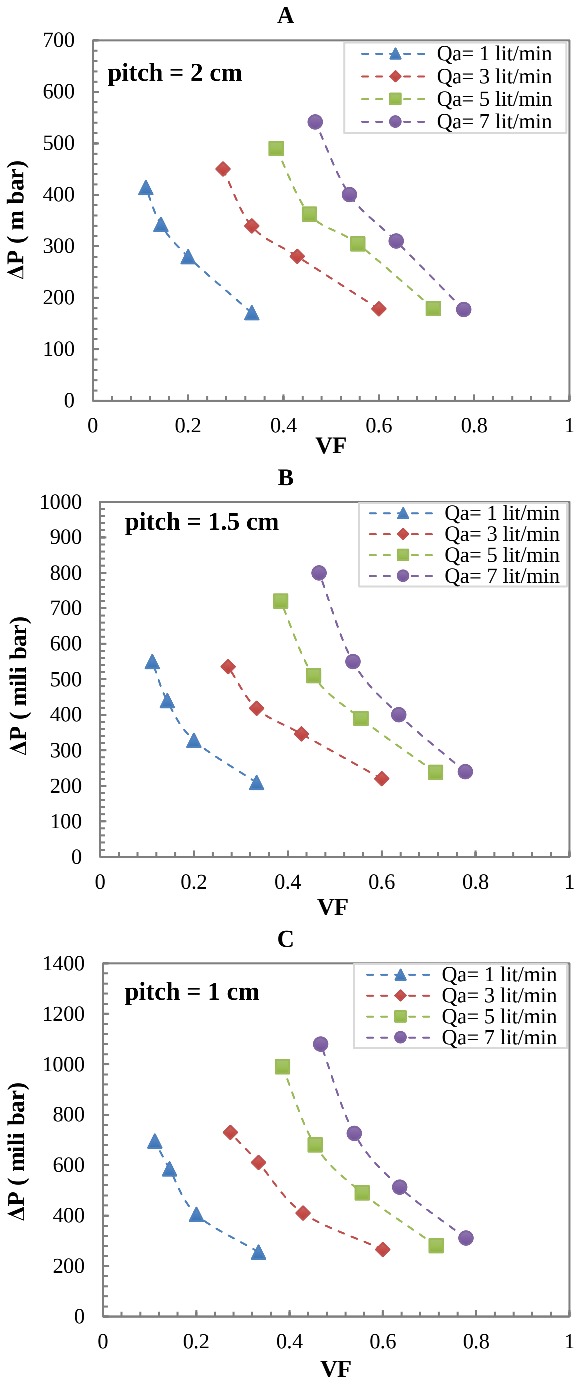

Figure 4. Variation of head loss versus volume fraction (VF) for different corrugation pitches A) Pitch = 2 cm, B) Pitch = 1.5 cm, C) Pitch = 1 cm

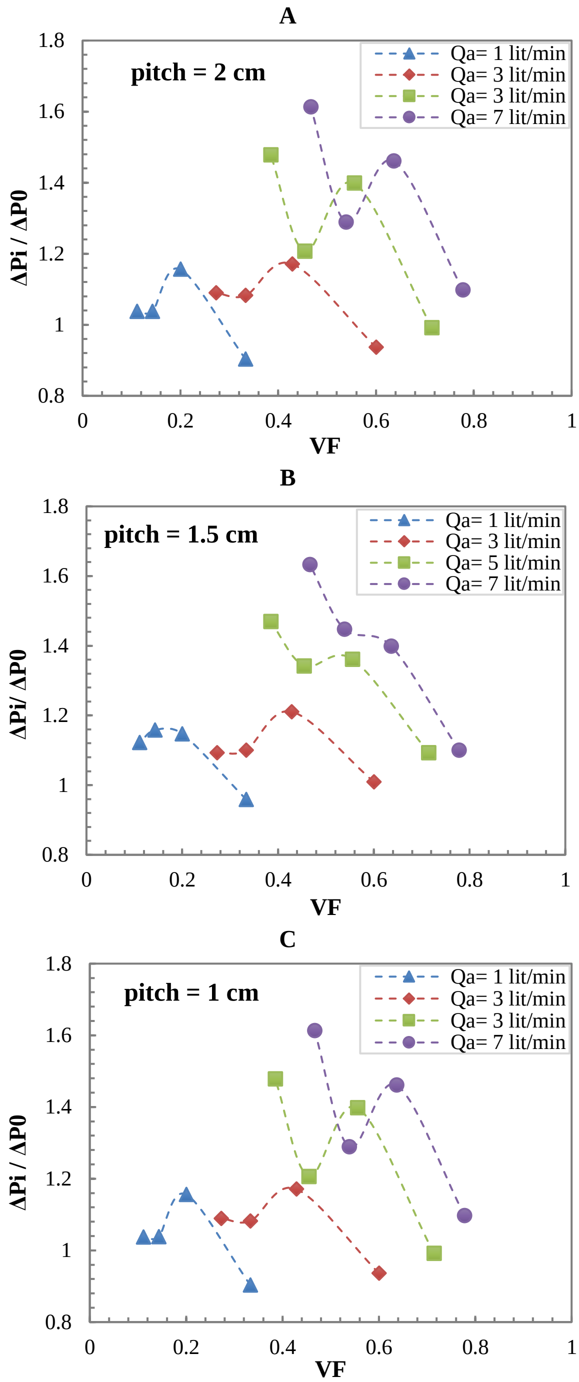

Figure 5. Changing the ratio of head loss versus volume fraction A) Pitch = 2 cm, B) Pitch = 1.5 cm, C) Pitch = 1 cm

Heat transfer evaluation

It is necessary to explain that in the process of evaluating thermal behavior, the best parameter is the Nusselt number. In fluid dynamics, the Nusselt number (Nu) is the ratio of displacement heat transfer to conduction at a boundary in a fluid. This number is a dimensionless number that is closely related to the fluid Reynolds number. Figure 6 shows the behavior of Nusselt number versus volume fraction for different corrugation pitches. The results show that the Nusselt number decreased with the increase in volume fraction. Looking at the figures related to Nusselt number, it is easy to see that the curves are drawn for a constant air flow rate. Consequently, an increase in VF is equal to a decrease in the water flow rate. By reducing the water flow rate, the intensity of the main flow is reduced the intensity of turbulence is also reduced and the heat transfer coefficient is reduced. The intensity of the flow turbulence increases with the increase of the airflow speed. It should be noted that when the velocity of the airflow increases, the size of the bubbles also increases [20], resulting in a stronger collision between the air bubbles and the water packets. Also, when the bubbles move inside the tube, they change the boundary layer, which means they interrupt the unified boundary layer in a discrete part and prevent it from strengthening. As the boundary layer remains in the initial conditions, the thickness of the viscous layer decreases. Viscous layers are part of the liquid and since there are very slow movements inside them, displacement has almost no role in heat transfer and is the main conduction mechanism. As a result, by keeping the thickness of the viscous layer small, the thermal resistance of the layer decreases so that the heat transfer increases. The maximum values of the Nusselt number correspond to the pipe with the smallest corrugation pitch. Figure 7 shows that the ratio of the Nusselt number in the injected air state to that of the base state is almost always greater than one. As a result, the heat transfer rate has increased due to air injection. In fact, with air injection, the effective cross-sectional area for each of the phases is reduced, making them pass faster. On the other hand, the collision of air bubbles with the solid wall of the spiral tube causes the boundary layer to collapse, which increases the heat transfer as mentioned before. Bubbles move in the central area of the tube without any connection with the outer or inner wall of the tube. In these conditions, both sides of the boundary layer are affected by the presence of air bubbles, and the mixing phenomenon increases in both boundary layers (boundary layers created on the inner wall and the outer wall) and heat transfer is improved.

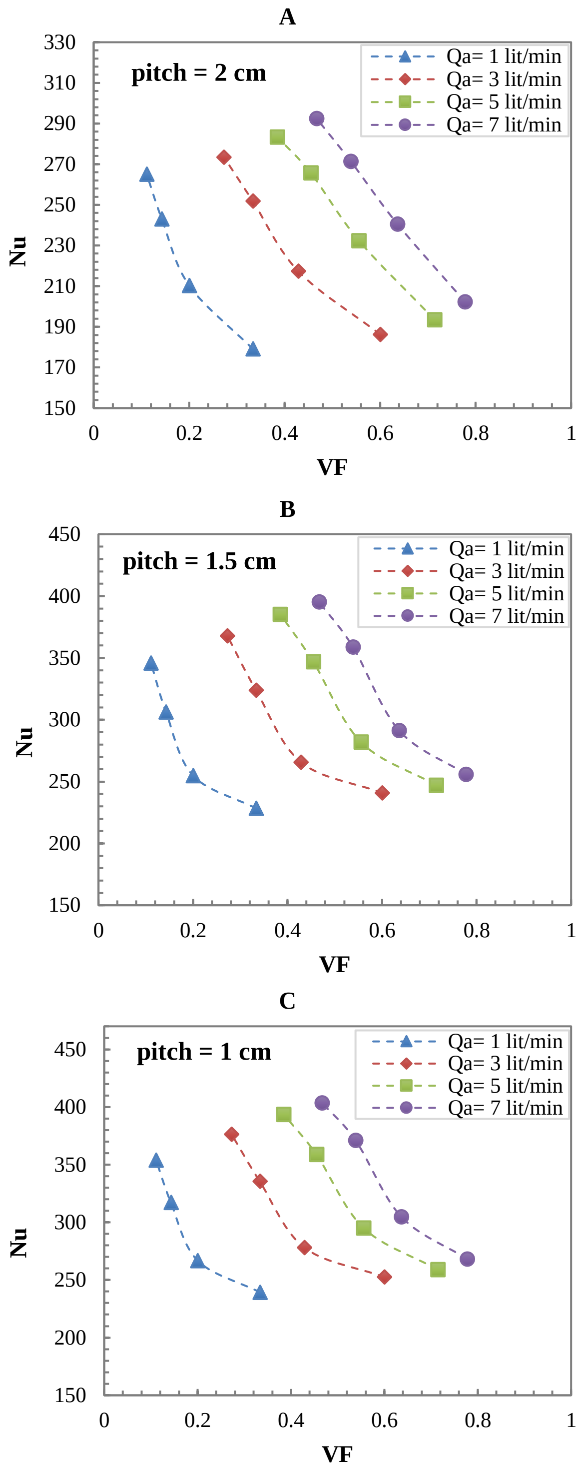

Figure 6. Change of Nusselt number versus volume fraction (VF) A) Pitch = 2 cm, B) Pitch = 1.5 cm, C) Pitch = 1 cm

C.B.R factor assessment

This variable defined in Equation (3), is an operational parameter and determines whether the considered heat transfer enhancement method is useful or not. Values below one for this criterion indicate that the proposed methodology causes an increase in heat transfer more than an increase in pressure loss. Values greater than one have the opposite meaning. The C.B.R values manner is shown in Figure 8. The curves are plotted in terms of VF and for different air flow rates as in the previous figures. Pipes with the largest corrugation pitch had the best C.B.R. factor values which means the lowest value). This means that air injection in larger corrugation pitch tubes was more beneficial than in smaller corrugation pitch tubes.

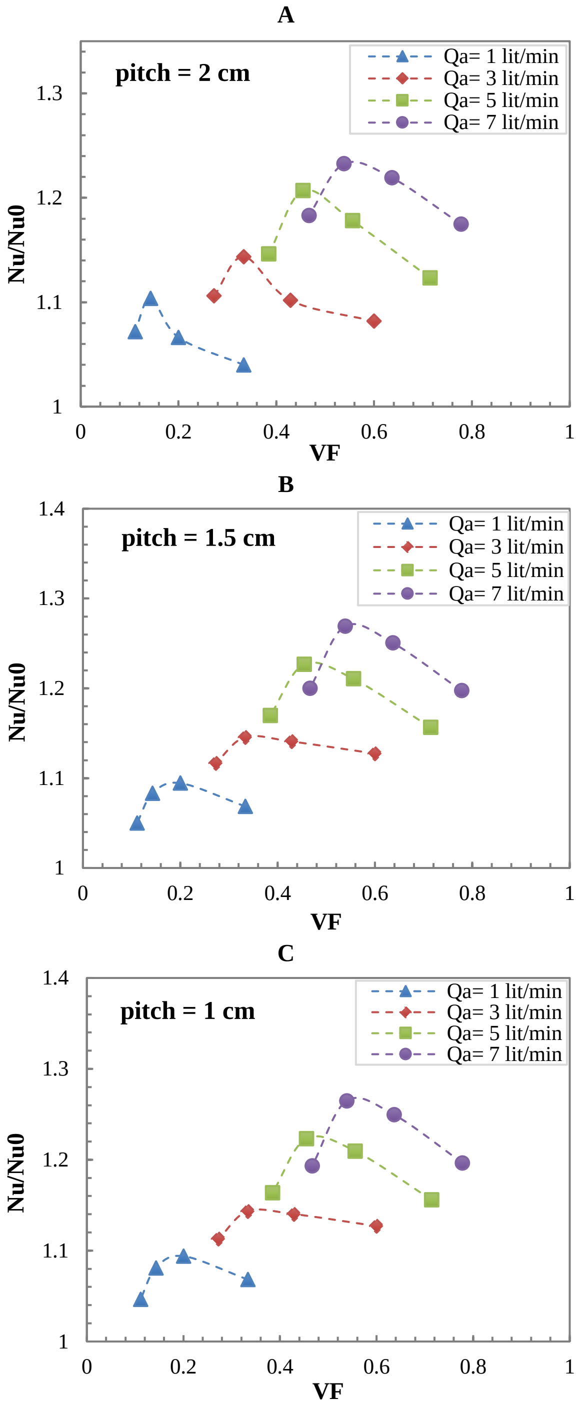

Figure 7. Change of ratio of Nusselt number against volume fraction A) Pitch = 2 cm, B) Pitch = 1.5 cm, C) Pitch = 1 cm

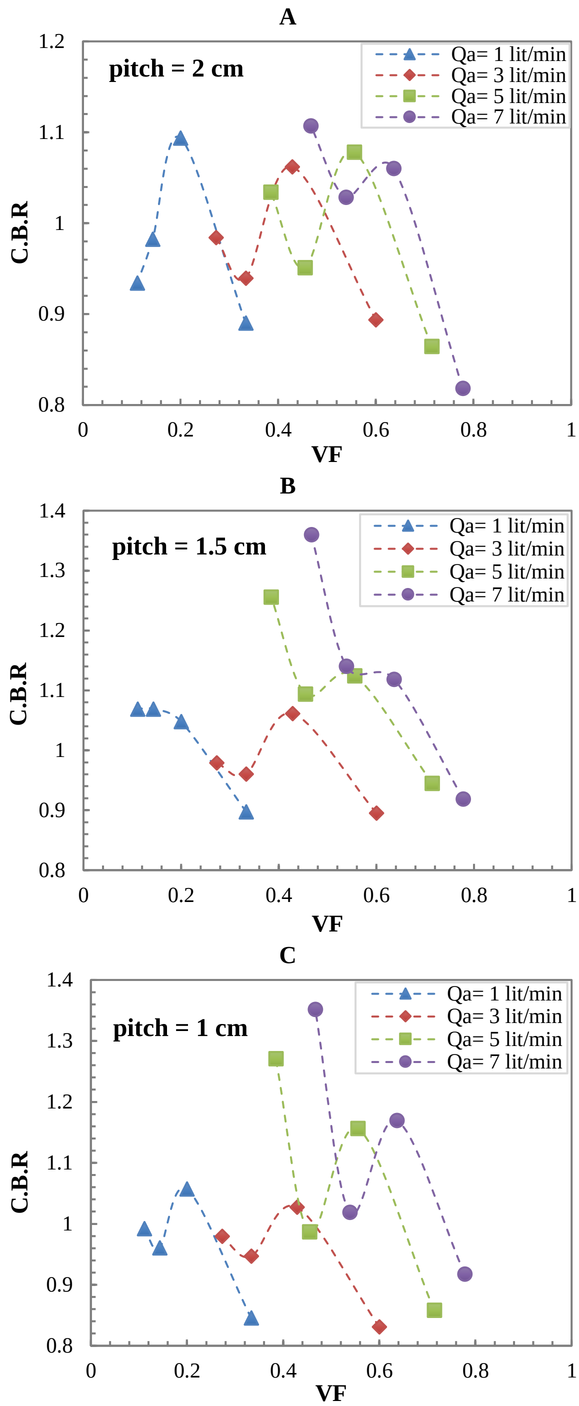

Figure 8. Change of C.B.R factor against volume fraction A) Pitch = 2 cm, B) Pitch = 1.5 cm, C) Pitch = 1 cm

CONCLUSION

This research studies experimentally the 2-phase non-boiling air and water ascending flow in a vertical pipe with a helical corrugation on it. The upcoming study is a laboratory work that studies heat transfer and pressure loss. Four flow rates for air with values of 1, 3, 5, and 7 liters per minute and four flow rates for water with values of 2, 4, 6, and 8 liters per minute are considered, and three corrugation pitches are 1, 1.5, and 2 cm is included in the present study. The number of suggested experiments in the CCD plan is 20 for independent input parameters, of which the final 5 experiments are repeated. The purpose of conducting repetitive tests is to prevent human error and to check reproducibility when conducting tests. Based on the data obtained in the 16th to 20th iterations of the tests for the power. should be noted that the error has been calculated as a percentage. The Error graph shows a value of less than 1% after 20 iterations. The main harvests in this work are listed as follows:

- When the volume fraction goes up, the head loss comes down. It may also be observed that the head loss ratio goes down with the increment in volume fraction.
- Nusselt number values have decreased with increasing volume fraction.
- It should be noted that pipes with the largest groove pitch had the best C.B.R. factor values (which shows the lowest value). This means that air injection in larger groove pitch tubes was more beneficial than in smaller corrugation pitch tubes.

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Persian Abstract

چکیده

در این بررسی تجربی، جریان سیال صعودی دو فازی هوا-آب بدون جوشش در یک لوله عمودی با موج‌های مارپیچ بررسی شده است. نتایج نشان می‌دهد که مقادیر افت هد با افزایش کسر حجمی کاهش می‌یابد. همچنین، با مقایسه مقادیر افت هد برای هر گام موجدار، می‌توان مشاهده کرد که با پایین آمدن گام موجدار، مقادیر افت هد به طور قابل توجهی افزایش می‌یابد. در نتیجه شدت بخارات عمود بر جریان اصلی آب افزایش می‌یابد که منجر به افزایش شدت اختلال در جریان می‌شود و سپس افت هد افزایش می‌یابد. نتایج برای عدد ناسلت نشان می‌دهد که وقتی کسر حجمی افزایش می‌یابد، مقادیر عدد ناسلت کاهش می‌یابد. با نگاهی به ارقام مربوط به عدد ناسلت، به راحتی می‌توان دریافت که منحنی‌ها برای سرعت جریان هوا ثابت ترسیم شده‌اند. در نتیجه، افزایش VF برابر با کاهش سرعت جریان آب است. با کاهش دبی آب، از شدت جریان اصلی کاسته می‌شود، از شدت تلاطم نیز کاسته می‌شود و ضریب انتقال حرارت کاهش می‌یابد. در نتیجه میزان انتقال حرارت در اثر تزریق هوا افزایش یافته است. لازم به ذکر است که لوله‌هایی با بیشترین گام موجدار دارای بهترین مقادیر فاکتور نسبت هزینه به فایده (C.B.R.) (که به معنی کمترین مقدار است) بودند. این به این معنی است که تزریق هوا در لوله‌های موجدار بزرگتر سودمندتر از لوله های موجدار کوچکتر بود.