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An Experimental Research on Heat Transfer Enhancement of a Circular Tube with Inclined Baffles

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ABSTRACT:- In the literature, internal tube baffles are widely studied. There is a lack of data for baffles mounted on outside of the tubes. This study aims to fill this gap. Therefore, the effect of baffle inclination angles on heat transfer improvement has been studied experimentally. The experiments were carried out for forced convection of air on a circular tube with inclined baffles. Air has been used as the cold fluid. Experimental results for eight different velocities of air flow (2 – 20 m/s) are presented. Pitch between baffles is 12 mm.The baffle inclination angles with respect to the tube axis were 45º, 60º and 80º. Water temperature is fixed as 65 °C. According to the experimental results, the baffles with an inclination angle of 45º enhance the heat transfer over 60º and 80º around 13.7 % and 10.5 %, respectively. However, pressure drop values for 45º and 60º are 18 % higher than pressure drop values for 80º. The empirical correlations of the Nusselt number have also been obtained for each angle.
Keywords:- Inclined baffle, inclination angle, heat transfer

I. INTRODUCTION

Many enhancement techniques have been identified for heat exchanger applications. They are active and passive. Passive techniques employ wavy surfaces, extended surfaces, vortex generators etc. Hence, passive techniques have been studied by many researchers.

Promvonge et al. [1] experimentally determined the effect of inclined horseshoes baffles located in a tubular heat exchanger on heat transfer rate, friction factor and thermal enhancement factor. Anvari et al. [2] experimentally studied forced convection of water in horizontal tubes with conical tube inserts. Karabacak and Yakar [3] experimentally investigated the influence of holes placed on perforated finned heat exchangers on convective heat transfer. Yakar and Karabacak [4] experimentally examined the thermal performance of perforated finned heat exchangers with an angle of rotation θ. Promvonge et al. [5] experimentally studied the influence of inclined vortex rings (VR) on heat transfer augmentation in a uniform heat – fluxed tube. Carvajal – Mariscal et al. [6] presented experimental results for the convective coefficient distribution in both the inside and conical end zones of the extended surface in a finned tube. Aydin et al. [7] experimentally carried out decaying turbulent swirl flow in a circular tube. Muthusamy et al. [8] investigated heat transfer, friction factor and thermal performance factor in a cylindrical tube with a conical cut – out turbulator integrated with internal fins. Eiamsa – ard and Promvonge [9] conducted experiments to investigate the heat transfer and friction factor characteristics of a fully developed turbulent airflow through a uniform heat flux tube with diamond – shaped turbulators in tandem arrangements. Gunes et al. [10] experimentally studied the pressure drop and heat transfer in a coiled wire inserted tube in a turbulent flow regime. Zohir et al. [11] studied the effect of pulsation with different amplitudes on the heat transfer rates in a double – tube heat exchanger with coiled wire inserts around the outer surface of the inner tube. Rivier et al. [12] examined the performances of a turbulator in respect to heat transfer and fluid friction characteristics in a heat exchanger tube. Sheikholeslami et al. [13] experimentally studied heat transfer for turbulent flow in an air to water double – tube heat exchanger. Chumpia and Hooman [14] tested five specimens of an Aluminium foam wrapped tubular heat exchanger for heat transfer performance and pressure drop characteristics.

The aim of this study is to investigate the importance of baffle inclination angles on heat transfer enhancement. In this study, outside inclined baffles for cross flow are used instead of traditional circular fins as they are very strong vortex generators.

II. EXPERIMENTAL INSTALLATION

The experimental installation is shown in Fig. 1.

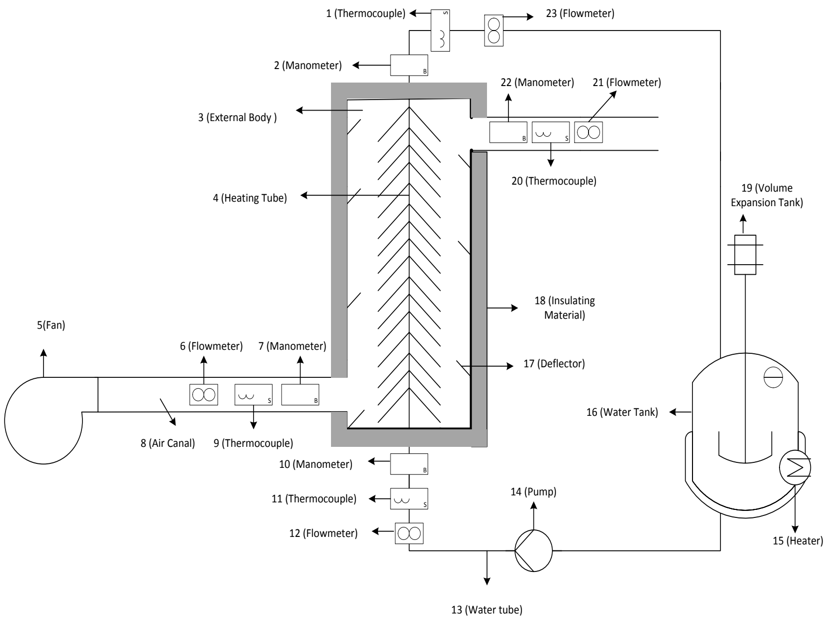


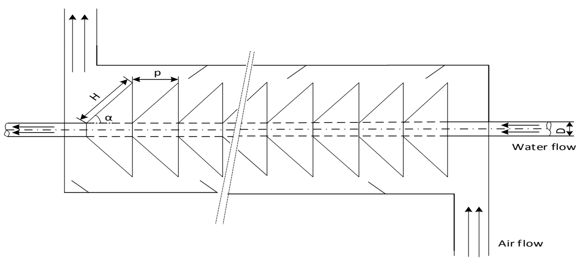
Figure 1. Experimental installation.

In the installation illustrated in Fig. 1, the air was directed to the air canal (number 8) by a fan (number 5). The measurement of mass flow of the air at the entrance and exit of body was determined by a flow meter (number 6 and 21). The air flow velocity was adjusted by the fan. The entrance and exit temperatures of air were quantified by T-type copper-constant thermocouples (number 9 and 20). The air temperatures of the baffle bottom (T_s) and between the baffles (T_∞) were measured by the same type thermocouples. The air pressure at the input and output of the body was determined with a differential manometer (number 7 and 22). The material of the heating tube is galvanized steel (number 4). Moreover, the pressure (number 2 and 10), temperature (number 1 and 11) and volumetric flow rate (number 12 and 23) of the hot fluid was determined for the entrance and exit of the tube. The hot fluid was carried to the test section by a pump (number 14). The heating fluid was heated by the electrical heaters (number 15) placed in the 250 liter water tank (number 16) and carried to the test section by a tube (number 13). The external body was insulated to reduce the heat loss to surroundings. In addition, the deflectors (number 17) extended the residence time of air flow on the heating tube.

The uncertainties of the measured values are as follows: temperature for air is ± 0.5 °C, heating tube diameter is ±2 mm, pressure difference for air is ± 0.16 mbar, velocity for air is ±0.2 m/s, pressure for water is ± 0.2 mbar, temperature for water is ± 0.1 °C and water flow is ± 0.4 L/h.

III. EXTERNAL BODY, CIRCULAR TUBE WITH INCLINED BAFFLES AND INCLINED BAFFLE GEOMETRIES

In the present study, the diameter of the body was 154 mm. The diameter of the tube with inclined baffles was 27 mm. The inclination angles of the baffle with respect to the tube axis were 45º, 60º and 80º. Pitch between baffles was 12 mm. The thickness of the baffle for all inclination angles studied is 0.6 mm. On the other hand, the height of the baffles are 35, 33, 31 mm for **α** = 45º, **α** = 60º, **α** = 80º, respectively. Fig. 2 shows the tube with inclined baffles.



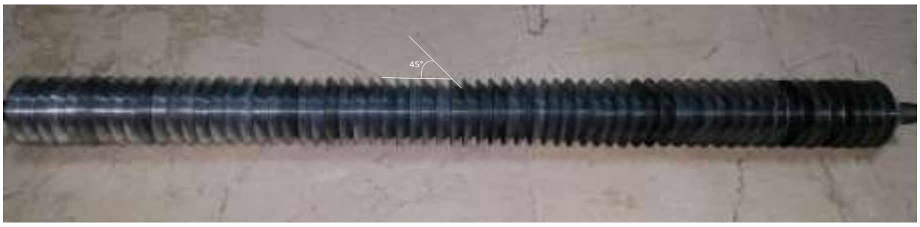


Figure 2. Tube with inclined baffles.

The circular tube with inclined baffles was exposed to a cross air - flow in the external body. To determine the effects of inclination angles, a series of experiments were carried out at three different inclination angles; 45º, 60º and 80º. The fan provided air at eight different velocities (2 – 20 m/s). All measurements were recorded by using software from PLC.

IV. DATA REDUCTION

The heat loss to surroundings was found to be very small as the external body was well insulated. Therefore, the heat transfer happening inside the test section was taken into account. That is,

$$\dot{Q}_{water} = \dot{Q}_{air} = \dot{Q}_{conv} \quad (1)$$

in which

$$\dot{Q}_{air} = \dot{m}_{air}\, c_{p,air}\left(T_{o,air} - T_{i,air}\right) \quad (2)$$

and

$$\dot{Q}_{water} = \dot{m}_{water}\, c_{water}\left(T_{i,water} - T_{o,water}\right) \quad (3)$$

The convective heat transfer from the heating tube can be written by

$$\dot{Q}_{conv} = hA_{total}\,(T_s - T_\infty) \quad (4)$$

where A_{total} is the total heat transfer surface area on the circular tube with inclined baffles.

$$A_{total} = n\left(A_s + \eta_{baffle}\, A_{baffle}\right) \quad (5)$$

in which A_s is the tube heat transfer area between two baffles and η_{baffle} represents the baffle efficiency. Moreover, n is the number of baffles.

The average heat transfer coefficient (h)

$$h = \frac{\dot{Q}_{conv}}{A_{total}\,(T_s - T_\infty)} \quad (6)$$

The average Nusselt number (Nu)

$$Nu = \frac{hD}{k} \quad (7)$$

The Reynolds number based on tube diameter is written as

$$Re = \frac{V_{max}\, D}{\nu} \quad (8)$$

and

$$V_{max} = \frac{\dot{m}_{air}}{\rho_{air}\, A_p} \quad (9)$$

in which V_{max} is the maximum velocity (velocity between two baffles) and A_p is the perpendicular area to the flow direction between to baffles.

V. RESULTS AND DISCUSSION

The heat transfer was identified at the cross flow arrangement with air flow velocities of 2, 5, 8, 10, 13, 15, 18 and 20 m/s. A series of experiments were performed at three different inclination angles (45º,60º and 80º). The air was heated by hot water with a temperature of 65 °C.

Validation of Experimental Installation

The Nusselt number obtained from a tube without baffles is compared with that from the correlation of Churchill and Bernstein [15] for cross flow over a cylinder. Thus, the validity of the experimental installation is verified.

Correlation proposed by Churchill and Bernstein:

$$Nu = \frac{hD}{k} = 0.3 + \frac{0.62\,Re^{1/2}Pr^{1/3}}{\left[1+(0.4/Pr)^{2/3}\right]^{1/4}}\left[1 + \left(\frac{Re}{282{,}000}\right)^{5/8}\right]^{4/5} \quad (10)$$

Fig. 3 shows a comparison of Nusselt number from Churchill and Bernstein correlation and the experimental Nusselt number.

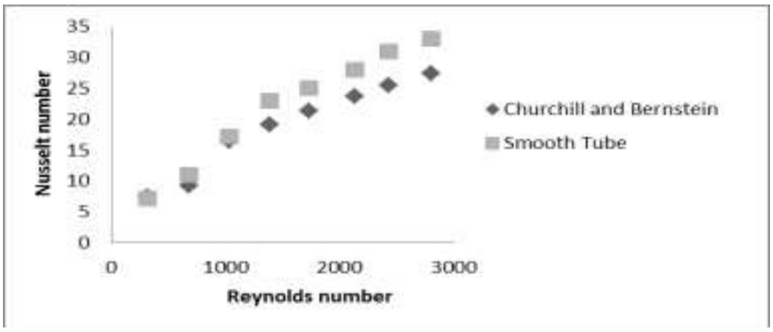


Figure 3. Verification of Nusselt numbers of smooth tube.

As shown in Fig. 3, the experimental results of this study are in good agreement, ± 13 % compared to the Churchill and Bernstein correlation.

Effect of Inclined Baffle

Fig. 4 illustrates influences of inclination angles (45º,60º and 80º) on the Nusselt number. As seen in Fig. 4, the Nusselt number increases with the increment in Reynolds number.

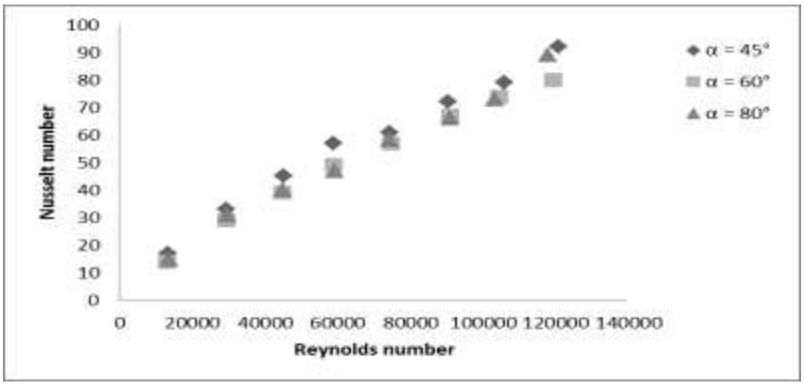


Figure 4. The change of Nusselt number with Reynolds number for different inclination angles.

In Fig. 4, the Nusselt number for the heating tube with 45º inclined baffles is higher than that of the other inclination angles. Furthermore, the difference between the Nusselt numbers of 45º and the others tends to increase with an increasing Reynolds number. The baffles with an inclination angle of 45º enhance the heat transfer over 60º and 80º around 13.7 % and 10.5 %, respectively. This situation indicates that the 45º inclined baffles accelerate the boundary layer separation and provides larger vortices than 60º and 80º. Thus, they extend the residence time of air flow in the heating tube. In addition, it is considered that the 45º inclined baffles cause higher flow interruption than 60º and 80º.

According to experimental results of this study, the correlation for Nusselt number of the heating tube with inclined baffles can be introduced as follows:

$$Nu = cRe^{m} \qquad (11)$$

The corresponding correlations for three different inclination angles (45º,60º and 80º) in cross – flow arrangement in this work are demonstrated in Table 1.

Table 1. Correlations of Nusselt number for different inclination angles in cross – flow arrangement.

Inclination angles (α)	Range of Re	Nu = f (Re)	Error (%)
45°	13,340 – 121,013	$Nu = 0.0155Re^{0.7414}$	3.54
60°	13,210 – 119,585	$Nu = 0.0085Re^{0.7859}$	2.41
80°	13,650 – 118,034	$Nu = 0.0092Re^{0.7805}$	3.60

Effect of Inclined Baffle on Pressure Drop

Fig. 5 shows the change of pressure drop with Reynolds number for three different inclination angles.

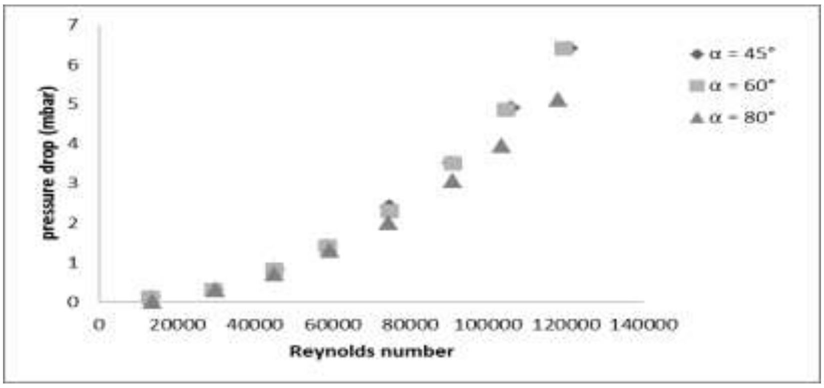
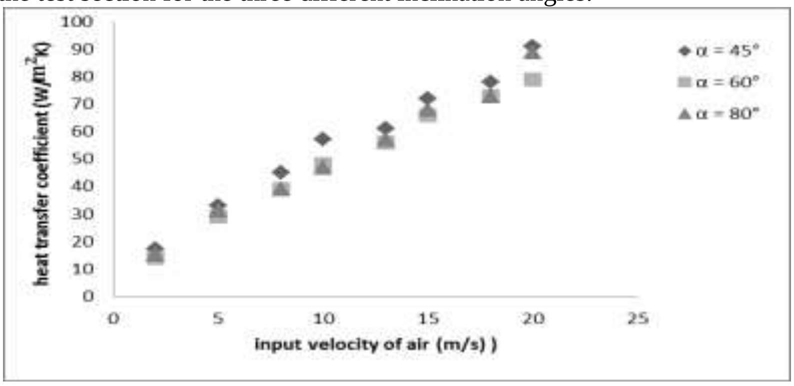


Figure 5. The change of pressure drop with Reynolds number for different inclination angles.

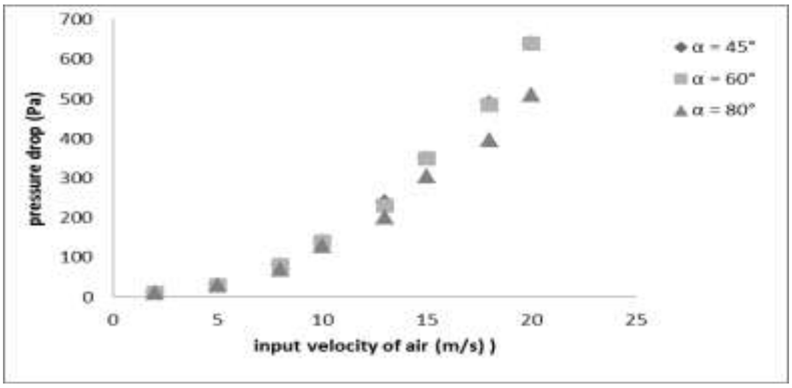
It is seen in Fig. 5 that the pressure drop increases with the increment of Reynolds number for all inclination angles. Although pressure drop for all configurations of baffles is almost the same, a significant deviation is observed beyond a certain value, 80,000. Moreover, pressure drop values of 45º and 60º are 18 % higher than those of 80º. This can be caused by large verticesat $\alpha = 45°$. It is also interesting that similar pressure drop characteristics have been observed for both 45º and 60º.

Performance for Varying Baffle Angles

Fig. 6 illustrates change of heat transfer coefficient (h) and pressure drop (Δp) according to input velocity of air into the test section for the three different inclination angles.



(a)



(b)

Figure 6. (a)Heat transfer coefficient values versus input velocity of air for three inclination angles (b) Pressure drop values versus input velocity of air for three inclination angles.

Although less air flow rate is allowed around heated tube for the 45º inclined baffles compared to 60º and 80º, higher heat transfer coefficient values have been attained as shown in Fig. 6a. Fig. 6a also implies that heat transfer coefficient is inversely proportional with inclination angle. For the same air inlet velocity, heat transfer coefficient values of the 45º inclined baffles are 1.19 times higher compared to the values of 60º. In addition, for the same pumping power, heat transfer coefficient is 1.13 times higher for the 45º baffles than the 60º baffles.

VI. CONCLUSIONS

The effect of different inclination angles on heat transfer improvement of the air was studied. The experiments were performed for three inclination angles (45º, 60º and 80º). The empirical correlation of the Nusselt number is presented. The Nusselt number and the pressure drop tend to increase with the rise in Reynolds number. Similar pressure drop characteristics are observed for both 45º and 60º. The inclined baffles with an inclination angle of 45º enhanced the heat transfer over the 60º and 80º baffles by approximately 13.7 % and 10.5 %, respectively. However, pressure drop values of the 45º and 60º baffles are 18 % higher than those of the 80º baffles. Moreover, for the same air inlet velocity heat transfer coefficient of the 45º inclined baffles are 1.19 times higher compared to the values of the 60º inclined baffles. For the same pumping power the heat transfer coefficient is 1.13 times higher for the 45º baffles than the 60º baffles.

VII. NOMENCLATURE

A_{total}	total surface area (m^2)
A_s	tube heat transfer area between two baffles (m^2)
A_{baffle}	baffle area on the tube (m^2)
A_p	perpendicular area to the flow between two baffles (m^2)
$c_{p,air}$	specific heat of air (kJ/kg°C)
c_{water}	specific heat of water (kJ/kg°C)
c, m	coefficients of formulation
D	diameter of tube with baffle (m)
H	height of baffle (m)
h	heat transfer coefficient (W/m^2K)
k	thermal conductivity (W/m°C)
L	tube length (m)
$\dot{m}_{air}$	mass flow of air (kg/s)
$\dot{m}_{water}$	mass flow of water (kg/s)
n	number of baffles
Nu	Nusselt number
Pr	Prandtl number
p	pitch between baffles (m)
$\dot{Q}_{air}$	heat transfer of air (W)
$\dot{Q}_{water}$	heat transfer of water (W)
$\dot{Q}_{conv}$	convective heat transfer (W)
Re	Reynolds number
$T_{i,air}$	air inlet temperature into heat exchanger (°C)
$T_{o,air}$	air outlet temperature from heat exchanger (°C)
$T_{i,water}$	water inlet temperature into heat exchanger (°C)
$T_{o,water}$	water outlet temperature from heat exchanger (°C)
T_s	tube surface temperature (°C)
T_∞	heated air temperature (°C)
t	baffle thickness (m)
V_{max}	maximum velocity (velocity between two baffles) (m/s)
$V_{i,air}$	input velocity of air into heat exchanger (m/s)

Greek Symbols

ν	kinematic viscosity (m^2/s)
μ	dynamic viscosity (kg/ms)
α	baffle inclination angle (°)
η_{baffle}	baffle efficiency
Δp	pressure drop (mbar, Pa)

Subscripts

air	air side
baffle	baffle
conv	convection
i	input
o	output
s	tube wall
total	total
Water	water side

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