

Heat transfer enhancement due to air bubble injection into a horizontal double pipe heat exchanger

H. Sadighi Dizaji^a, S. Jafarmadar^{a*}

^a Department of mechanical Engineering, Urmia University, Urmia, Iran

* S.jafarmadar@urmia.ac.ir

Abstract

If an air flow is injected into a liquid fluid, many ambulant air bubbles are formed inside the fluid. Air bubbles move inside the liquid fluid because of the buoyancy force, and the mobility of these air bubbles makes sizable commixture and turbulence inside the fluid. This mechanism was employed to enhance the heat transfer rate of a horizontal double pipe heat exchanger in this paper. However it can be used in any other type of heat exchanger. Especially, this method can be expanded as a promising heat transfer improvement technique in automotive cooling system, for instance in radiator which contains of water or other liquid fluid. Bubbles were injected via a special method. Present type of air bubbles injection and also the use of this mechanism for double tube heat exchanger have not been investigated before. Results are reported for varying bubble inlet parameters. The main scope of the present work is to experimentally clarify the effect of air bubble injection on the heat transfer rate and effectiveness through a horizontal double pipe heat exchanger.

Keywords: Air bubble injection, Heat exchanger, Heat transfer, Effectiveness

1. Introduction

Numerous methods have been presented to increase the heat transfer rate and performance of heat exchangers in the past decades. Generally, these techniques can be categorized into two principal types: (1) passive techniques which require no direct application of external power, such as using of nanofluids, coarsening heat exchanger surfaces and inserting fluid turbulators (2) active techniques which require external power, for instance surface vibration and electrostatic fields. Sub millimeter bubble injection has been studied as one of the promising techniques for heat transfer intensification for the laminar natural convection of static liquids by some researchers (for instance Kitagawa et al. [1] (2008)). Some other researchers (such as Vlasogiannis et al. [2] (2002)) focused on the use of air-water two phase flow to enhance the heat transfer rate of heat exchangers (forced convection). It should be noted that, in their study air flow was combined with water flow before they could arrive inside the heat exchanger. So there was a complete-mixed two phase flow along the heat exchanger. In those cases, heat transfer enhancement is related to considerable interaction between liquid, gas and solid bounding surfaces, and obviously it produces extra shear, and

inevitably mixing can cause more hydraulic power requirement. But, this is not the main scope of this study. Here, we want to use of two air bubbles important properties for heat transfer enhancement. First, the vertical mobility of air bubbles which is due to buoyancy force and it occurs when an air bubble is begotten under a liquid. Indeed, this mechanism can act as a turbulator along the heat exchanger. Second, the use of air stream pressure (which has been produced by the air bump) as an extra motive power.

Indeed, it is released when the air flow is exited from the tiny holes which were contrived inside the test section. Hence, in this study, air flow and water flow don't have any contact outside of the test section and the air mass flow rate is negligible compared to the water mass flow rate. Bubbles were injected via a special method (see Fig. 1) which is explained in next sections. So the main scope of the present work is to experimentally clarify the effect of air bubble injection on heat transfer rate, number of heat transfer units (NTU) and effectiveness through a horizontal double pipe heat exchanger. Investigations on air injection into a liquid fluid and double pipe heat exchangers are summarized chronologically as follows. Oh et al. [3] (2000) Studied on bubble behavior and boiling heat transfer enhancement under electric field. Gabillet et al. [4] (2002) experimentally studied on the bubble injection in a turbulent

boundary layer. Experiments were performed in a horizontal channel in order to simulate the dynamical effects of the nucleation of bubbles. Their findings showed that the mean velocity is nearly the same as in single phase flow, except near the wall where the shear stress is greater than in single phase flow. Funfschilling and Li [5] (2006) studied the influence of the injection period on the bubble rise velocity. They found that the rise velocity decreases significantly with the injection period. Ide et al. [6] (2007) measured the void fraction and bubble size distributions in a microchannel. Kitagawa et al. [1] (2008) studied on heat transfer enhancement for laminar natural convection along a vertical plate due to sub millimeter bubble injection. Their measurements showed that the ratio of the heat transfer coefficient with sub millimeter bubble injection to that without injection increases with an increase in the bubble flow rate or a decrease in the wall heat flux and that the ratio ranges from 1.35 to 1.85. Nouri et al. [7] (2009) carried out an experimental study on the effect of air bubble injection on the flow induced rotational hub. Kitagawa and Kitada [8] (2010) studied experimentally on turbulent natural convection heat transfer in water with sub millimeter bubble injection. Their results showed that in the transition region, the maximum heat transfer coefficient ratio is approximately 1.9. Sub millimeter bubble injection is also effective in the laminar region as well as the transition region. In the turbulent region, the heat transfer coefficient ratio for $Q = 56 \text{ mm}^3/\text{s}$ is 1.2–1.3, which means that the heat transfer enhancement occurs as a result of the bubble injection. Safari et al. [9] (2013) investigated the effect of bubble injection on pressure drop reduction in helical coil. The experimental results indicated that the maximum reduction of friction drag is 25%, which occurs at low Reynolds numbers. Samaroo et al. [10] (2014) performed an experiment on the turbulent flow characteristics in an annulus under air bubble injection and subcooled flow boiling conditions with water as the working fluid. Their findings indicated that, in the laminar flow case, the coalescence of two bubbles successively injected is seen, and in turbulent flow, the bubble departure frequency increases and no coalescence are observed.

It is noted, the novelty of this study in comparison with above studies was totally described in second paragraph of introduction.

2. Experiments

2.1. Air bubble injection method

If an air flow is injected into the inner or outer tube (annular space between the two tubes) of a horizontal double pipe heat exchanger, many ambulant air bubbles are formed inside the test section. The mobility of said air bubbles (because of buoyancy force) makes considerable commixture inside the heat exchanger. Hence, the movement of air bubbles through the heat exchanger increases the heat transfer rate by increasing the turbulence level of the water flow and mixing the thermal boundary layer. This mechanism was employed to enhance the heat transfer rate through a horizontal double pipe heat exchanger in this paper as described below.

Air bubbles were injected inside the double pipe heat exchanger as shown in Fig.1. As seen in Fig. 1, some tiny holes have been begotten on a plastic tube. This tube was inserted inside the inner tube or outer tube of heat exchanger, and air flow was injected from the two side of the plastic tube inside the heat exchanger (See Fig. 1). Many small bubbles were formed inside the heat exchanger duo to the air flow exit from the tiny holes on the plastic tube. The diameter of plastic tube was 3 mm, and the number of holes and their diameter are two variant parameters in this study. The mass flow rate and temperate of the air flow through the plastic tube were $0.098 \times 10^{-3} \text{ Kg/s}$ and 26°C respectively. It is noted, air mass flow rate was negligible in comparison with water mass flow rate (at least 0.083 Kg/s). Indeed, air flow was injected by means of a small air pump (aquarium air pump).

2.2. Experimental apparatus

Fig. 2 represents a general view of test set-up. As seen in Fig. 2 the system basically comprises a test section, a cooling unit and a heating unit. The test section consists of an inner tube, an outer tube, a plastic tube, two insulated grooved end plates and four screwed steel rods. The tubes of test section were placed between the end-plates, and screwed steel rods were used to hold and adjust the position of the end-plates. The inner tube is made from copper material and the outer tube is made from PVC. Geometric specifications of the tubes are tabulated in table 1 where t , L , D and $2r$, are the air inlet diameter, tube length, tube diameter and diameter of cold water (outer tube) inlets or outlets respectively.

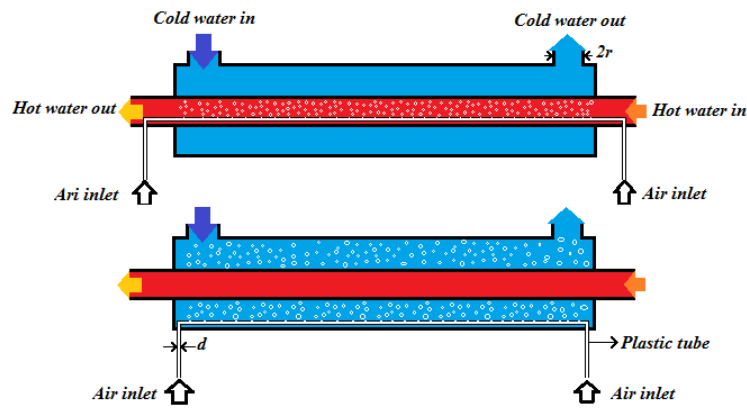


Fig1. A general view of air bubble injection methods

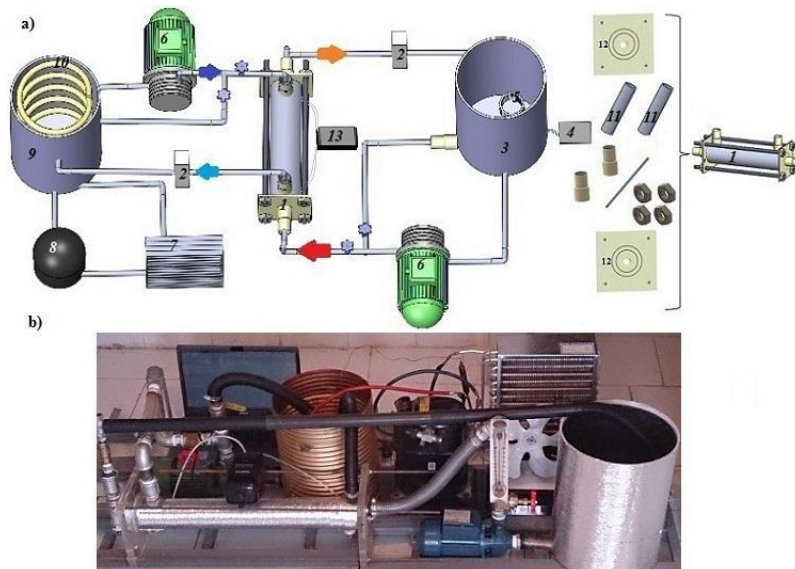


Fig2. (a) A schematic illustration of the test set-up: 1-test section, 2-Rotameter, 3-warm water tank, 4-dimmer and thermostat, 5-heater, 6-water pump, 7-codenser, 8-compressor, 9-cold water tank, 10-evaporator, 11-tube, 12-endplates of test section, 13-air pump and (b) Experimental setup

Table1. Experiment conditions and air bubble injection

Test no	n (mm)	d (mm)	Plastic tube situation	Range of inner tube Re
1	Without air injection	-	-	5000 - 16000
2	40	0.3	Inner tube	5000 - 16000
3	40	0.7	Inner tube	5000 - 16000
4	80	0.3	Inner tube	5000 - 16000
5	80	0.7	Inner tube	5000 - 16000
6	80	0.3	Outer tube	5000 - 16000
7	80	0.7	Outer tube	5000 - 16000

2.3. Experiments procedure

Inside of the inner tube and outer tube were occupied with hot and cold water respectively. Counter flow was used through the heat exchanger for all conditions. Table 2 provides seven various experiment conditions of this study, where n, d are number of holes on plastic tube (with equal distances) and holes diameter respectively. Each condition was performed with five different amount of hot water mass flow rate. It should be noted that, the effects of other parameters of double tube heat exchanger such as, fluids inlet temperature, flows directions and etc. have been investigated abundantly in previous studies.

For this reason, the variants of this study are related to bubbles inlet parameters. Outer tube and water tanks were covered with a 2-cm layer of the glass wool insulation to prevent heat loss to surrounding. Cold water (outer tube) water flow rate and inlet temperature were kept at around 0.083 kg/s (Reynolds number of 4000 based on water flow rate) and 25°C respectively. Hot water inlet temperature was maintained at around 40°C and it was pumped inside the inner tube with different mass flow rate from 0.0831 Kg/s to 0.2495 kg/s (Reynolds number of 5000 to 16000). During the experiments, inlets and outlets bulk temperature were measured at steady state condition.

3. Results and discussions

3.1 Validation

Nusselt number (without air injection) was validated with equation of Naphon et al [11] study. This experimental correlation is given as follow:

$$Nu = 1.84 (Re - 1500)^{0.32} Pr^{0.7} \quad 5000 \leq Re \leq 25000 \quad (1)$$

Where, Re is Reynolds number and Pr is Prandtl number. Fig. 3 presents the results of this validation. As seen in Fig. 3 the results of this present study agree admissibly with mentioned equation within 8% maximum difference for Nusselt number. Entrance effects, deference between roughness of two tubes, unavoidable errors in the present study and aforesaid equation can be discussed as reasons of discrepancies.

3.2. Heat transfer studies

The average heat transfer rate (Qave) in a double pipe heat exchanger can be calculated with:

$$Q_{ave} = (Q_h + Q_c) \quad (1)$$

$$Q_h = \dot{m}_h C_p (T_{h,in} - T_{h,out}), \quad Q_c = \dot{m}_c C_p (T_{c,out} - T_{c,in})$$

Where \dot{m} , C_p , and T represent the mass flow rate, specific heat of the fluid at constant pressure, bulk temperature of the fluid. The subscripts h, c, in and out designate the hot fluid, cold fluid, inlet and outlet respectively.

It is noted that, the air mass flow rate (0.098×10^{-3} kg/s) assumed to be negligible compared to the water mass flow rate (at least 0.083 kg/s) through the test heat exchanger in this study. Indeed, the effect of air mass flow rate on water properties is very small and negligible.

The experimental average overall heat transfer coefficient (U_{exp}) in a double pipe heat exchanger can be obtained by the following correlations.

$$U_{exp} = \frac{Q_{ave}}{A \Delta T_{LMTD}} \quad (2)$$

$$\Delta T_{LMTD} = \frac{(T_{h,out} - T_{c,out}) - (T_{h,in} - T_{c,in})}{\ln \left(\frac{T_{h,out} - T_{c,out}}{T_{h,in} - T_{c,in}} \right)} \quad (3)$$

Where A is the inner tube surface area, ΔT_{LMTD} is the logarithmic mean temperature difference across heat exchanger, and the subscripts h, c, in, out, designate the hot fluid, cold fluid, inlet and outlet respectively.

Heat transfer coefficients (h_i), are evaluated by “Wilson plots” method as describe below; (Wilson plots method has been exactly described in Rose study [12] and also it was employed to “h” calculation by many other researchers, for instances Wongcharee et al. [13], Petkhool et al. [14], Jamshidi et al. [15] and Shokouhmand et al. [16]).

$$\frac{1}{U_i} = \frac{1}{h_i} + \frac{A_i \ln \left(\frac{d_o}{d_i} \right)}{2KL\pi} + \frac{A_i}{A_o h_o} \quad (4)$$

Where, the subscripts i and o pertain to the inside and outside of the inner tube. L is the length of heat exchanger. Shell side Reynolds number (water mass flow rate) is a constant value. So, it can be assumed that h_o and thereupon the last two terms on the right-hand side of Eq. (4) are constants. Hence, the Eq. (4) can be re-written as

$$\frac{1}{U_i} = \frac{1}{h_i} + M \quad (5)$$

The shell side (outer tube) heat transfer coefficient is assumed to behave in the following manner with the hot water Reynolds number [13]

$$h_o = B Re^m \quad (6)$$

Substituting Eq. (6) into Eq. (5) yields

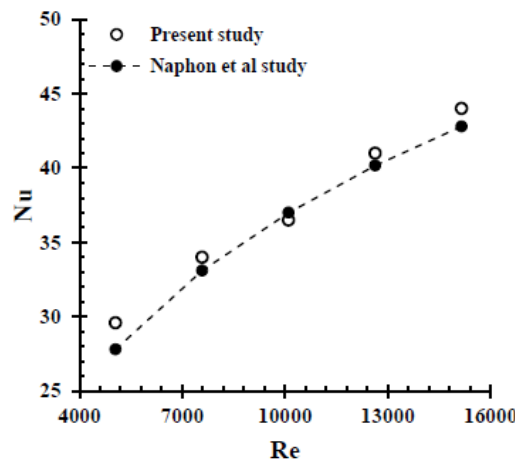


Fig3. Nusselt number validation (Without air injection)

Table 2. Tubes geometry

Tube	t (mm)	L (mm)	D _i (mm)	D _o (mm)	2r (mm)
Inner tube	-	587	32	35	-
Outer tube	-	587	57	62	25.4
Plastic tube	3	587	-	-	-

$$\frac{1}{U_i} = \frac{1}{BRe^m} + M \tag{7}$$

Constants B and M, and also the exponent m can be obtained through curve fitting. The amount of h_i can then be calculated.

Finally, the experimental Nusselt number can be evaluated by:

$$Nu = \frac{h_i D}{K} \tag{8}$$

Here, k is the thermal conductivity of the working fluid. The Nusselt number results are demonstrated in Fig. 4 for all cases. Fig. 4a represents the changes of Nusselt number with Reynolds number for air bubble injection into the inner tube with n = 40. Fig. 4b shows the changes of Nusselt number with Reynolds number for air bubble injection into the inner tube with n = 80. And Fig.4c shows the changes of Nusselt number with Reynolds number for air bubble injection into the outer tube. Comparisons of increased Nusselt number (air injection) with the non – increased Nusselt number (Nun, without air injection) are presented in Fig. 4d-f.

As seen in Fig. 4, in all arrangements, the heat exchanger with air bubble injection were gave higher

amounts of Nusselt number than those for the heat exchanger without air bubble injection. Dependent on air injection condition and Reynolds number, air bubbles increased the amount of Nusselt number about 6% - 35%. Maximum Nusselt number enhancement was obtained for air bubble injection into the outer tube with n = 80 at low amount of Reynolds number (about 5000). Minimum Nusselt number enhancement was occurred for air bubble injection into the inner tube with n = 40 and d=0.7 at high amount of Reynolds number (about 15000). The ratio of enhanced Nusselt number to the non – enhanced Nusselt number decreases with the increase of Reynolds number for all conditions.

The key findings from the heat transfer study are described as follows:

a) Air bubble injection into the inner tube of heat exchanger:

The influence of air bubble injection into the inner tube is less than the influence of the air bubble injection into the outer tube on heat transfer rate. This result can be due to two factors. Firstly, despite the air bubbles increase the turbulence level of the fluid flow, but also these air bubbles may be congregated near the inner side of the inner tube (when the bubbles are injected into the inner tube) and act as an insulator. Secondly, outer tube Reynolds number was

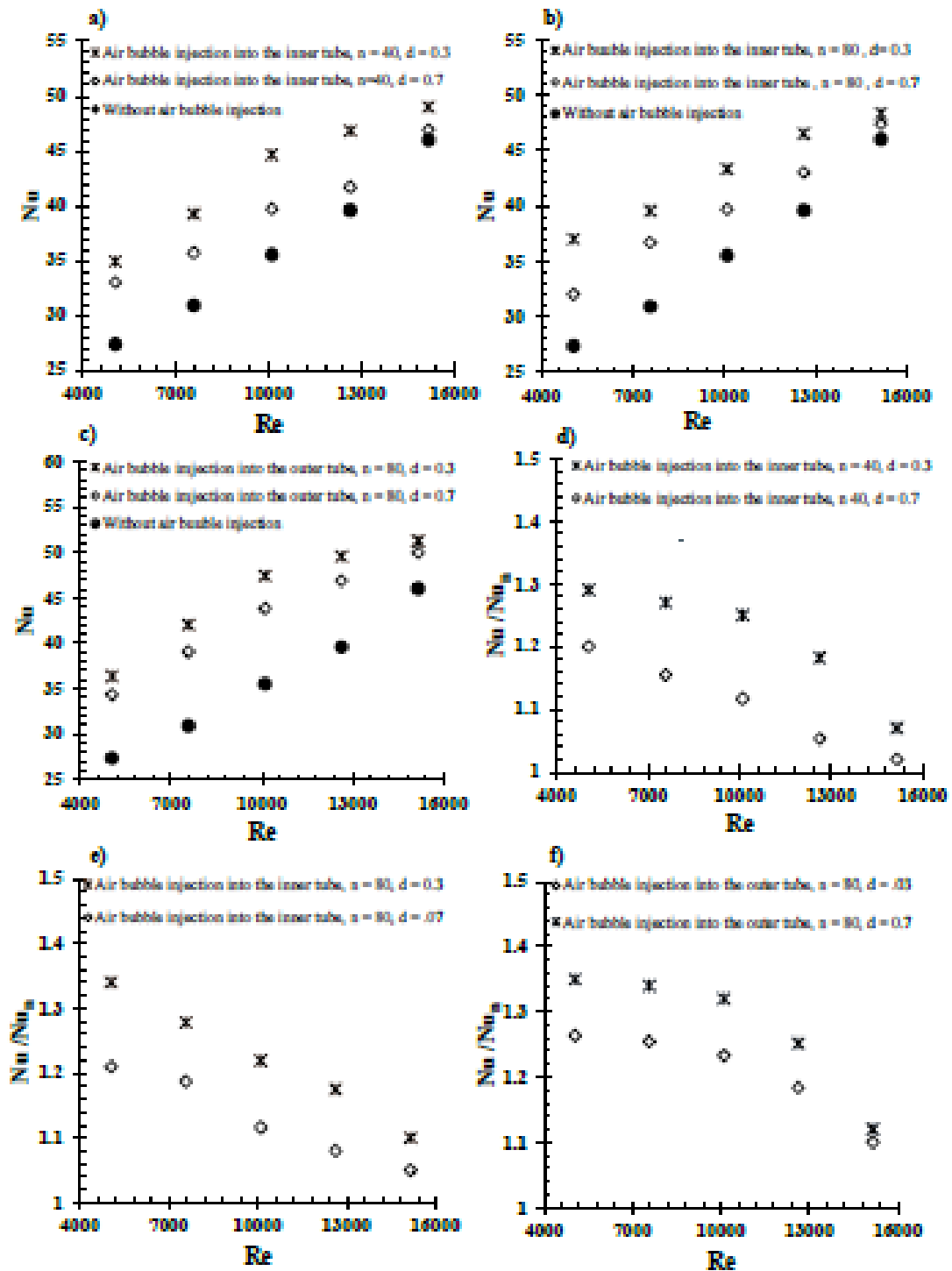


Fig4. (a – c): Relationship between Nusselt number and Reynolds number. (d – f): Comparison between enh Nusselt number with non-enhanced Nusselt number

Kept constant at 4000 in all conditions whereas the Reynolds number of the inner tube was changed from 5000 to 16000. Indeed, it can be said that the velocity of water flow (Reynolds number) may impress the effect of air bubble injection on heat transfer rate.

In the air bubble injection into the inner tube, Nusselt number increases with increase of n and decrease of d . Indeed, the use of plastic tube with more number of holes increases the number of air bubbles inside the inner tube. Also, in the same air flow rate through the plastic tube, smaller holes cause higher air bubble velocity at the air outlets (the holes on plastic tube). It seems that the influence of d (holes diameter) is more significant than the influence of n on the amount of heat transfer rate. To this reason, the plastic tube with $n=40$ and $d = 0.3$ has more positive efficacy on heat transfer rate compared to the plastic tube with $n = 80$ and $d = 0.7$. Indeed, as mentioned before, big air bubbles may be congregated on the inner side of the inner tube and act as an insulator. On the other hand, despite the use of plastic tube with more number of holes, increases the number of air bubbles inside the inner tube, but also it decreases the air bubbles velocity at the outlet of holes on plastic tube (because the air flow rate through the plastic tube is constant).

Generally, it can be concluded that the ratio of n to d (n/d) is a determinant parameter in these cases. Hence, high amount of n to d ratio (n /d) gives more heat transfer rate through the horizontal double pipe heat exchanger. It means that, more number of bubbles with the smallest size can be better condition for heat transfer enhancement.

b) Air bubble injection into the outer tube of heat exchanger:

The influence of the air bubble injection into the outer tube is more than the influence of the air bubble injection into the inner tube on heat transfer rate. If the air bubbles are injected into the outer tube, the probable accumulation of the air bubbles can occur on the inner side of the outer tube. And obviously it has no negative affect on heat transfer rate between the two tubes.

3.3. Effectiveness

The effectiveness-NTU charts can be of great practical utility in design problems. More elaborate design procedures, requiring analytical expression for these curves. NTU (number of heat transfer units) is

indicative of the size of the heat exchanger and it is evaluated by,

$$NTU = \frac{AU}{C_{min}}$$

Where C_{min} is the minimum thermal capacity and it is defined as bellow,

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

Double pipe heat exchanger effectiveness can be calculated with:

$$\varepsilon = \frac{\text{actual heat transfer}}{\text{maximum possible heat transfer}}$$

Maximum possible heat transfer is expressed as

$$Q_{max} = (\dot{m}c)_{min}(T_{h \text{ inlet}} - T_{c \text{ inlet}})$$

Heat exchanger effectiveness was calculated for all cases. The heat exchanger effectiveness for heat exchanger without air bubble injection was defined as E_s .

n : Heat exchanger effectiveness without air bubble injection. (Non-enhanced)

Changes of the E / E_n with NTU are shown in Fig.5a-c. Also, changes of the NTU with Reynolds number are shown in Fig.5d-f. It is observed that with the increase of NTU, the amount of E / E_n decreases. Air bubble injection has increased the effectiveness of heat exchanger. It is observed that with the increase of Re , the amount of NTU increases. Dependent on air bubbles injection conditions and Reynolds number, air bubble injection increased the amount of effectiveness about 10% - 40%. Maximum effectiveness (E/E_n) was obtained about 40% when air bubbles were injected into the annular space between the two tubes (outer tube). In high amounts of Reynolds numbers or NTU, bubbles size is important than the number of bubbles. For example, in each of the Fig.5a to Fig.5c, at high amounts of NTU, “ $d=0.7$ ” (big air bubbles) have equal or better effectiveness compared to the “ $d=0.3$ ”. In other words, despite “ $d=0.3$ ” has more effectiveness at lower amounts of Reynolds number, but the slope of the E/E_n curve reduction, in “ $d=0.3$ ” is faster than the other ($d=0.7$). So the amount of E/E_n slakes rapidly in “ $d=0.3$ ”. However, the proficient design of air outlets (holes on plastic tube) and logical choice of other

parameters can improve the effectiveness of heat exchanger.

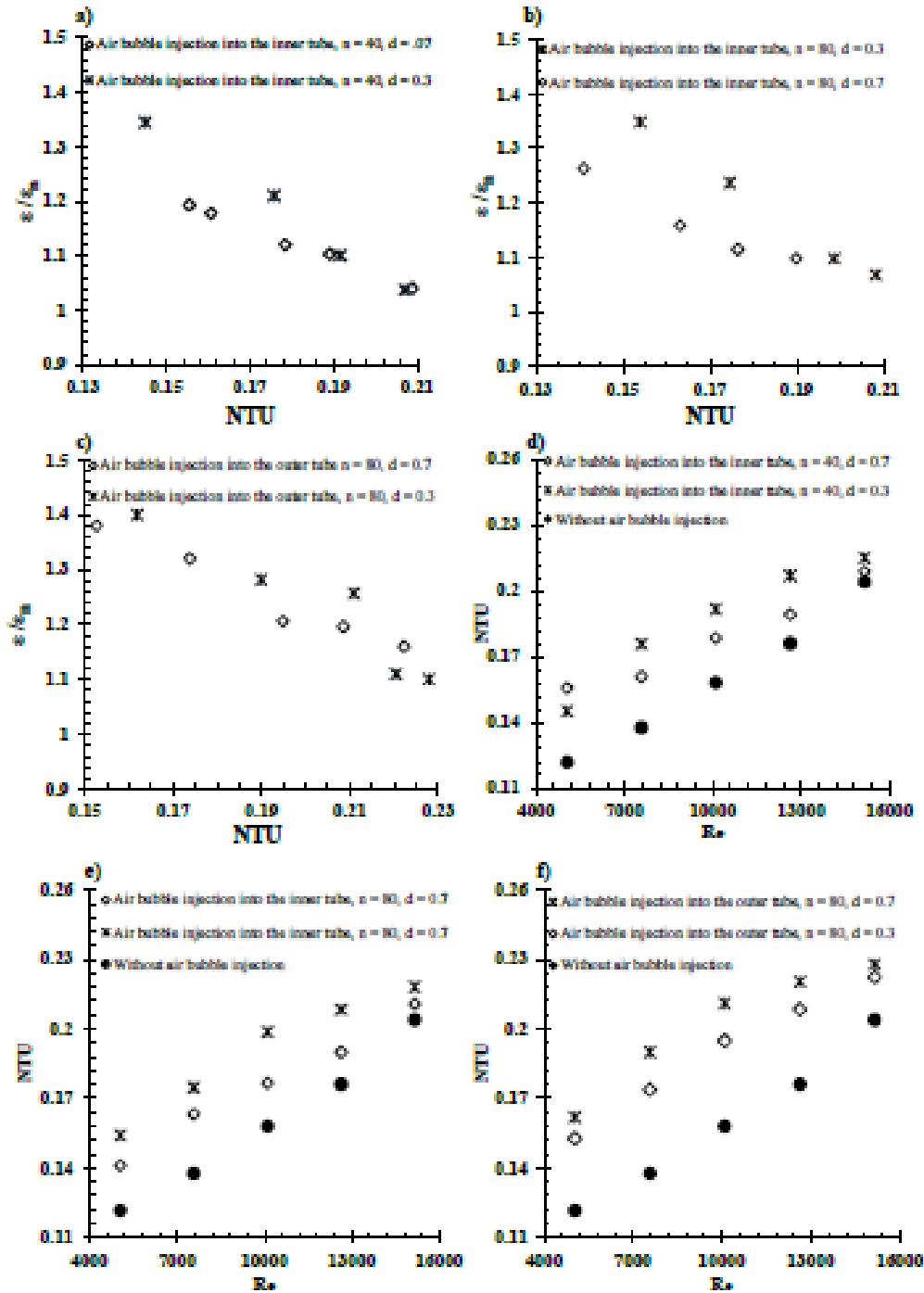


Fig5. (a – c) :Relationship between enhanced effectiveness to non – enhanced effectiveness ratio and NTU. (d – f) : Relationship between NTU and Reynolds number

4. Conclusion

The main scope of the present study is to experimentally clarify the effect of air bubble injection on heat transfer rate, number of heat transfer units and effectiveness in a horizontal double pipe heat exchanger. Air bubbles were injected at various conditions into the heat exchanger. Air bubble injection was found as a promising technique to increase the heat transfer rate through the horizontal double pipe heat exchanger in this study, and the key findings are summarized as follows:

Dependent on air injection condition and Reynolds number, air bubbles increased the amount of Nusselt number about 6% - 35%.

Air bubble injection increased the effectiveness of heat exchanger about 10%- 40%.

Maximum effectiveness was obtained when air bubbles were injected into the annular space between the two tubes (outer tube).

Generally, it can be concluded that the ratio of n to d (n / d) is a considerable parameter in these cases. However, proficient design of holes on plastic tube and logical choice of their number and diameter can improve the performance of heat exchangers.

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