July 2013

THERMOHYDRAULIC PERFORMANCE OF AN EQUILATERAL TRIANGULAR DUCT WITH ARTIFICIAL ROUGHNESS USED IN SOLAR AIR HEATER

GAURAV BHARADWAJ  
Mechanical Engineering dept. National Institute of Technology, Hamirpur (H.P) - 177005, India, gauravmech2211@gmail.com

VARUN .  
Mechanical Engineering dept. National Institute of Technology, Hamirpur (H.P) - 177005, India, VARUN@gmail.com

AVDHESH SHARMA  
Mechanical Engineering dept. National Institute of Technology, Hamirpur (H.P) - 177005, India, AVDHESHSHARMA@gmail.com

Follow this and additional works at: https://www.interscience.in/ijmie

Part of the Manufacturing Commons, Operations Research, Systems Engineering and Industrial Engineering Commons, and the Risk Analysis Commons

Recommended Citation
BHARADWAJ, GAURAV; ., VARUN; and SHARMA, AVDHESH (2013) "THERMOHYDRAULIC PERFORMANCE OF AN EQUILATERAL TRIANGULAR DUCT WITH ARTIFICIAL ROUGHNESS USED IN SOLAR AIR HEATER," International Journal of Mechanical and Industrial Engineering: Vol. 3 : Iss. 1 , Article 10. Available at: https://www.interscience.in/ijmie/vol3/iss1/10

This Article is brought to you for free and open access by Interscience Research Network. It has been accepted for inclusion in International Journal of Mechanical and Industrial Engineering by an authorized editor of Interscience Research Network. For more information, please contact sritampatnaik@gmail.com.
Abstract—The thermohydraulic performance of artificially roughened equilateral triangular solar air heater duct has been investigated and the comparison of the same has been presented with that of a conventional smooth solar air heater duct. The range of relative roughness height ($e/D_h$) is from 0.021 to 0.043, value of angle of attack ($\alpha$) and relative roughness pitch ($p/e$) has been 30° and 8 respectively. The range of Reynolds number is from 5600 to 28000 and aspect ratio of the duct is 1.15. It has been found that the thermohydraulic performance of artificially roughened triangular solar air heater duct is always more than that of the smooth absorber plate in the range of Reynolds number investigated.

Keywords—Thermohydraulic performance; Artificial roughness; Solar air heater; Triangular duct.

1. INTRODUCTION

Energy plays a very crucial role in the life of every one either it is the matter of economic growth or the growth of industrialization [1]. As the population goes on increasing, the demand for energy also goes on increasing day by day. The depletion of the fossil fuels has been started due to the continuous use of fossil fuels for energy generation. On the other hand, energy generation with the help of fossil fuels creates lot of pollution which in turn deteriorates the life cycle of the planet Earth [1]. Development in the field of renewable energy resources work as the catalyst for the energy generation. Use of renewable energy resources for energy generation is free from pollution. Among all the available renewable resources the sun is of dominating nature.

The easiest methodology for making the proper use of solar energy is its conversion to thermal energy using solar collector. These solar collector are the part of solar air heater and solar water heater which are used for heating air and water respectively. Fabrication of solar air heater is quiet easy due to its compactness. Moreover, solar air heater are cheaper as compared to solar water heater due to use of less material. Solar air heater has wide area of application such as curing of industrial products, space heating, crop drying, wood seasoning, etc. Efficiency of solar air heater is low due to the low specific heat of air and low heat transfer rate between absorber plate and flowing air inside duct. So, to make solar air heater efficient it is necessary to enhance the heat transfer rate.

Artificial roughness provides the turbulence to the flow which leads to increase the heat transfer between the air and the heated wall. Roughness is created in such a way that it breaks the laminar sublayer region i.e. near the wall. There are several method to provide artificial roughness on the absorber plate such as casting, forming, machining, blasting, welding ribs and/or fixing thin circular wires, etc [2-4]. The easiest and cheapest way of providing artificial roughness on the underside of the absorber plate is sticking of ribs.

Bharadwaj and Varun [5] experimentally investigated that in an artificially roughened equilateral triangular solar air heater duct maximum heat transfer and friction factor occur at relative roughness height of $(e/D_h)$ of 0.043. Mittal and Varun [6] experimentally observed that maximum thermohydraulic performance in case of discrete inclined ribs and transverse full ribs occur at relative roughness pitch $(p/e)$ of 8. Verma and Prasad [7] carried out an experimental study for the optimization of thermohydraulic performance. They kept the range of Reynolds number from 5000-20000, relative roughness height $(e/D_h)$ 0.01-0.03 and relative roughness pitch $(p/e)$ 10-40. They found that for the given range of parameters optimal thermohydraulic performance comes to be 71%. Gupta et al. [8] experimentally investigated the effect of relative roughness height $(e/D_h)$, angle of attack $(\alpha)$ and Reynolds number on the thermohydraulic performance. They found that with the increase in relative roughness height $(e/D_h)$, the value of Reynolds number decreases for which thermohydraulic performance was maximum. They found that best thermohydraulic performance was maximum and Reynolds number of 14000. Various investigators like Prasad and Mullick [9], Prasad and Saini [10-11], Sahu and Bhagoria [12], Aharwal et al. [13], Varun et al.[14] utilized different types of rib roughness on the absorber plate of the solar air heater to increase the heat transfer coefficient.

However, any method adopted to increase the heat transfer is always accompanied by an increase in...
frictional losses in the duct. Therefore, investigation of the thermohydraulic parameter is necessary in order to find the pumping power required to force the air through the duct.

In this investigation, circular ribs of relative roughness height \((e/D_h) 0.021-0.043\) are attached to one side of the absorber at inclination of \(30^\circ\) and relative roughness pitch \((p/e)\) of 8.

II. CONCEPT OF ARTIFICIAL ROUGHNESS

Surface roughness is one of the first active techniques to be considered for the augmentation of forced convection heat transfer. It is necessary that the flow near the heat transfer surface should be turbulent so as to attain higher coefficient of heat transfer. However, energy for creating such turbulence has to come from the fan or blower and the excessive turbulence leads to excessive power requirement to make the air flow through the duct.

Hence, it is necessary that the turbulence must be created in the vicinity of heat transfer surface i.e. laminar sublayer only where the heat exchange takes place and the flow should not be unduly disturbed so as to avoid excessive friction losses. This can be done by keeping the height of the roughness element to be small in comparison with the duct dimensions.

III. EXPERIMENTAL SET-UP

The schematic and sectional view of the equilateral triangular duct is shown in Fig. 1 (a and b). The duct is fabricated from wooden planks of different cross-sections. The inner dimension of the duct is \(2300 \text{ mm} \times 160 \text{ mm} \times 138 \text{ mm}\) and the aspect ratio \((W/H)\) of the duct is 1.15. The length of the test-section is 1000 mm. The entry and exit length are kept equal. Consequently, the flow can be assumed to be fully developed turbulent flow in the entire length of the test section. Hence, the entry and exit lengths are 650 mm and 650 mm respectively. Entry and exit length are required in order to minimize the end effects in the test section. An electric heater of size \(1000 \text{ mm} \times 160 \text{ mm}\) was fabricated using series and parallel loops of nichrome wires. Heater was designed in such a way that it can provide maximum heat flux upto \(800 \text{ W/m}^2\). Heat flux may be varied using a variac which is connected across an electric heater. 60 mm thick glasswool layer and 12 mm thick wooden planks are provided on the back side of the heaters to minimize the heat losses from the top side of the heater.

The roughness was produced by fixing the ribs of different diameter at \(30^\circ\) inclination and relative roughness pitch \((p/e)\) of 8 on the underside of the absorber plate. The schematic and pictorial view of the absorber plate is shown in Fig. 2 (a and b). At the end of the duct, a plenum was provided to connect the triangular duct to a circular pipe.

Ambient air is sucked through the duct by means of a centrifugal blower driven by 1.5 kW, three phase, 230 V and 2820 rpm motor. For precise control of the air flow rate through the system, two gate valves are...
provided, one on the inlet side and other on the outlet side of the blower.

IV. INSTRUMENTATION

A. Temperature Measurement
Calibrated copper-constant (T type), thermocouples were used for the temperature measurement of air and the absorber plate. 12 Thermocouples were mounted on the absorber plate to measure its mean temperature. The location of thermocouples on the absorber plate is shown in Fig 3.

![Figure 3. Location of thermocouples on the absorber plate](image)

B. Measurement of Air flow
The air flow rate through the duct was measured by using concentric orifice plate with 45° beveled edges which was designed, fabricated and fitted in the 80 mm pipe carrying the air from plenum to the blower. The orifice plate was calibrated against pitot tube and the value of coefficient of discharge (C_d) was determined as 0.612 and it is used to measure mass flow rate of the air. Pressure drop across the orifice meter was measured by means of a U-tube manometer.

C. Pressure Drop Measurement
The pressure drop across the test section of the duct was measured with the help of a micro-manometer having a least count of 0.01 mm. The micro-manometer consists of a movable reservoir, a fixed reservoir and a transparent tube connected to these reservoirs through flexible tubing. The movable reservoir is mounted using a lead screw having a pitch of 1.0 mm and a graduated dial having a 100 division; each division showing a movement of 0.01 mm of the meniscus is maintained at a fixed prescribed mark by air traps of the duct through flexible tubes. The reservoirs were connected with the movable reservoir through flexible tubing. The two reservoirs were mounted using a lead screw having a pitch of 1.0 mm and a graduated dial having 100 division; each division showing a movement of 0.01 mm of the reservoir. The two reservoirs were connected with the air traps of the duct through flexible tubes. The meniscus is maintained at fixed prescribed mark by moving the reservoir up and down and the movement is noted, which yields the pressure difference across the two pressure tapping.

V. EXPERIMENTAL PROCEDURE
The measuring equipments i.e. orifice meter, millivoltmeter and U-tube manometers were properly checked. The micro-manometer and the U-tube manometer were properly leveled by means of spirit level. Thermocouples were tested to insure that all thermocouples yield the same output corresponds to ambient temperature before heater has been switched on. Pressure tapings and the tubes were cleaned and checked for leakage and blockage before each test run. After proper checking of instruments the set up was used for conducting experiment. The power supply to the centrifugal blower and the electric heater was switched on and the desired flow rate was set with the help of control valves.

The experimental runs were conducted under quasi-steady state to collect the relevant data for heat transfer and friction factor. The setup was allowed to attain quasi-steady state before the data was recorded at different mass flow rates. The following data were recorded:
1. Air temperature at different points on the duct and the temperature of absorber plate at 12 different locations on the absorber plate.
2. Pressure drop across the test section.
3. Pressure measurement across the orifice meter.

Before starting the experimentation for the roughened duct, the set-up was checked by conducting the experiment for a smooth duct. The Nusselt number and friction factor calculated from the experimental data for smooth duct have been compared with the predicted value of the Nusselt number and friction factor respectively obtained from Dittus-Boelter equation [14] and Modified Blasius equation [15]

Dittus-Boelter equation

\[ Nu = 0.024 \text{Re}^{0.8} \text{Pr}^{0.4} \]  \hspace{1cm} (1)

Modified Blasius equation:

\[ f = 0.085 \text{Re}^{-0.25} \]  \hspace{1cm} (2)

VI. DATA REDUCTION

The raw data have been reduced to obtain mean plate temperature, mean air temperature, mass flow rate and Reynolds number. These data were then used to determine heat transfer coefficient, Nusselt number and friction factor. Relevant expressions for the computation of above mentioned parameters and some intermediate parameters have been given below;

Mass flow rate of air has been determined from the pressure drop measurement across the calibrated orifice meter using the following expression.

\[ m = C_d A_d \sqrt{\frac{2 \rho (\Delta P)}{1 - \beta^4}} \]  \hspace{1cm} (3)

The heat transfer coefficient is calculated from the relationship given below;

\[ h = \frac{Q_u}{A_p (T_{pm} - T_{fm})} \]  \hspace{1cm} (4)

Where heat transfer rate \(Q_u\) to the air is given by
Thermohydraulic Performance of an Equilateral Triangular Duct with Artificial Roughness used in Solar Air Heater

\[ Q_u = mC_p(T_u - T_i) \]  

(5)

The heat transfer coefficient calculated using equation (4) is then used to determine the Nusselt number as given below:

\[ Nu = \frac{hD_h}{k} \]  

(6)

Where \( D_h \) is the hydraulic diameter of the duct.

The friction factor is determined from the measured values of pressure drop \( (\Delta P)_h \) across the test section length using Darcy Wiesbach equation as below,

\[ f = \frac{2(\Delta P)_h D_h}{4\rho LV^2} \]  

(7)

VII. THERMOHYDRAULIC PERFORMANCE

Thermohydraulic performance is the performance of the system that includes the consideration of thermal as well as hydraulic characteristics. It is necessary to take electrical energy required for pumping into account, while evaluating the performance of solar air heater. From second law of thermodynamics considerations, the power from the thermal output of the collector, loosing always considerable part of the energy in conversion and transmission. Therefore, the pumping power required is converted to equipment thermal energy to obtain evaluated the real performance of the collector in terms of the effective efficiency that taken into account the useful thermal gain and equivalent thermal energy that will be required to provide corresponding mechanical energy for overcoming friction power losses, and is given by:

\[ \eta_{ef} = \frac{Q_u - P_p}{CIA_p} \]  

(8)

where \( C = \eta_F\eta_M\eta_{Tr}\eta_{Th} \) is the conversion factor accounting for net conversion efficiency from thermal energy of the resource to mechanical energy. In the conversion factor \( C \)

- \( \eta_F = \) Efficiency of fan or blower.
- \( \eta_M = \) Efficiency of the electrical motor used for driving fan.
- \( \eta_{Tr} = \) Efficiency of electrical transmission.
- \( \eta_{Th} = \) Thermal conversion efficiency of power plant.

The rate of useful thermal energy gain for roughened solar air heater can be calculated by using the following expression:

\[ Q_u = mC_p(T_u - T_i) \]  

(9)

The mechanical power required to propel the air through the solar air heater duct is the product of the rate of heat gain and the pressure drop \( \Delta P_h \).

\[ P_m = VA_p (\Delta P_h) \]  

(10)

The effective efficiency has been evaluated by using equation (8) for fixed value of relative roughness pitch \( (p/e) \) of 8 and angle of attack \( (\alpha) \) of 30°. It can also be seen that roughened plate gives the better enhancement in the heat transfer than that of the smooth plate.

The thermohydraulic performance has been obtained by varying the Range of Reynolds number along with the values of geometrical and operating parameters as shown in Table I.

| Parameters | Values |
|-----------|--------|
| Length    | 1 metre |
| Width     | 160 mm  |
| Reynolds number | 5600-28000 |
| Relative roughness height \((e/D_h)\) | 0.021-0.043 |
| Relative roughness pitch \((p/e)\) | 8 |
| Angle of attack \((\alpha)\) | 30° |
| Intensity | 800 W/m² |

VIII. RESULT AND DISCUSSION

In this section of the paper variation of the Nusselt number and thermohydraulic performance have been presented and discussed.

A. Effect of Reynolds number on Nusselt number

Fig. 4 shows the variation of Nusselt number as a function of relative roughness height \((e/D_h)\) for various values of the Reynolds number and for fixed value of relative roughness pitch \((p/e)\) of 8 and angle of attack \((\alpha)\) of 30°. It can be clearly seen from the fig. 4 that the Nusselt number increases with the increase in Reynolds number.

Replotting fig. 4 get fig. 5. Fig. 5 shows the variation of Nusselt number as a function of Reynolds number for different value of relative roughness height \((e/D_h)\) and for fixed value of relative roughness pitch \((p/e)\) of 8 and angle of attack \((\alpha)\) of 30°. The value of the Nusselt number increase with the value of relative roughness height \((e/D_h)\). The maximum Nusselt number occur at 0.043 and minimum at 0.021 as reported by Bharadwaj and Varun [2]. This is due to the reason that relative roughness height should be sufficient in order to break the laminar sublayer so that maximum heat transfer takes place. It can also be seen that roughened plate gives the better enhancement in the heat transfer than that of the smooth plate.
Thermohydraulic Performance of an Equilateral Triangular Duct with Artificial Roughness used in Solar Air Heater

**IX. CONCLUSION**

It is concluded that the presence of the inclined ribs on the absorber plate of an equilateral triangular solar air heater duct enhance the heat transfer rate. The maximum heat transfer and thermohydraulic performance of the roughened solar air heater duct occur at the relative roughness height \( e/D_h \) of 0.043.

**NOMENCLATURE**

\( A \) - Area of the flow \((m^2)\)
\( A_o \) - Throat area of the orifice \((m^2)\)
\( A_p \) - Area of the absorber plate \((m^2)\)
\( C_d \) - Coefficient of discharge for the orifice meter
\( C_p \) - Specific heat of air \((kJ/kg/K)\)
\( D_h \) - Hydraulic diameter of the duct \((m)\)
\( = 4 \times 0.5 \times W H / (3 W) \)
\( e \) - Height of the roughness element \((m)\)
\( f_r \) - Friction factor for roughened absorber plates
\( f_s \) - Friction factor for the smooth absorber plate
\( H \) - Height of the duct \((m)\)
\( h \) - Average heat transfer coefficient \((W/m^2/K)\)
\( k \) - Thermal conductivity \((W/m/K)\)
\( L \) - Length of the absorber plate \((m)\)
\( n \) - Mass flow rate \((kg/s)\)
\( N_{ur} \) - Nusselt number for the roughened plates
\( N_{us} \) - Nusselt number for the smooth plates
\( P \) - Roughness pitch \((m)\)
\( e/D \) - Relative roughness height
\( P_e \) - Relative roughness pitch
\( Pr \) - Prandtl number
\( \Delta P_o \) - Pressure drop across the orifice meter \((N/m^2)\)
\( \Delta P_d \) - Pressure drop across the test section \((N/m^2)\)
\( Re \) - Reynolds number
\( W \) - Width of the duct \((m)\)
\( D_1 \) - Diameter of orifice \((m)\)
\( D_2 \) - Diameter of pipe \((m)\)
\( T_1 \) - Inlet temperature of air \((^\circ C)\)
\( T_2 \) - Outlet temperature of air \((^\circ C)\)
\( T_{fo} \) - Average temperature of air \((^\circ C)\)
\( T_{pm} \) - Average temperature of the absorbing plate \((^\circ C)\)
\( \rho \) - Density of fluid \((kg/m^3)\)
\( \beta \) - Diameter ratio, \( D_2/D_1 \)
\( \alpha \) - Angle of attack
\( \eta_{ef} \) - Effective efficiency

**B. Effect of Reynolds number on Effective Efficiency**

It has been found that there is a considerable enhancement in the heat transfer by providing the inclined ribs on the absorber plate of the equilateral triangular solar air heater duct. This enhancement in the heat transfer is accompanied by an ample increase in friction factor. It is evident from the fig. 6 that roughened solar air heater duct results in better effective efficiency than the smooth duct. It can also be seen from the figure that effective efficiency increases with the increase in Reynolds number and after a certain value it starts decreasing. This is due to the reason that the quality of collected heat decreases and pump work increases.

**Figure 6. Effect of Reynolds number on Effective Efficiency**
REFERENCES

[1] Z. Sen, “Energy and Climate Change, Solar energy fundamentals and modeling techniques,” Verlag London limited, Springer, Chapter 1, pp. 3-6, 2008. doi: 10.1007/978-1-84800-134-3.

[2] V. S. Hans, R. P. Saini and J. S. Saini, “Performance of artificially roughened solar air heaters – A review,” Renewable and Sustainable Energy Reviews, vol. 13, pp. 1854-1869, Oct 2010. doi:10.1016/j.rser.2009.01.030.

[3] Varun, R. P. Saini and S. K. Singal, “A review on roughness geometry used in solar air heaters,” Solar energy, vol. 81, pp. 1340-1350, Nov 2007. doi:10.1016/j.solener.2007.01.017.

[4] B. Bhushan and R. Singh, “A review on methodology of artificial roughness used in duct of solar air heater,” Energy, vol. 35, pp. 202-212, Jan 2010. doi:10.1016/j.energy.2009.09.010.

[5] G. Bharadwaj and Varun, “Effect of artificial roughness on heat transfer and friction characteristics of equilateral triangular duct,” Proceeding of conference on Thermal, Fluid and Manufacturing science (TFMS 12), Narosa publication, Jan 2012, pp. 178-183.

[6] M. K. Mittal and Varun, “Thermohydraulic performance of the solar air heater provided with artificial roughness on the absorber plate,” Journal of Institution of Engineers (India), vol 90, pp. 43-48, July 2009.

[7] S. K. Verma, B. N. Prasad, “Investigation for the optimal thermohydraulic performance of artificially roughened solar air heaters,” Renewable Energy, vol. 20, pp.19–36, May 2000. DOI: S0960-1481(99)00081-6.

[8] D. Gupta, S. C. Solanki, J. S. Saini, “Thermohydraulic performance of solar air heaters with roughened absorber plates,” Solar Energy, vol.61, pp. 33–42, Jan 1997. DOI: S0038-092X(97)00005-4.

[9] K. Prasad, S. C. Mullick, “Heat transfer characteristics of a solar air heater used for drying purposes,” Applied Energy, vol.13, pp. 83–93, Feb 1983. doi: 10.1016/0306-2619(83)90001-6.

[10] B. N. Prasad, J. S. Saini, “Optimal thermohydraulic performance of artificially roughened solar air heaters,” Solar Energy, vol.47, pp. 91-96,1991. doi: 10.1016/j.solener.1991.0038.092.

[11] B. N. Prasad, J. S. Saini, “Effect of artificial roughness on heat transfer and friction factor in a solar air heater,” Solar Energy, vol. 41, pp. 555-560, 1988. doi:10.1016/j.solener.1988.0038.092

[12] M. M. Sahu, J. L. Bhagoria, “Augmentation of heat transfer coefficient by using 90° broken transverse ribs on absorber plate of solar air heater,” Renewable Energy, vol. 30, pp. 2057-2063, May 2005. doi:10.1016/j.renene.2004.10.016

[13] K. R. Aharwal, B. K. Gandhi and J. S. Saini, “Heat transfer and friction characteristics of solar air heater ducts having integral inclined discrete ribs on absorber plate,” Int. J. of Heat and Mass Transfer, vol. 52, pp. 5970-5977,2009. doi: 10.1016/j.ijheatmasstransfer.2009.05.032.

[14] Varun, R. P. Saini and S. K. Singal, “Investigation of thermal performance of solar air heater having roughness elements as a combination of inclined and transverse ribs on absorber plate,” Renewable energy, vol. 133, pp. 1398-1405, Jun 2008. doi:10.1016/j.renene.2008.07.013.