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Experimental Investigation on Forced Convection Heat Transfer Augmentation Using Annular Blockages

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Abstract— Heat exchangers have several industrial and engineering applications. The design procedure of heat exchangers is quite complicated, as it needs exact analysis of heat transfer rate and pressure drop estimations apart from issues such as long-term performance and the economic aspect of the equipment. Whenever inserts are used for the heat transfer enhancement, along with the increase in the heat transfer rate, the pressure drop also increases. This increase in pressure drop increases the pumping cost. Therefore any augmentation device should optimize between the benefits due to the increased heat transfer coefficient and the higher cost involved because of the increased frictional losses.

Experimental work on heat transfer augmentation using annular blockages. Inserts when placed in the path of the flow of the fluid, create a high degree of turbulence resulting in an increase in the heat transfer rate and the pressure drop. The work includes the determination of friction factor and heat transfer coefficient for various annular blockages and annular blockages having different diameter. The results of annular blockages having different diameter have been compared with the values for the plain tube. Four annular blockages (di=20%, 30%, 40% & 50% reduction in outer diameter) are used in the study.

Keywords— Annular Blockages, heat transfer augmentation, forced convection, heat exchangers, passive techniques, heat transfer enhancement technique, inserts.

INTRODUCTION

Heat exchangers have several industrial and engineering applications. The design procedure of heat exchangers is quite complicated, as it needs exact analysis of heat transfer rate and pressure drop estimations apart from issues such as long-term performance and the economic aspect of the equipment. [1] The major challenge in designing a heat exchanger is to make the equipment compact and achieve a high heat transfer rate using minimum pumping power. [1, 5]Techniques for heat transfer augmentation are relevant to several engineering applications. In recent years, the high cost of energy and material has resulted in an increased effort aimed at producing more efficient heat exchange equipment. Furthermore, sometimes there is a need for miniaturization of a heat exchanger in specific applications, such as space application, through an augmentation of heat transfer. For example, a heat exchanger for an ocean thermal energy conversion (OTEC) plant requires a heat transfer surface area of the order of 10000 m2/MW. [5] Therefore, an increase in the efficiency of the heat exchanger through an augmentation technique may result in a considerable saving in the material cost.[2] Furthermore, as a heat exchanger becomes older, the resistance to heat transfer increases owing to fouling or scaling. These problems are more common for heat exchangers used in marine applications and in chemical industries. In some specific applications, such as heat exchangers dealing with fluids of low thermal conductivity (gases and oils) and desalination plants, there is a need to increase the heat transfer rate. The heat transfer rate can be improved by introducing a disturbance in the fluid flow (breaking the viscous and thermal boundary layers), but in the process pumping power may increase significantly and ultimately the pumping cost becomes high. Therefore, to achieve a desired heat transfer rate in an existing heat exchanger at an economic pumping power, several techniques have been proposed in recent years.

1.1 Heat Transfer Augmentation Techniques:

The study of improved heat transfer performance is referred to as heat transfer enhancement, augmentation, or intensification. In general, this means an increase in heat transfer coefficient. [2, 4]

The heat transfer can be increased by the following different Augmentation Techniques. They are broadly classified into three different categories:

i. Passive Technique

These techniques generally use surface or geometrical modifications to the flow channel by incorporating inserts or additional devices. They promote higher heat transfer coefficients by disturbing or altering the existing flow behavior (except for extended surfaces) which also leads to increase in the pressure drop. In case of extended surfaces, effective heat transfer area on the side of the extended surface is increased. Passive techniques hold the advantage over the active techniques as they do not require any direct input of external power. [16]

ii. Active Techniques

These techniques are more complex from the use and design point of view as the method requires some external power input to cause the desired flow modification and improvement in the rate of heat transfer. It finds limited application because of the need of external power in many practical applications. In comparison to the passive techniques, these techniques have not shown much potential as it is difficult to provide external power input in many cases. [18]

iii. Compound Techniques.

A compound augmentation technique is the one where more than one of the above mentioned techniques is used in combination with the purpose of further improving the thermo-hydraulic performance of a heat exchanger. [4]

EXPERIMENTAL DETAILS

Experimental Set-up

An experimental set-up has been designed and fabricated to study the effect of annular blockages on heat transfer and fluid flow characteristics in circular pipe. A schematic diagram of the experimental set-up is shown in Figure 2.1

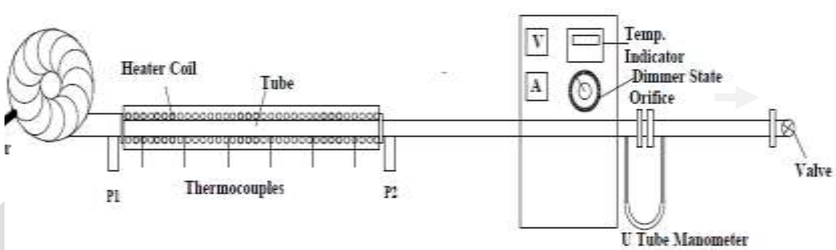

Fig.1Experimental Set up

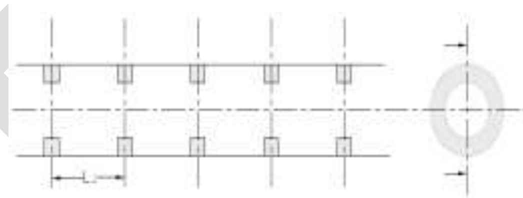

Fig.2. Annular Blockages

The test apparatus is an open air flow loop that consists of a centrifugal blower (1), flow control valve (2), orifice meter along with water manometer to measure mass flow rate of air (3), test section 0.5m length, 25mm diameter, L1=0.1m (4), Annular blockages (material aluminum) having thickness 3mm, outer diameter 25mm & inner diameter with 20%,30%,40% & 40% reduction in outer diameter.(5), Band heater nicrome wire with GI gladding encloses the test section to a length 0.5m to cause electric heating (6), pressure sensor digital(7), Temp. Indicator digital (8), 10 thermocouples T2, T3, T4, T5, T6, T7, T8, T9 (0 to 200ºC) calibrated are embedded on the walls of the test tube and T1 and T10 are placed in air stream (10),one at the entrance and the other at the exit of test section to measure the temperature of flowing air. The types of thermocouples used are copper constant. The control panel consists of dimmer state 2 amps& 0 to 200 volts (10), ammeter digital 0 to 2 amps (11), volt meter digital 0 to 200 volt (12), Temp. Indicator digital, and Selector switch.

Difference in the levels of manometer fluid represents the variations in the flow rate of air. The velocity of air flowing in the tube is measured with the help of an orifice meter and the water manometer is fitted on the board. The pipe consists of a valve which controls the rate of air flow through it. The diameter of orifice is 12.5mm and coefficient of discharge was found as 0.65.

Pressure drop across test section is measured by connecting pressure tapings at each end of test section to digital pressure indicator. The outer surface of the test section was well insulated to minimize heat loss to surrounding.

Fig.3. Experimental sets- up

Fabrication of annular blockages

Aluminum bar of 25mm outer diameter is taken. Firstly all the values of diameter are determined i.e. diameter of 20%, 30%, 40% and 50% blockages. The bar which has outer diameter equal to pipe inner diameter is taken, the boring operation is performed. Boring is a process of producing circular internal profiles on a hole made by drilling or another process. It uses single point cutting tool called a boring bar. The required diameter is achieved by boring operation. After boring operation the parting is done. Parting uses a blade-like cutting tool plunged directly into the work piece to cut off the work piece at a specific length. It is normally used to remove the finished end of a work piece from the bar stock that is clamped in the chuck. Total 10 numbers of blockages are prepared for each set. At the last the facing is done on the blockages. The surface of blockages is made very smooth. Following figure shows the different types of annular blockages.

Fig. 4. 20% Annular Blockages

Fig. 5. 30% Annular Blockages


Fig.6. 40% Annular Blockages Fig.7. 50% Annular Blockages

Blockages Insert arrangement:

The screw arrangement is done on the test section for inserting annular blockages. The two sets of screw are provided for holding the blockage. Therefore such 10 sets are inserted in the test section. The following fig shows the arrangement for the inserts.


Fig.8. Test section pipe with arrangement for inserting annular blockages Fig.9. Insert blockage in pipe.

Experimental procedure

1. The test section is assembled in test bracket and checked for air leakage.
2. The blower was switched on to let a predetermined rate of airflow through the pipe.
3. Initially the experiment was carried out for plain tube. The experiment were carried out for different insert such as annular blockages which having inner diameter with 20%, 30%, 40% & 50% reduction in outer diameter.
4. A constant heat flux is applied to the test section.
5. The changes in temperature are determined with the help of thermocouples placed on it.
6. Four values of flow rates were used for each set at same or fixed uniform heat flux.
7. At each value of flow rate and the corresponding heat flux, system was allowed to attain a steady state before the temperature data were recorded.
8. The pressure drops were measured when steady state is reached.

During experimentation the following parameters were measured:

I) Pressure difference across the orifice meter.

ii) Temperature of the heated surface and temperatures of air at inlet and outlet of the test section and

iii) Pressure drop across the test section.

Data Reduction

i. Average temperature of tube wall

$$T_S = \frac{T2 + T3 + T4 + T5 + T6 + T7 + T8 + T9}{8}$$

ii. Bulk temperature of air

$$T_b = \frac{T1 + T10}{2}$$

Properties of air were taken from the air table corresponding to above bulk temperature of air

- ✓ Density of air (ρa)
- ✓ Specific heat of air (Cp)
- ✓ Kinematic viscosity of air (υ)
- ✓ Prandtl no. (Pr)
- ✓ Thermal conductivity (k)

iii. Area

a) Convective heat transfer area (A)
A=πDiL

b) Area of orifice (ao)

$$ao = \frac{\pi}{4} \times do^2$$

c) Test section inner tube area (Ai)

$$Ai = \frac{\pi}{4} \times di^2$$

iv. Equivalent height of air column

$$ha = \frac{\rho_w \times h_w}{\rho_a}$$

v. Mass flow rate of air

$$m = C_d \times a_o \times \frac{\rho_{air} \times \sqrt{2gha}}{\sqrt{1 - \beta^4}}$$

Where,

Cd = Coefficient of discharge for orifice

ao = Cross sectional area of orifice

β = d/D, diameter of pipe/ diameter of orifice

g = Acceleration due to gravity

ha = Height of air column

vi. Discharge of air through test section

$$q = \frac{m}{\rho_a}$$

vii. Convective heat transferred to air

$$Q = m \times C_p \times (T_{10} - T_1)$$

Where,

T10 = Fluid temperature at the exit of the duct (°C)

T1= Fluid temperature at the inlet of the duct (°C)

m = Mass flow rate of air

Cp = Specific heat of air

Q = Convective heat transfer to air

viii. Convective heat transfer coefficient

$$h = \frac{Q}{A \times (Ts - Tb)}$$

Where,

Ts is the average temperature of the test surface
Tb is the bulk temperature of air in the duct = T1 + T10 /2
A is projected surface area of test surface
h is convective heat transfer coefficient

ix. Velocity of air

$$U = \frac{q}{Ai}$$

x. Reynolds Number

$$Re = \frac{U \times Di}{\vartheta}$$

xi. Experimental Nusselt no. is calculated by

$$Nu = \frac{h \times Di}{k}$$

xii. Nusselt no. by Dittus – Boelter equation is given by

$$Nu = 0.023 \times Re^{0.8} \times Pr^{0.4}$$

xiii. Friction factor

$$fexp = \frac{\Delta p \times Di}{2\rho_{air} \times L \times {V_{air}}^2}$$

xiv. Theoretical friction factor for plain tube

$$f_{the=0.079 \times Re^{-0.25}}$$

xv. Overall enhancement ratio

$$\eta = \frac{\frac{Nui}{Nu}}{\left(\frac{fexp}{fthe}\right)^{\frac{1}{3}}}$$

RESULTS AND DISCUSSION

Using the data obtained from experiments, the heat transfer, friction factor and the thermal performance characteristics of annular blockages are discussed in the following subsections. [6]

Effect of Inserts on Heat transfer

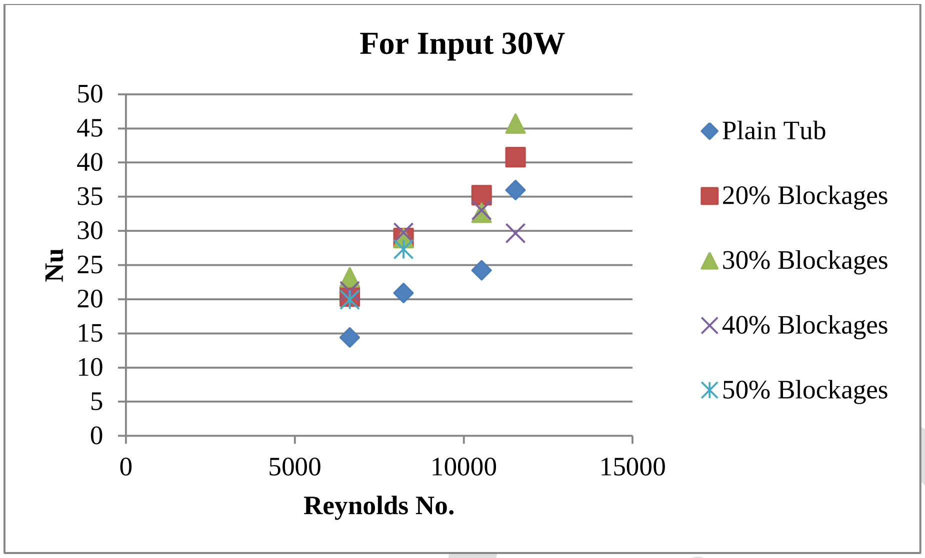

Fig 10 Comparison of Experimental Nusselt No. Vs Reynolds No. for 30 W Input

Baseline Nusselt numbers are in a smooth circular test section with smooth walls on all surfaces and no blockages. Baseline Nusselt numbers Nu are used to normalize values of measured Nusselt numbers on blockage surface. The baseline Nusselt numbers obtained from experiment are compared with Ditus-Boelter correlation which is given by

$$\mathrm{Nu} = 0.023 \times \mathrm{Re}^{0.8} \times \mathrm{Pr}^{0.4}$$

Fig. 10 shows the variation of Nusselt number with Reynolds number for all types of blockages in comparison with plain tube for 30W, 60W, 90W and 120W input. Nusselt number increases with increase in Reynolds no. The highest value of Nusselt number is 52.83 for 30% Blockages at Reynolds number 14579. As shown in these figures, the local Nusselt number decreases with axial position along the flow direction and the decrease in the Reynolds number, also that the local Nusselt number increases with the increase of the heat flux. It is evident from Figure 10 shows that when annular blockages are inserted into a plain tube there is a significant improvement in Nusselt number because of secondary flow, with greater enhancement being realized at higher Reynolds numbers and lower diameter of blockages. In general, some kind of inserts is placed in the flow passage to augment the heat transfer rate, and this reduces the hydraulic diameter of the flow passage. Heat transfer enhancement in a tube flow by inserts such as annular blockages is mainly due to flow blockage, partitioning of the flow and secondary flow. Flow blockage increases the pressure drop and leads to increased viscous effects because of a reduced free flow area. Blockage also increases the flow velocity and in some situations leads to a significant secondary flow. Secondary flow further provides a better thermal contact between the surface and the fluid because secondary flow creates swirl and the resulting mixing of fluid improves the temperature gradient, which ultimately leads to a high heat transfer coefficient. For annular blockages it was observed that the heat transfer coefficient could vary from 30% to 48% times the plain tube value but the corresponding friction factor increases by 4 to 9.6 times the smooth tube values.

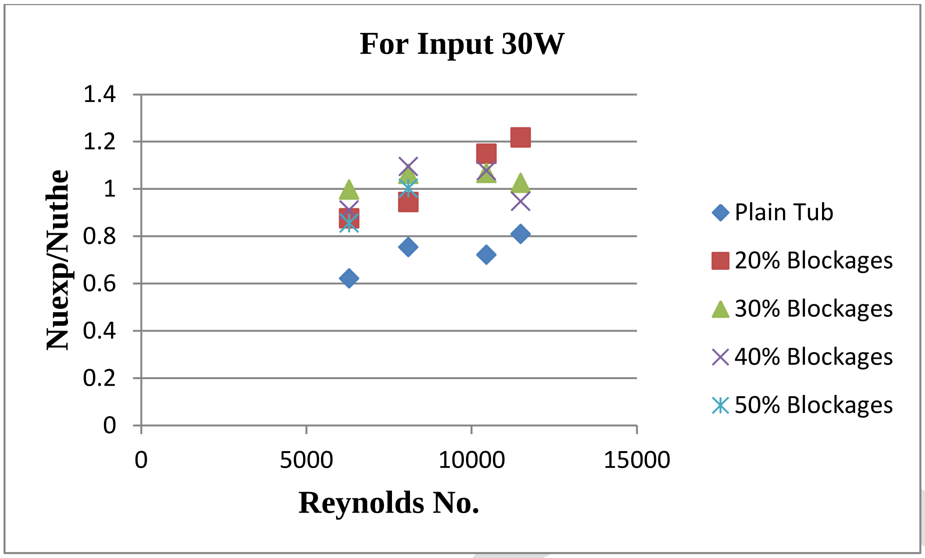

Fig.11 Normalized Nusselt number ratio Vs Reynolds number for different annular blockages for 30W Input

Effect of Insert on Friction Factor

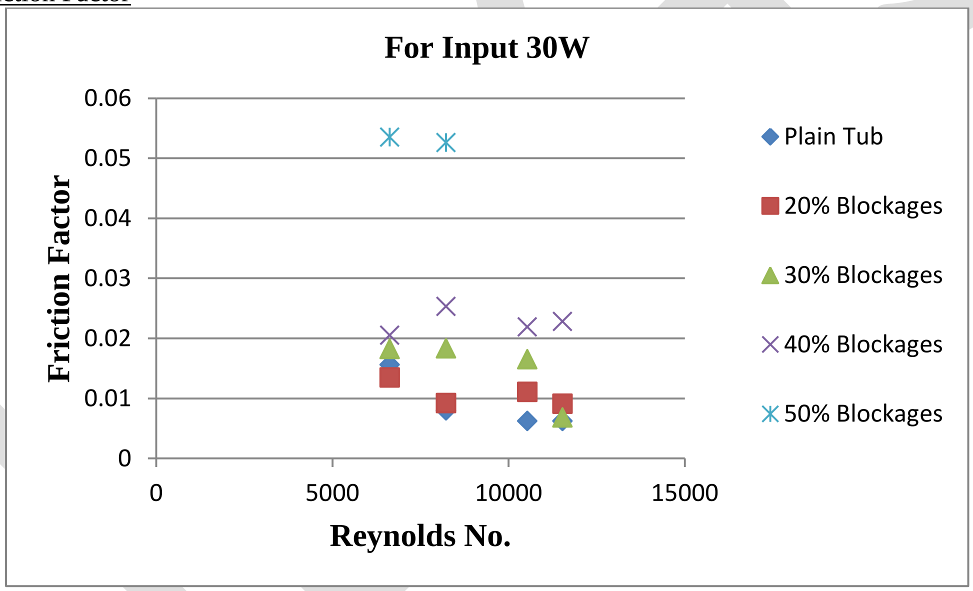

Fig. 12 Comparison of Experimental Friction Factor Vs Reynolds Number

Friction factor is a measure of the pressure losses in a system to the kinetic energy of the fluid. In the present work, the pressure losses include losses due to friction and due to drag force exerted by obstacles. Fig.6.9 shows the variation friction factor with Reynolds number for tube fitted with different annular blockages. It is noticed that the increase in Reynolds number leads to decrease in the friction factor, because the friction factor is proportional with pressure drop and inversely proportional to the square root of flow speed. These figures also indicate that the larger the diameter for annular blockages causes higher – pressure drop because each increase in the width and changing the configuration of annular blockages means increase in the size of obstacles and hence the pressure drop also increases.

Effect of insert on Overall Enhancement ratio

Overall enhancement ratio is defined as the ratio of heat transfer enhancement ratio to the friction factor ratio. This parameter is used to differentiate passive technique and a comparison of different configurations for the technique itself. The overall enhancement ratio is defined as

$$\eta = \frac{\frac{Nui}{Nu}}{\left(\frac{fexp}{fthe}\right)^{\frac{1}{3}}}$$

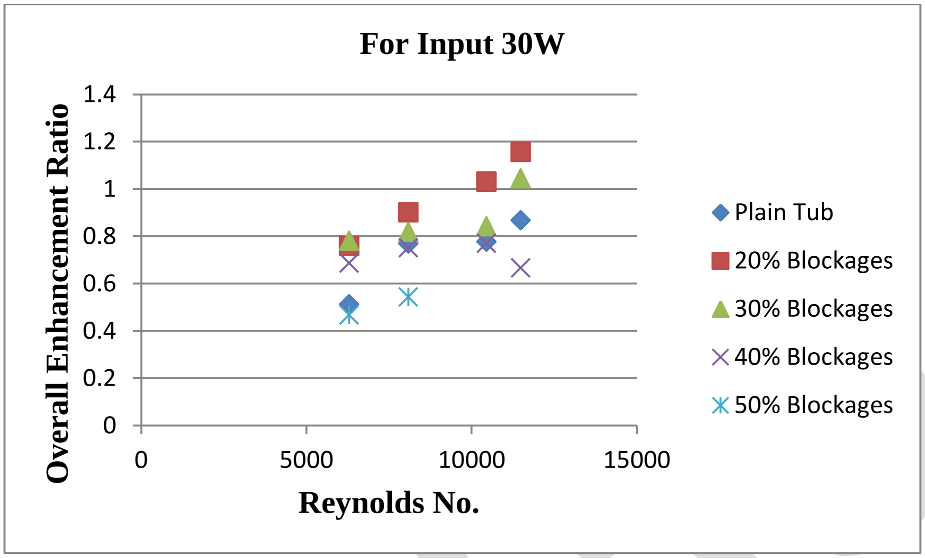

Fig. 13 Variation of Overall enhancement ratio with Reynolds number for 30W Input

Thermal performance shown in fig 13 it was seen that in comparison with plain tube, the inserts is giving best thermo hydraulic performance for the studied range of Reynolds number. This overall enhancement ratio is used to determine the quality of enhancement technique. The highest value of overall enhancement ratio is 1.15 with 20% blockage. Also the enhancement ratio decrease for 40% and 50 % blockages.

CONCLUSION

An experimental study of the flow of air in a circular channel with annular blockage, subjected to uniform heat flux boundary condition has been performed. The effect of Reynolds number and annular blockage diameter on the heat transfer coefficient and friction factor has been studied. Experimental results measured with annular blockage in test surfaces, with different diameter of annular blockages are given for Reynolds numbers from 6000 to11000.

Following conclusions have been drawn:

1. With increases in Reynolds number Nusselt number and friction factor also increases.
2. The heat transfer enhancement can be achieved up to 30% blockages, further decrease in inner diameter of annular blockage can results in decreases in heat transfer and increase in friction factor.
3. Overall enhancement ratio is increases with inserting annular blockages.

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