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An Experimental Investigation of Double Pipe Heat Exchanger Performance and Exergy Analysis Using Air Bubble Injection Technique

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Abstract

To ensure the transfer of thermal energy in high efficiency, a heat exchanger which has the ability to transfer thermal energy in the least time and cost, is used. There are many drawbacks to traditional surface-type heat exchangers, such as the problem of fouling, high resistance to heat transfer to the surface, and increased cost. The technique of air bubble injection is inexpensive, hopeful, and rarely used for improving the heat exchangers' thermal performance. The present article covers heat transfer and exergy analysis even without injecting an air bubble (3 mm in diameter) at the intake of a tube, shell, and tube and shell heat exchanger. The obtained findings indicate that those heat exchangers that injected air bubbles had a higher Nusselt number than heat exchangers that did not inject air bubbles. The technique of bubble injecting through both shell and tube raises the Nusselt number by a factor of between 2.13%-25.18%. The maximum NTU was achieved by injecting an air bubble into both the shell and tube intakes at a Re=15000. Estimated heat transfer improvements associated with injecting air bubbles into the intake of a tube, shell, or both tube and shell are 8.31% and 13.50%, respectively. Compared to the absence of an injected air bubble, the performance increases by 31.8%, 45.1%, and 54.2%, respectively, when the tube, shell, or both the tube and shell are injected with air bubbles.

Keywords: Injection of the air bubble, heat transfer enhancement, bubbly heat exchanger, two-phase flow.

Abbreviation

HE	heat exchanger
HEs	heat exchangers
STHE	shell and tube heat exchanger
STHEs	shell and tube heat exchangers
ICE's	internal combustion engines

Nomenclature

Q	heat transfer rate (kW)
m	mass flow rate (kg/s)
C_p	specific heat (kJ/kg.ºC)
T	temperature (ºC)
U	overall heat transfer coefficient (kW/m^2.ºC)
A	area (m^2)
LMTD	logarithmic mean temperature difference (ºC)
E	exergy loss (Joules)
e	non-dimensional exergy loss (----)
h	heat transfer coefficient (W/m^2.ºC)
k	thermal conductivity (W/m.ºC)
L	length (m)
u	velocity (m/s)
Re	Reynolds number (---)
NTU	number of transfer units (---)
Nu	usselt number (---)
D	diameter (m)
Pr	Prandtl number (---)

Greek

ε	effectiveness (---)
Δ	forward difference
v	kinematic viscosity (m^2/s)

Subscripts

h	hot
c	cold
in	inlet
out	outlet
e	exit
i	inside
o	outside

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1. Introduction

During the last decades, many researchers were searching to optimize energy systems or conserve energy because of the limited fossil fuel resources and enormous ecological issues generated by the excellent direction of energy attrition. This route of work spreads through large areas, from energy transmutation in tiny scales like domestic appliances and internal combustion engines, to energy transformation systems in considerable scale industries. The HE can be considered as the one among the most popular customarily applied in transfer phenomena of thermal energy, which is applied in small and large applications, such as petrochemical industries, medical, food, power plants, ventilation,air conditioning systems, wastewater treatment, and heating. Improving the HE efficiency by enhancing the heat transfer rate was addressed by numerous researchers. There are two kinds of methods for increasing the heat transfer rate named passive and active methods. In the case of the passive method, it is not required to have an outer power to keep the strength of heat transfer augmentation mechanism such as additives for fluidsand swirl flow devices. The active methods demand outer power like vibrating the surface or stirring the fluid [1]. Heat transfer plays an important part in the energy world because higher heat transfer efficiency means more heat is recovered from the process under examination, and higher heat recovery efficiency means more energy savings. As a result, a HE is a device that may save energy by recovering heat by the heat transfer process, and the stored heat may be used for many applications [2]. Out of all HEs, STHE is the most common type of HEs used in industrial applications. This might be owing to a variety of reasons, including the working fluid's ability to tolerate extreme temperatures ranging(-250-800 °C) and ultimate pressures (6000psi), as well as ease of maintenance and manufacture. The main applications of this HE are found in industries, such as food processing industries, power plants, manufacturing industries, chemical and petrochemical industries, etc. To upgrade the double pipe HE performance, several heat transfer enhancement techniques were used. The air bubble injection technique may be thought of as a low-cost and promising method of improving the thermal properties of an STHE. In this technique, air bubbles are injected into the flowing fluids which move along the fluid leaving behind the void which is occupied by the ambient fluid causing turbulence in the animated fluid which results in augmenting the heat transfer rate. Moreover, the injection of air bubbles can reduce the skin friction drag near the wall which also causes turbulence in the moving fluid. This technique can be applied for heat transfer enhancement [3].Over the latest few years, injection of air-gas bubbles into the STHEs has been specified as an active method for creating turbulence in the fluid flow [4, 5]. Gabillet et al. [5] wrote an increment in the velocity and turbulence of flowing fluid when injection of air bubbles in the flowing fluid stream. The innovative work adopted by Zavaragh et al. [6], who injected air bubbles through an ICE's cooling arrangement to minimize emission and specify fuel consumption of the engine, and to obtain higher heat transfer rates.

Celeta et al. [7] presented a heat transfer enhancement by 10 times on studying the impact of injection of AB (air bubbles) at the entry of a heated canal. Dizaji and Jafar[8] discussed the effect of injection of air bubbles on effectiveness and Nusselt in STHEs. Researchers found 6-35% augmentation in the Nusselt number and 10-40% enhancement in the effectiveness. Jiacai et al. [9] studied the phenomena behind the reduction of skin friction drag in boundary layers due to the injection of air bubbles.

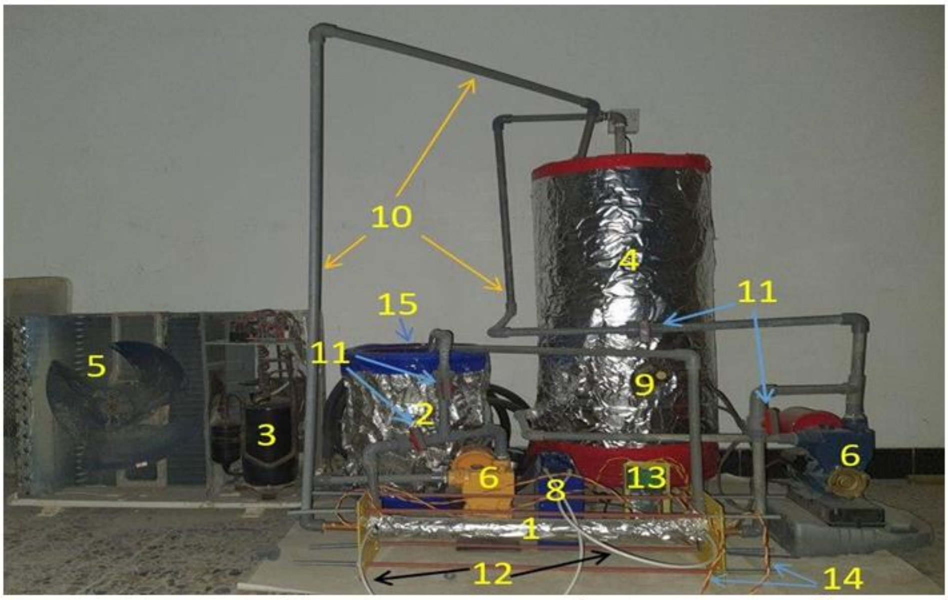
Mattsonand Mahesh [10] revealed the bubble sizing effect on the fluid flow turbulence and found that the bubbles of smaller size just affect the flow close to the wall or the generation point while bubbles of larger size are easily able to penetrate to further space in a turbulent flow regime.

Delaure et al. [11] investigated the impact of an ellipsoidal air bubblerising in sluggish water on heat flow and discovered that heat flux was increased. Jacob et al. [12] performed a comparison of the near-wall shear stress and Reynolds stress of two-phase flow (air bubble-water mixture) to single-phase flow and found that these stresses are more important in two-phase flow than in liquid phase flow only. Nandan and Singh [13] used air bubbles in double pipe HEs where they succeeded in obtaining a remarkable increase in the HEperformance. Celeta et al. [14] investigated the impact of injection of the air bubble at the inflow of a heated canal and found that it increased heat transmission by tenfold. Shaheed et al. [15] used a double pipe HE to investigate the heat transfer performance and exergy analysis of air injection in various places. They reported that injecting air bubbles through the exchanger increased the Nusselt number by 2.41-25.5% in comparison to the exchanger with no air injection. Marzouk et al. [16] used a simple approach to explore the impact of air bubble injection in tube sidewalls. The flow rate was increased from 14 to 18 LPM, while the wet shell-side flow rate remained constant at 18 LPM. Emad et al. [17] developed techniques for predicting the influence of air injection into STHEs on thermal performance using supervised machine-learning algorithms. This procedure was carried out by introducing air bubbles into the shell at various flow rates in order to get the HE's best thermal performance. Nazaruddin et al. [18] investigated the thermal performance of a twin-pipe HE when an air bubble was injected into the inner tube's water stream. The heat transfer coefficient and the number of transfer units both were enhanced by 33% and 38%, respectively. Sajida et al. [19] researched the influence of injecting air bubbles on the augmentation ofheat transfer pressure drop for turbulent flow in 2- helical coil HEs. The exergy loss and NTU can be intensified by injecting air bubbles because of the bubbles' mobility (buoyancy force) and increasing the turbulence level and mixing the boundary layer of the fluid flow.

The major goal of this research is to explore the effects of injecting different air bubbles flow rates on the thermal properties of a horizontal double pipe HE. The injection of air bubbles was performed at several locations, including the shell inlet, tube inlet, and combined shell and tube inlets. A comparison was performed between the results obtained in this study and those obtained by Naphon et al. [20], it is apparent that the current study's findings corresponded to the aforementioned equation.

2. Experimental Setup

Figure (1) presents a schematic representation of the experimental rig. The air injection system, cold water loop, hot water loop, and test section make up the experimental setup. The test section instances are shown in Figure (3).



1. test section , 2. cold-water storage , 3. air-compressor , 4. hot-water storage, 5. condenser, 6. water pump, 7. water-rotameter, 8. air pump, 9. thermostat and dimmer, 10. connecting pipes, 11. valves, 12. air transmission tubes, 13. data-logger, 14. thermocouple wire,15. evaporator

Figure 1. The experimental rig

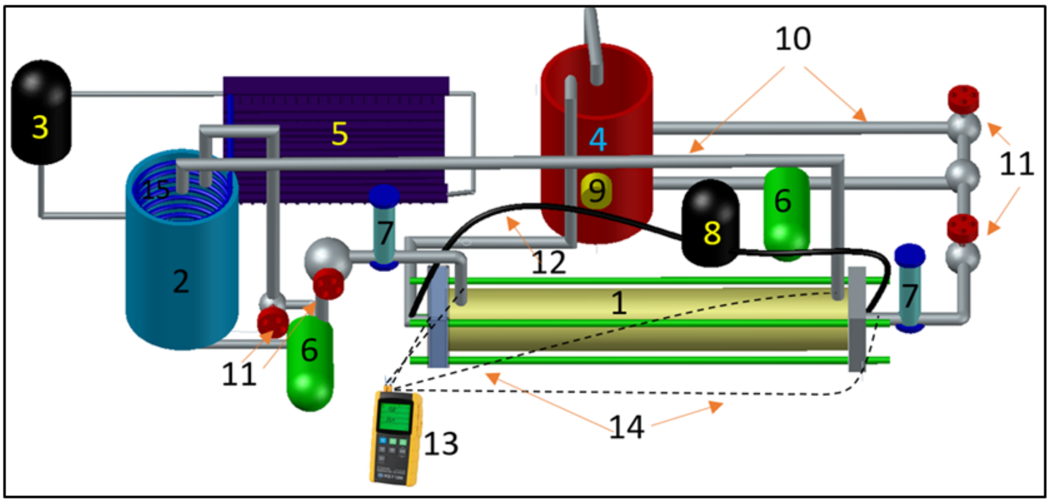


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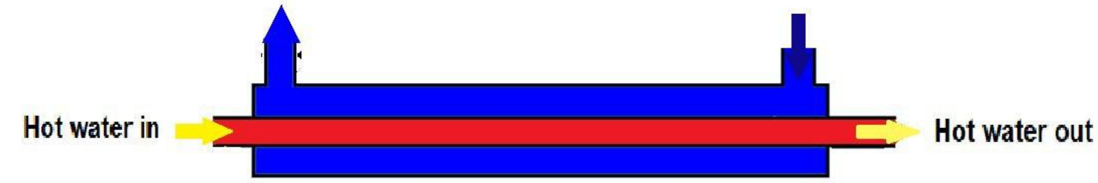
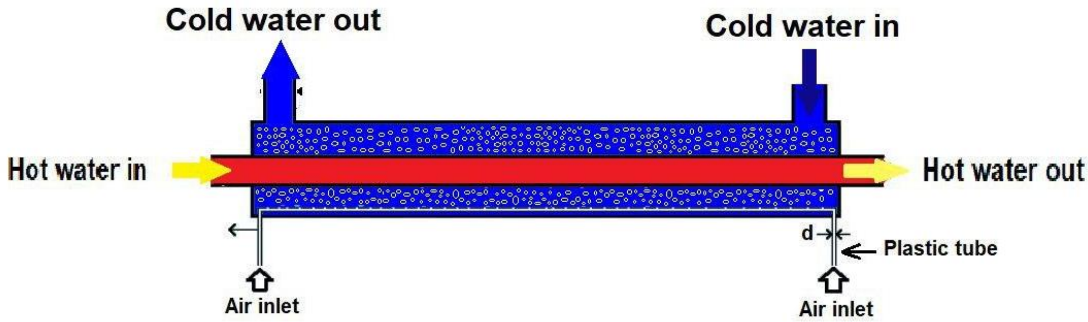
Figure 2. Graphical representation of the experimental setup



a)



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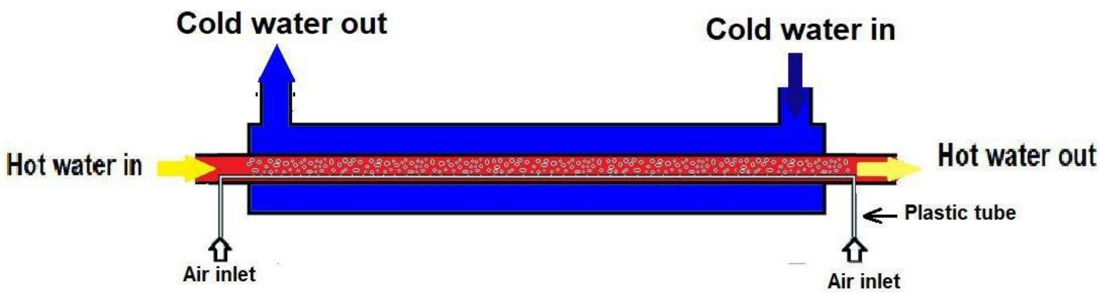

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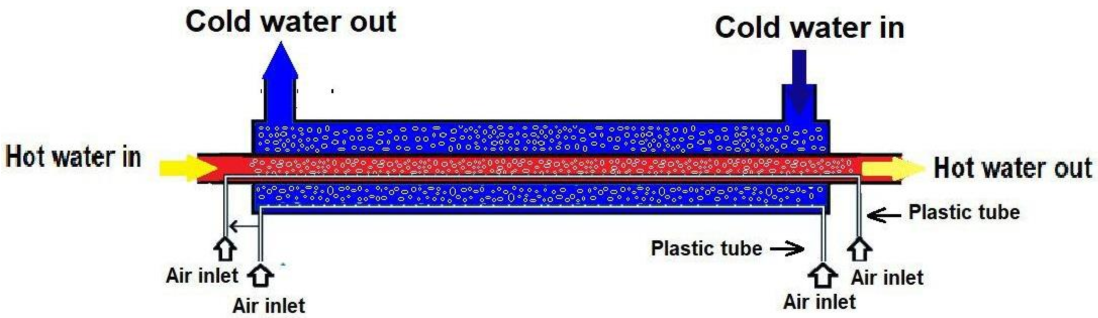

d)

Figure 3. Test section

a) no air bubble injection, b) injecting air bubble through the shell, c) injecting air bubble through the tube, d) injecting air bubble into both tube and shell

The specifics of each test part are provided in table (1). To acquire the wall temperature, thermocouples of K-type with a reliability of 0.1ºC were placed at the entrance and outflow of the tube and shell, as well as on its wall boundary.

The needed water is warmed up in hot water storage of 50-liter capacity. A controller of proportional-integral-derivative (PID) has been applied to adjust the hot water temperature. At a temperature of 50ºC, several flow rates of hot water (4, 5.25, 6.5, 7.65, 8.9, 10.1, 11.3, 12.5 LPM) were investigated at the shell side. The cold water is pumped at room temperature and 4 LPM (constant flow rate). To adjust the fluid flow on the tube and shell sides, two flow devices with an accuracy of around 1% each were fitted. Air was injected at a flow rate of 0.06 LPM using an aquarium pump.

Before the test, the instruments were calibrated. Tests have been carried out in a variety of circumstances (four). The first was performed with hot water (distilled) in the tube and cold water (distilled) in the shell. Different readings were obtained during five minutes, and the average of the data was used for analysis.

Table 1. Details of the test section

Item	Value
Length	610 mm
Diameter of shell	57 mm
External tube diameter	29 mm
Internal tube diameter	26 mm

The uncertainty and accuracy of the tests are recorded in the table below (2).

Table 2. Theuncertainty andaccuracy of the tests

Instruments	Accuracy (%)	Uncertainty
Thermocouple type K	0.1	$\pm$0.10
Rotameter (kg/s)	0.2	$\pm$0.01
Data Logger (°C)	0.1	---

3. Data reduction

For the counter flow of multi-coil HE, the experimental heat transfer rate isobtained by[21]:

$$Q_h = m_h C_{ph}(T_{in,h} - T_{out,h}) \quad (1)$$

$$Q_c = m_c C_{pc}(T_{out,c} - T_{in,c}) \quad (2)$$

Q_{ave} (the averaged heat transfer)can be estimated by using equation (3):

$$Q_{ave} = \frac{Q_h + Q_c}{2} \quad (3)$$

Uh (the overall heat transfer coefficient) ispredicted using Eqn. (4):

$$U_h = \frac{Q_{ave}}{A_h LMTD} \quad (4)$$

Where

LMTD: defined as logarithmic mean temperature difference, which may be predicted using equation (5):

$$LMTD = \frac{\Delta T_1 + \Delta T_2}{ln\frac{\Delta T_1}{\Delta T_2}} \quad (5)$$

$$\Delta T_1 = T_{in,h} - T_{out,c} \quad (6)$$

$$\Delta T_2 = T_{out,h} - T_{in,c} \quad (7)$$

Where, $T_{in,h}$, and $T_{out,h}$, are the temperature of hot water inletand outlet, respectively and, $T_{in,c}$, and $T_{out,c}$indicates the inlet cold water and outlet cold water temperature, respectively.

The exergy loss and the non-dimensional exergy loss arepredictedby using the methods of Akpinar and Bicer with aids of equations (8-12) [22].

$$E_h = T_e\left\{\dot{m}_h \times C_{ph} \times \ln\frac{T_{ho}}{T_{hi}}\right\} \quad (8)$$

$$E_c = T_e\{\dot{m}_c \times C_{pc} \times \ln\frac{T_{co}}{T_{ci}}\} \quad (9)$$

$$E = E_h + E_c \quad (10)$$

$$e = \frac{E}{T_e \times C_{min}} \quad (11)$$

$$C_{min} = \mathrm{Min}\{C_h \mathrm{and} C_c\} \quad (12)$$

h_i (heat transfer coefficients) are calculatedusingthe Wilson plots method with aids of equations (13-15) [23-29].

$$\frac{1}{U_i} = \frac{1}{h_i} + \frac{A_i \ln(\frac{d_o}{d_i})}{2KL\pi} + \frac{A_i}{A_o h_o} \quad (13)$$

$$\frac{1}{U_i} = \frac{1}{h_i} + \mathrm{M} \quad (14)$$

$$h_i = BRe^m \quad (15)$$

B, M, and m may be calculated using curve fitting.

$$\frac{1}{U_i} = \frac{1}{BRe^m} + M \quad (16)$$

NTU (the number of heat transfer units)is calculated by using equation (17):

$$\mathrm{NTU} = \frac{AU}{C_{min}} \quad (17)$$

C_{min} (minimum heat capacity) can be predictedusing equation (18):

$$C_h = \dot{m}_h c_{ph}, C_c = \dot{m}_c c_{pc}\ ,\ \ C_{min} = \mathrm{Min}\{C_h \mathrm{and} C_c\} \quad (18)$$

The effectiveness of the double pipe HEis predicted by equation (19):

$$\varepsilon = \frac{\text{heat transfer (actual)}}{\text{maximum heat transfer}} \quad (19)$$

The maximum heat transfer value is calculated by using equation (20):

$$Q_{max} = (m\cdot c)_{min}(T_{inlet,h} - T_{inlet,c}) \quad (20)$$

The experimental value of the Nusselt number is predicted by equation (21):

$$Nu = \frac{h_i D}{K} \quad (21)$$

4. Results and Discussion

Before injecting air in the HE, Nusselt number was validated with Naphon et al. correlation [21], which is written as:

$$Nu = 1.84(Re - 1500)0.32 \qquad 5000 \leq Re \leq 25000, Pr = 0.7 \quad (22)$$

Figure (4) shows the validation with Naphon et al. [20] correlation. It is clear that the results obtained by the current study agreed well with the aforementioned equation with a maximum difference for the Nusselt number of 7.2%.

Results of the Nusselt number are shown in Figs. (4, 5, and 6). Figure (5) reveals the variation of Nusselt number with Reynolds number for air bubbles injection in the inlet of the shell. Figure (6) presents the variation of Nusselt number with Reynolds number for injection of air bubble in the tube inlet. Figure (7) illustrates the variation of Nusselt number with Reynolds number for air bubbles injection in the inlet of both tube and shell.

In figures (5-7), injecting air bubbles in the HE produced a higher Nusselt number than the exchanger without injectingair bubbles.The effect of air bubble injection into the inner tube is less than that of air bubble injection into the outer tube in terms of the heat transfer rate. This could be because the air bubbles increase the turbulence level of the water flow, and the air bubbles may collect near the inner wall of the inner tube and thus act as an insulator.As for the Reynolds number, it ranged between 5000 and 16000, so changing this number (increasing the flow rate) will lead to an increase in the heat transfer rate and thus the Nusselt number will increase. Depending on the condition of injection of the air bubble in the HE and Reynolds number, the increment in Nusselt number ranged from 2.13% to 25.18%.

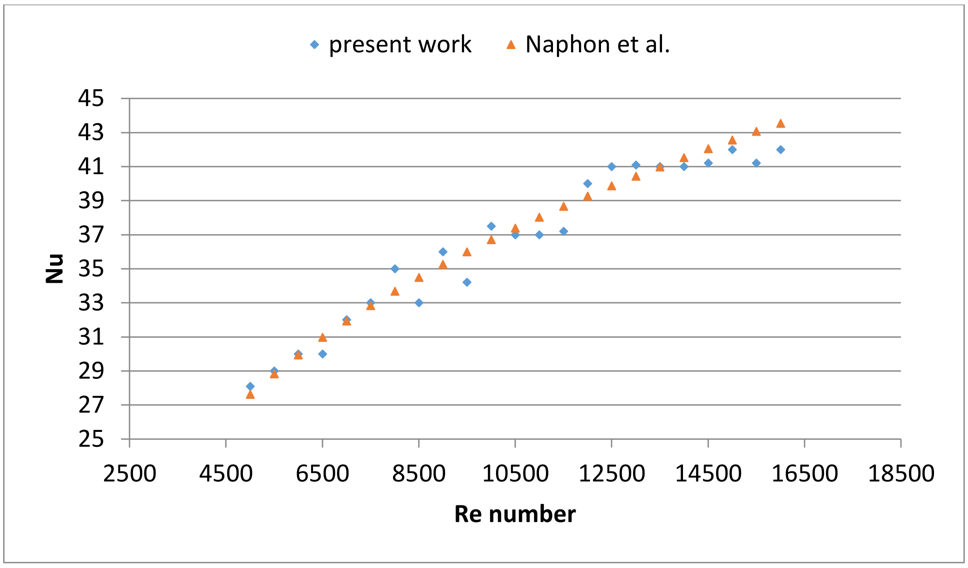

Figure 4. Verification of the present work results with reference [20] for the case of no air bubble injection

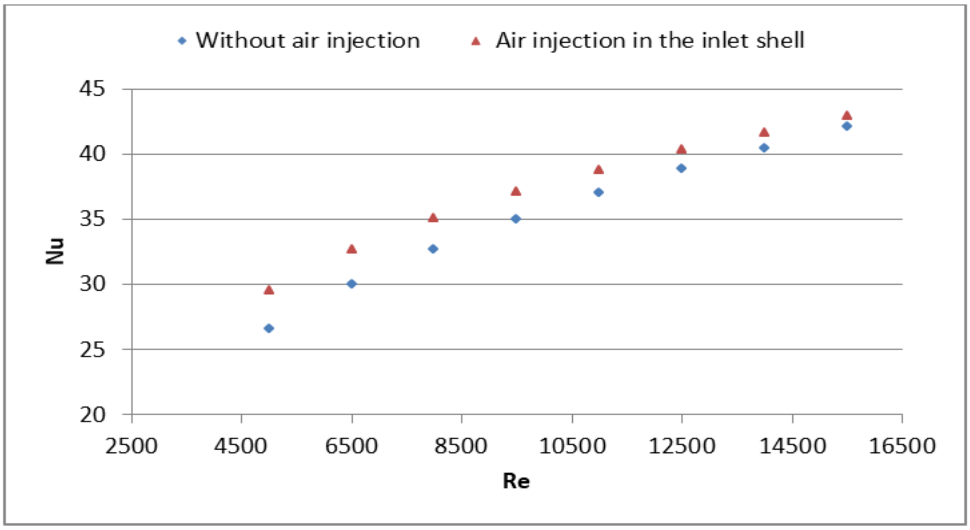

Figure 5. Nusselt number against Reynolds number with/without air bubbles injection through the inlet of the shell

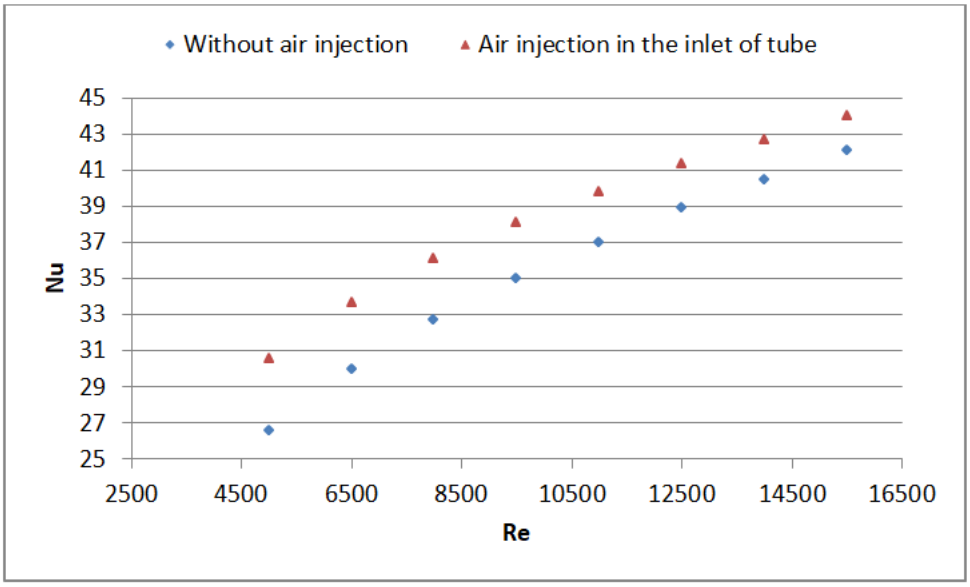

Figure 6. Nusselt number vs. Reynolds number without and with injecting air bubble in the tube inlet

Figure (8) manifest that the highest augmentation in Nusselt number was done for injecting air bubble in the tube and shell inlet at the minimum value of Reynolds number (5000). The lowest augmentation in Nusselt number took place for injection of air bubble in the inlet of the shell at the maximum value of Reynolds number (15000). For all cases, increasing Reynolds number enhances the ratio of augmented Nusselt number/ non-augmented Nusselt number.The air bubbles increase the water flow turbulence level, and the air bubbles may collect near the inner wall of the inner tube and thus act as an insulator.Increasing the Reynolds number, which means increasing the flow rate, will lead to an increase in the heat transfer rate and thus the ratio of augmented Nusselt number/ non-augmented Nusselt number will increases.

Fig. (9) Shows a variation of NTU with Reynolds number. It has been shown that the increment in Reynolds number directly enhances the amount of NTU. This may be due to the formation of a vacuum through the rising air bubbles during the flow along the water causing turbulence in the flowing fluid which leads to more heat transfer from the surfaces by the running water. Depending on the injection of air bubble situation, minimum NTU was occurred for injectingair bubble in the inlet of the shell at the minimum value of Reynolds number (Re=5000), and highest NTU value was achieved for injectingair bubble in the tube and shell inlet at the maximum value of Reynolds number (Re=15000).

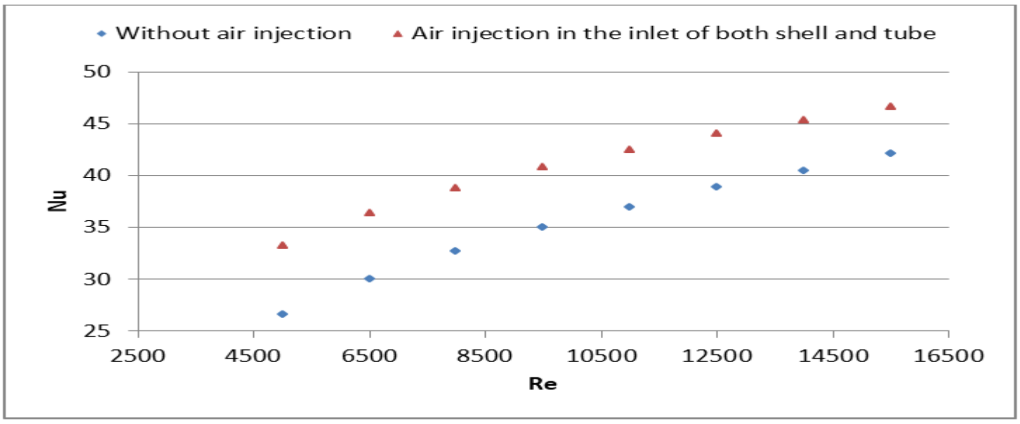

Figure 7. Nusselt number against Reynolds number without and with injecting air bubble through the inlet of both shell a

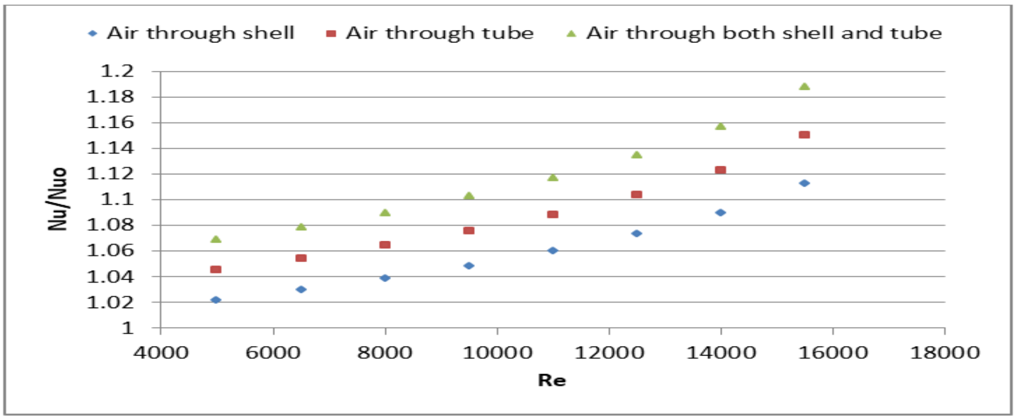

Figure 8. Enhanced Nusselt number against Reynolds number

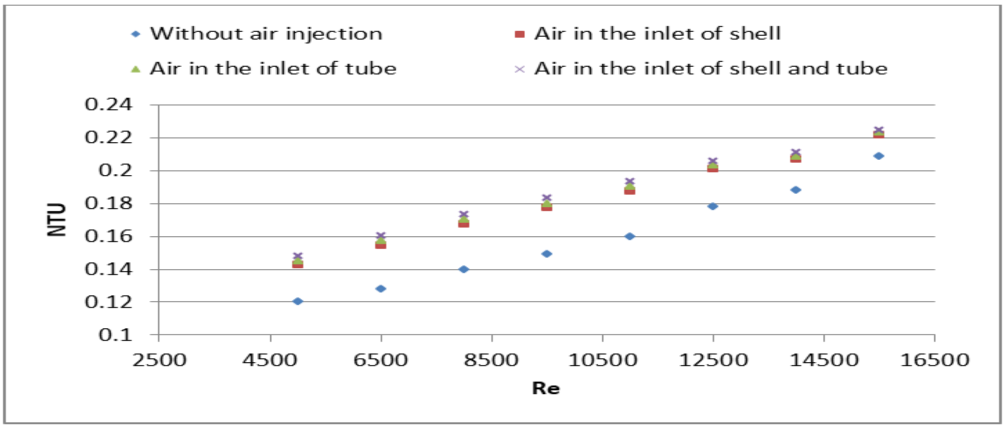

Figure 9. Enhanced NTU vs. Reynolds number

The analysis of exergy loss is asubstantial factor in the design ofthe HE. Exergy is the ultimate beneficial work gained from any thermal system. Attaining higher performance of the HE means attaining maximum work from the system. One of the primary sources of exergy loss in HEs is the difference in temperature between hot and cold fluids. When increasing the dimensionless exergy loss, the system will extract the maximum amount of energy possible. The injection of an air bubble in the inlet of a shell has the lowest dimensionless exergy, whereas the injection of an air bubble in the inlet of both tube and shell has the highest dimensionless exergy. The air bubbles injection produces greater dimensionless exergy, in comparison to that produced in the case of no air bubble injection.

Figure (11) suggests that the heat transfer rate is in direct proportion to the Reynolds number.In other words, the rate of heat transfer is directly proportional to the mass flow rate. If the flow rate increases, the rate of heat transfer will increase. Furthermore, figure (11) indicates that injecting air bubbles through the inlet of both the tube and shell produced the highest rate of heat transfer, followed by air bubbles injection into the tube's inlet, then the injectionof the air bubble into the shell's inlet, and finally the case of no air bubble injection. In comparison to the case of no air bubbles injection, the heat transfer augmentation for injection of air bubbles in the intake of the tube, shell inlet,and both tube and shell inlets is 4.41%, 8.31%, and 13.50%, respectively. This increase occurs at various Reynolds numbers, depending on how the experiment was conducted.

The HE effectiveness is the ratio of verifiable to the maximum heat transfer achievable. As a result, a high heat transfer rate denotes a high HE efficiency. The effectiveness is directly proportional to the Reynolds number, as seen in figure (12). Figure (12) also presents that injecting air bubbles in the inlet of both tube and shell resulted in the greatest effectiveness, followed by air bubble injection into the inlet of tube, air bubbles injection into the shell inlet, and finally without injecting air bubbles. In comparison to the situation of no injecting air bubbles, the augmentation in the effectiveness for air injecting in the intake of shell, tube, and both tube and shell is 31.8%, 45.1%, and 54.2%, respectively. It is worth noting that these improvements happened at various Reynolds numbers when the experiment was carried out.

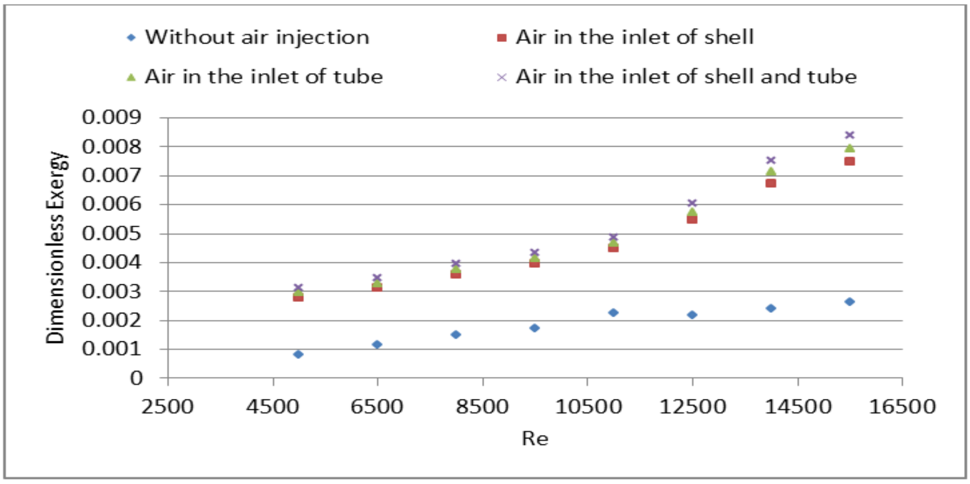

Figure 10. Dimensionless exergy vs. Reynolds number

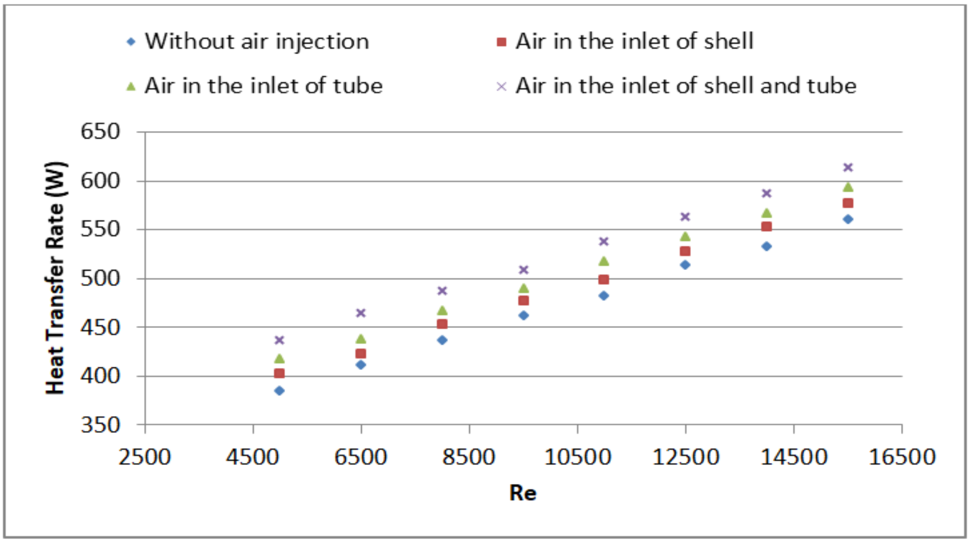

Figure 11. Average heat transfer vs.Reynolds number

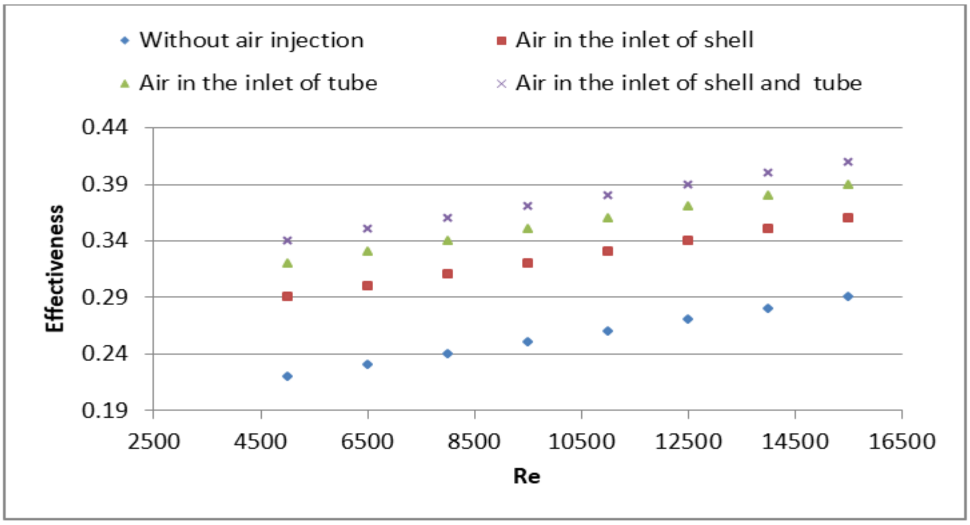

Figure 12. Effectiveness vs. Reynolds number

5. Conclusions

In this work, the counter-current flow performance in a horizontally mounted double-pipe HE under the impact of air bubbles injection was presented. The following key findings were concluded:

1. Injection of air bubbles is one of the hopeful ways in augmenting the heat transfer rates.
2. Generally, the injection of air bubbles through the HE resulted in a higher Nusselt number in comparison with the HE with no air bubbles injection.
3. The Nusselt number was increased by 2.13% to 25.18% when injecting air bubbles into the HE.The maximum enhancement in Nusselt number occurred for air bubbles injection in the inlet of both tube and shell at the minimum value of Reynolds number. Minimum enhancement in Nusselt number occurred for injecting air bubbles in the inlet of the shell at the maximum value of Reynolds number. Increasing Reynolds number (flow rate) decreases the ratio of enhanced Nusselt number/ non-enhanced Nusselt number.
4. As the Reynolds number rises, the value of NTU rises as well. At low minimum Reynolds numbers, the lowest NTU was seen for injecting air bubbles through the shell inlet, while maximum NTU was observed for injecting air bubbles in the inlet of both the shell and the tube at maximum Reynolds numbers.
5. Generally, injecting air bubbles through the HE resulted in higher values of dimensionless exergy when compared to the case of no air bubbles injection. Air bubbles injection in the shell inlet has the lowest dimensionless exergy, whereas air bubbles injection in the inlet of both tube and shell has the highest.
6. In comparison to the situation of no air bubbles injection, the enhancement in heat transfer rate for injecting air bubbles in the intake of shell, tube, and both shell and tube is 4.41%, 8.31%, and 13.50%, respectively.
7. In comparison with the case of no air bubbles injection, the efficacy increase for air bubble injection in the intake of shell, tube inlet, and both shell and tube inlets is 31.8%, 45.1%, and 54.2%, respectively. This increase occurs at various Reynolds numbers, depending on how the experiment was conducted.

Acknowledgment

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