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Comparative study of effect of various blockage arrangements on thermal hydraulic performance in a roughened air passage

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ABSTRACT

The aim of present article, experimental investigation of heat transfer and fluid flow characteristics in an air passage with different type of blockage arrangements as roughness elements employed over one wall. The different blockage arrangements such as transverse perforated blockage, angled perforated blockage, V-type solid blockage, V-type blockage with gap and V-type perforated blockage have been careful in the present study. During the experimental examination air was passed through the test passage under a uniform wall heat flux of the heated wall plate. The heat transfer and fluid flow behavior are presented for *Re* based on the passage hydraulic diameter ranging from 3000 to 18000. During the experimental study author found that the V-type perforated blockage provides better thermal hydraulic performance as compared with other type blockage air passage.

1. Introduction

Energy that is available in several forms played significant role in globally in the sustenance of human existence. Environmental pollution and human health-threatening diseases are composed of the use of fossil-based energy sources [1,2]. In parallel with the increase in human population, energy necessities have increased. Therefore, researches have concentrated on renewable energy sources. Among various renewable energy sources solar energy has a low cost and pollution free [3,4]. The device which is used to collect energy from the sun is called solar collector. Solar collector is the type of heat exchanger that transmits energy from other medium to air. In order to improve the thermal performance of a solar air heater various designs with distinct shapes and dimensions of air stream passage in smooth type solar air collectors have been developed [5,6]. Improving the thermal performance of air passage by using blockages of distinct arrangements as absorber plate in solar air channel was studied by various investigators [7]. The thermal performance of air passage has been found to be poor because of the low convective heat transfer rate from the heated plate to the air. The heat transfer between the heated surface of air passage and flowing fluid can be improved by either increasing the heat transferring surface area using extended and corrugated surfaces without enhancing heat transfer coefficient or by increasing heat transfer coefficient using the turbulence promoters in the form of artificial roughness on heated plate [8,9]. The roughness, on the heated plate can be provided by several methods such as sand blasting, machining, casting, forming, welding ribs and or fixing thin circular wires. The use of blockage roughness in different forms and shapes is the most effective and economic way of improving the performance of an air passage. A lot of experimental investigations involving roughness elements of different shapes, sizes and orientations with respect to flow direction have been carried out in order to obtain an optimum arrangement of roughness element geometry [10,11].

2. Concept of blockages roughness to enhancement of heat transfer

Performance of the air passage is found to be low as development of the viscous sublayer adjacent to the surface of the heated plate. Blockage roughness on heated plate diminishes this viscous layer and creates the randomness in the fluid adjacent to the surface of the plate. Joule introduced the concept of roughness and found the considerable enhancement in the heat transfer rate for in tube contraction of water vapour and after that, various mathematical and experimental researches were conducted on the techniques of blockage roughened shapes in the fields of electronic equipment, reactor for nuclear energy, cooling of gas turbine and compact heat exchanger etc [12,13].

Surface roughness on a heated surface is a very popular and effective technique to augment forced convection heat transfer. To achieve a higher Nu_{rs}, the fluid flow over the heat transferring surface

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Nomenclature

A_p	Heated plate surface area (m^2)
A_o	Orifice area (m^2)
C_{do}	Coefficient of discharge
C_p	Specific heat of air (J/kgK)
d	Baffle distance (m)
d/W	Relative baffle distance
d_h	Hole diameter of perforated blockage (m)
D_{hd}	Hydraulic diameter of air passage (m)
G_D	Gap or discrete distance m
f	Friction factor
f_{rs}	Friction factor with blockage
f_{ss}	Friction factor without blockage
g_w	Gap or discrete width (m)
h_t	Convective heat transfer coefficient (W/m^2K)
H_D	Height of air passage (m)
H_B	Height of blockage (m)
H_B/H_D	Relative blockage height
G_D/L_v	Relative discrete distance
g_w/H_B	Relative gap width
K_a	Thermal Conductivity of air (W/mK)
L	Length of flow channel (m)
L_t	Length of test section (m)
L_v	Length of blockage (m)
m_a	Mass flow rate of air (kg/s)
Nu	Nusselt number
Nu_{rs}	Nusselt number of rough surface
Nu_{ss}	Nusselt number of surface without blockage
O_B	Hole position from base of blockage (m)
O_B/H_B	Relative hole position
P	Pitch of baffle (m)
P_B	Pitch of blockage (m)
P/D	Relative pitch ratio
P_B/H_B	Relative blockage pitch ratio
P_l/e	Longitudinal pitch the baffle (m)
P_t/e	Relative baffle transverse pitch(m)
$(\Delta_p)_d$	Pressure drop across test section (Pa)
$(\Delta_p)_o$	Pressure drop across orifice plate (Pa)
Q_u	Useful energy gain (W)
Re	Reynolds number of fluid
T_f	Average temperature of air (K)
T_i	Inlet temperature of air (K)
T_o	Outlet temperature of air (K)
T_p	Plate temperature of air (K)
U	Mean air velocity (m/s)
V	Velocity of air (m/s)
W	Width of baffle (m)
W_D/H_D	Air passage aspect ratio
W_D	Width of air passage (m)
SAC	Solar air channel

Greek symbols

α_a	Angle of attack (°)
β_O	Open area ratio (%)
β_R	Ratio of orifice meter to pipe diameter, dimensionless
ρ_a	Air density (kg/m^3)
ν_a	Kinematic viscosity of air (m^2/s)
η_p	Thermal hydraulic performance

should be made turbulent. but the energy to create the turbulent flow is drawn from the blower/fan [14]. The high turbulence consumes excessive power for flowing the air through the duct. Thus the turbulence must be created in the vicinity of the heat transferring surface i.e. only in the laminar sub-layer where heat exchange occurs and the fluid flow should not be disturbed to avoid excessive friction losses [15]. Although tabulators with a larger height can produce a higher heat transfer, the pressure drop is also higher. Due to flow recirculation a hot zone behind these elements is developed, that weakens the heat transfer from these zones. Therefore, researchers provide perforations in the block/baffles to eliminate this problem. These perforations apart from enhancing the heat transfer reduce the pressure drop across the channel. An enhanced turbulence is produced as fraction of the flow passes through the perforations and mixes with the main flow. Several parameters that characterize the arrangement and shape of the roughness, the roughness element height (H_B) and pitch (P_B) are the most important. Attempts to increase the heat transfer rate using different roughness heights have been reported for over a century. Nikuradse [16] studies the effect of pipes roughened by sand blasting on f_{rs} and velocity distributions. A relative roughness height were in the range of 0.001–0.033 with different Re values were selected.

Nunner [17] develops a relationship between the heat transfer and the f_{rs} by investigating the roughness for heat transfer in tubes. The following relationship relates Nu_{rs}, Re, and f_{rs}:

$$Nu_{rs} = \frac{(f_{rs}/2)Re.Pr)}{1 + 1.5Re^{-0.125}\left[\Pr\left(\frac{f_{rs}}{f_{ss}}\right) - 1\right]} \tag{1}$$

For air, the data could be correlated as

$$\frac{Nu_{rs}}{Nu_{ss}} = \left(\frac{f_{rs}}{f_{ss}}\right)^{0.5} \tag{2}$$

$$Nu = 0.384Re^{0.67}f^{0.5} \tag{3}$$

Wilkie [18] experimentally investigated the heat transfer using the transverse ribs for an annular flow. In this work, the friction factor was independent of Re and the roughness height at a high Re. It was observed that increasing the rib roughness width at a constant rib pitch and roughness height increased the f_{rs}.

Webb [19] developed general statistical . A correlations for the St_{rs} and f_{rs} for a duct with repeated rib roughness considering the P/e as a geometrically roughness parameter. The correlation is given as

$$\sqrt{\frac{f}{2}} = 2.5\ln\ [D/2e] - 3.75 + 0.95[P/e]^{0.53} \tag{4}$$

The correlation for the Stanton number is given as

$$St = \frac{f/2}{1+\sqrt{f/2}[4.5(e^{+})^{0.28}Pr^{0.57} - 0.95(P/e)^{0.53}]} \tag{5}$$

Han et al. [20] developed a correlation for St_{rs} and f_{rs} for a flow inside a rectangular channel with various rib in form of angular geometries. The parameter considered were rib spacing, rib shape, and angle of attack. The $St_{rs}$and f_{rs} increases with increase in the pitch of roughness and the maximum value was found for relative roughness pitch value of 10.0.

Firth and Meyer [21] experimentally examined square transverse, helically and trapezoidal transverse and three dimensional surface roughness ribbed wall for evaluating the St_{rs} and f_{rs}.

Khanna and Kant [22] examined the effect of rib roughened pipe on St_{rs} and f_{rs} in a turbulent flow regime. An enhancements in the St_{rs} and f_{rs} of 1.63 and 1.98 times, respectively, as compared to a smooth pipe flow was reported. A truncated cone roughness was investigated by Hosni et al. [23] to determine the effect on the local Stanton number and skin coefficient friction in smooth, transitionally rough, and fully rough flow regimes.

Wu and Cooper [24] studied the St_{rs} and f_{rs} of hemispherical