EXPERIMENTAL STUDY ON HEAT TRANSFER AND FLUID-FLOW ENHANCEMENT OF A SPHERICAL SHAPE OBSTACLE SOLAR AIR PASSAGE

by

Ashok Kumar BHARDWAJ^a, Anil KUMAR^{a*}, Rajesh MAITHANI^b, Raj KUMAR^a, Sunil KUMAR^a, and Ranchan CHAUHAN^a

^a School of Mechanical and Civil Engineering, Shoolini University, Solan, India ^b Department of Mechanical Engineering, DIT University, Deharadun, India

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This paper presents the outcome of experimental examined of Nusselt number and friction factors in a spherical obstacles solar air passage. Investigation has been performed to examine the thermal and hydraulic data from a solar air passage with spherical obstacles on the heated wall. The Reynolds number base on the hydraulic diameter of the solar air passage varied from 45.00 to 16.500, relative sphere diameter varied from 0.130 to 0.217, stream wise spacing of 4.04 and span wise spacing of 4.04. Experimental results pertinent to heat transfer and pressure drop was determined for various sets of roughness and flow parameters. The experimental results show that the heat transfer is increased around 4.7 times than plane surface solar air passage. The thermal and hydrodynamic performance parameter based on equal pumping power was found to be highest for spherical shape dia of 0.195. The superior value of overall thermal performance parameter is 2.83 corresponding to spherical shape dia of 0.195.

Key words: thermal behaviour, flow passage, stream wise spacing, sphere diameter

Introduction

Renewable energy can minimize our dependency on fossil fuels, thereby, renewable energy is getting importance in the recent years because energy can renew and will never run out. Renewable energy is eco-friendly and results in little to no effect to the environment [1]. Out of many renewable energies, solar energy is considerable to be clean source of energy and available on every part of the world [2]. Solar energy is exploited in many application, included heating purposes and generation of electricity [3]. Solar air passage (SAP) is one of the most economical and elementary device which employ to supply the heated air to drying the crops, industrial purposes, heating the building and space [4]. The techniques of local heat transfer improvement attract the interests of researchers [5]. Obstacles are often used to improve local heat transfer among the wall and fluid because they cause stream separation and reattachment, consequently resulting in destroying the laminar viscous layer [6-12]. Bhushan and Singh [8] experimentally investigated the performance of a staggered dimple type roughness SAP. The outcome indicates that the greatest improvement of and factor was 3.12 and 4.16 times, respectively, in comparison to smooth passage. Chang et al. [9] examine the comparative full-field distribution on two opposing improved passage walls, including and the thermal performance factor of the two radially rotating obstacles passage with and without dimpled obstacles.

^{*} Corresponding author, e-mail: anilkumar88242@gmail.com

Shen *et al.* [10] examine the effect of rotation on fluid stream and heat transfer performance of turbine blade with U-shaped passage with the combined structure of obstacles, dimples or protrusions. The outcome shows that rib-protrusion structure found to be the most efficient structure while rib-dimple structure has only minor advantage than ribbed passage. Kumar and Kim [11] investigated the thermal hydraulic performance of a 3-D obstacles-roughened SAP having W_p/H_p of 12.0. They found that thermal hydraulic performance for V-pattern shaped obstacles combined with dimpled obstacles is superior as compared with dimpled obstacles shape and V-pattern obstacles shape SAP. Lian *et al.* [12] investigated Nu_{rs} and f_{rs} behaviours of air stream through a passage with hemispherical protrusion/dimple on the heated plate. The outcome shows that the hemispherical dimple roughened air passage is the better choice as compared with smooth passage.

Negi and Pattamatta [13] deal with shape determination of dimples on the target plane in multi-jet impingement, Nu_{rs}. They revealed that the standard deviation in Nu_{rs} was considerably higher than the reference spherical dimpled profile and the optimized dimple profile shows highest local Nu_{rs} values calculated to the reference semi-circular dimpled plate optimized form which can be used to get better local temperature hot spots on target surface. Jin *et al.* [14] presented a numerical study of Nu_{rs} and f_{rs} characteristics in a SAP channel having multi V-shaped ribs on the absorber plate. It was found that for the range of investigated factors the highest value of the η_P parameter was achieved to be 1.93. Ekadewi *et al.* [15] numerically investigated the influence of delta-shaped obstacles spacing on Nu_{rs} and pressure drop in V-corrugated canal of SAP. Authors obtained that Nu_{rs} was improved by 3.46 times and f_{rs} was increased up to 19.9 times.

The literature survey shows that obstacles of dimple, hemispherical, V-type, protrusion and multiple type shapes have been investigated previously which is common shape. In order to increase heat transfer further spherical obstacles have been investigated in this work

Table 1. Ranges of sphericalobstacles parameters

Parameter	Range
D_{S}/D_{H}	0.130-0.217
H_{S}/D_{S}	4.04
Y_{S}/D_{S}	4.04
Reynolds number	4.500-16.500



Figure 1. Discussed spherical shapes parameters

with aim of different sphere diameter would contribute the turbulence in the flow resulting high heat transfer rate from heated plate. In this regards, experimental study has been conducted to investigate the effect of relative sphere diameter of obstacles attached to heated plate on thermal behaviour.

Range of parameter

The geometrical parameters for the SAP with spherical obstacles are hydraulic diameter of passage, D_{H} , of 46.15, height of passage, H_P , of 25 mm, width of passage, W_P , of 300 mm, and length of passage, L_p , of 2395 mm. The dimnesionless parameters are relative sphere diameter, D_S/D_H , stream wise spacing, X_S/D_S , and span wise spacing, Y_S/D_S . In this experimental investigation the SAP has $L_t = 1100$ mm, H_P is adjusted on 50 mm, and different diameter of sphere, D_S . The ranges of different parameters are depicted in tab. 1. The shematic and photographic view of spherical shape obstacles are presented in figs. 1 and 2.

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Figure 2. Photographic view of spherical roughened shape absorber plate

Experimental program and procedure

Experimental approach has been adopted to produce the data in form of Nu_{rs} and f_{rs} for air passage with spherical shape obstacle roughness to search the effect of D_s/D_H and Reynolds number on Nu_{rs}, and f_{rs} . The experimental study encompasses the fabrication and installation of indoor test facility. The experimental set-up has been validated by comparing experimental data collected on without spherical obstacle wall with the available standard data. After validation of experimental set-up, extensive experimentations have been conducted on spherical shape obstacle to produce raw data on heated wall temperatures, air stream rates, and entrance and exit temperature of air and pressure drop across the passage under stable conditions. To examine the influence of spherical shape obstacle turbulent promoter on Nu_{rs} and f_{rs} of air stream, an experimental set-up was designed and made-up according to ASHRAE standard [16]. A schematic diagram of an experimental set-up is shown in fig. 3. The experimental set-up comprised a rectangular wooden channel coupled to a centrifugal blower through a circular galvanized iron (GI) pipe. The rectangular channel had W_P of 300 mm, H_P of 30 mm, and W_{P}/H_{P} of 10. The examination was carried out to achieve the experimental values for Nu_{rs} and f_{rs} in an air stream passage provided with spherical shape obstacle to enhance Nu_{rs} and f_{rs} descriptions with respect to individual obstacle deviations.

The manufacturing and the appropriate setting of the experimental test set-up were performed, which were validated with existing criterion data on the air passage with smooth surface passage. The optimal validation was achieved to perform advanced examinations with

spherical shape obstacle. The testing for air temperature at the entry of the passage and the exit, pressure drop of air from corner to corner of the passage, and the heated wall temperature have been approximated, which is necessary to meet the aims of the investigation. In order to examine the influence of spherical shape obstacle, flat solar air rectangular passage functioning under same



Figure 3. Schematic of experimental set-up

flow situations was also investigated. Before performing each investigational run, large care was taken to ensure appropriate functioning of all apparatus and that there was no seepage at the joints in the testing set-up. The equivalent instruments provided the data beneath stable condition which was supposed to have been attained when there was no appreciable difference in passage air and collector plate temperature was noticed over a time period of larger than 12 minutes. The following amount of data was reported for each:

- pressure head variation across the orifice plate in order to determine the air-flow rate,
- heated plate temperatures at variant plate positions,
- temperatures of inlet air,
- temperatures of passage air, and
- pressure head drop across the test segment.

Data reduction

The data composed have been used to determine Nusselt number and pressure drop. Relevant expressions for the computation of the previous parameters and some intermediate parameters have been given.

The mean temperature of the plate is the average of all temperatures of the heated plate:

$$T_p = \frac{\sum T_{pi}}{N} \tag{1}$$

The mean air temperature is a simple arithmetic mean of the inlet and outlet temperature of air flowing through the test section:

$$T_f = \frac{T_i + T_o}{2} \tag{2}$$

where $T_{o} = (T_{o1} + T_{o2} + T_{o3})/3$, $T_i = T_{A1}$.

Mass-flow rate of air, m_a , has been calculated from the pressure drop measurement across the calibrated orifice meter by using the following formula:

$$\dot{m}_a = C_{do} A_o \left[\frac{2\rho_a \left(\Delta p\right)_0}{1 - \beta_R^4} \right]^{0.5}$$
(3)

where $(\Delta p)_0 = 9.81(\Delta p)_0 \rho_a \dot{m}_a \sin\theta$.

The velocity of air, V, is calculated from the mass-flow rate and given by:

$$V = \frac{m_a}{\rho_a W_P H_P} \tag{4}$$

The hydraulic diameter, D_H , is given by:

$$D_{H} = \frac{4(W_{P}H_{P})}{2(W_{P}+H_{P})}$$
(5)

The Reynolds number of the air-flow in the rectangular channel is determined:

$$\operatorname{Re} = \frac{VD_{H}}{v_{a}} \tag{6}$$

The friction factor, f, is calculated from the measured value of $(\Delta p)_d$ across the test section length using the Darcy equation:

$$f = \frac{2\left(\Delta_p\right)_d D_H}{4\rho_a L_t V^2} \tag{7}$$

where $(\Delta p)_d = 9.81 \ (\Delta h)_d D_H \rho_a \dot{m}_a$.

The useful heat gained by air is calculated:

$$Q_{u} = \dot{m}_{a}c_{p}\left(T_{o} - T_{i}\right) \tag{8}$$

The heat transfer coefficient for the heated test section has been calculated from:

$$h_t = \frac{Q_u}{A_p \left(T_p - T_f\right)} \tag{9}$$

The h_t can be used to determine the Nusselt number, which is given by:

$$Nu = \frac{h_t D_H}{K_a}$$
(10)

Uncertainties analysis

Uncertainty is the possible numerical value of the error encountered during experimentation. To evaluate uncertainty involve in this experiment method suggested by Kline and McClintock [17] is used. If the data of any parameter is calculated using certain measured quantities then error in measurement of y (parameter) is given:

$$\frac{\delta y}{y} = \left[\left(\frac{\delta y}{\delta x_1} \delta x_1 \right)^2 + \left(\frac{\delta y}{\delta x_2} \delta x_2 \right)^2 + \left(\frac{\delta y}{\delta x_3} \delta x_3 \right)^2 + \dots + \left(\frac{\delta y}{\delta x_n} \delta x_n \right)^2 \right]^{0.3}$$
(11)

where δx_1 , δx_2 , δx_3 , ..., δx_n are the possible error in measurement of x_1 , x_2 , x_3 ,..., x_n , δy is the absolute uncertainty and $\delta y/y$ is known as relative uncertainty.

The important parameters considered for the calculation of uncertainty are: Reynolds number, heat transfer coefficient, Nusselt number, friction factor, *etc.* – uncertainty in area of absorber plate:

$$A_{p} = W_{p}L_{t}$$

$$\frac{\delta A_{p}}{A_{p}} = \left[\left(\frac{\delta L_{t}}{L_{t}} \right)^{2} + \left(\frac{\delta W_{p}}{W_{p}} \right)^{2} \right]^{0.5}$$
(12)

- uncertainty in area of flow:

$$A_{p} = W_{P}H_{P}$$

$$\frac{\delta A_{p}}{A_{p}} = \left[\left(\frac{\delta H_{P}}{H_{P}} \right)^{2} + \left(\frac{\delta W_{P}}{W_{P}} \right)^{2} \right]^{0.5}$$
(13)

- uncertainty in mass-flow rate measurement:

$$\dot{m}_{a} = C_{do} A_{o} \left[\frac{2\rho_{a} \left(\Delta p\right)_{0}}{1 - \beta_{R}^{4}} \right]^{0.5}$$

$$\frac{\delta \dot{m}_{a}}{\dot{m}_{a}} = \left[\left(\frac{\delta C_{do}}{C_{do}} \right)^{2} + \left(\frac{\delta A_{o}}{A_{o}} \right)^{2} + \left(\frac{\delta \rho_{a}}{\rho_{a}} \right)^{2} + \left(\frac{\delta \left(\Delta p\right)_{0}}{\left(\Delta p\right)_{0}} \right)^{2} \right]^{0.5}$$
(14)

- uncertainty in measurement of air velocity in channel:

$$V = \frac{\dot{m}_a}{\rho_a W_P H_P}$$

$$\frac{\delta V}{V} = \left[\left(\frac{\delta \dot{m}_a}{\dot{m}_a} \right)^2 + \left(\frac{\delta \rho_a}{\rho_a} \right)^2 + \left(\frac{\delta W_P}{W_P} \right)^2 + \left(\frac{\delta H_P}{H_P} \right)^2 \right]^{0.5}$$
(15)

- uncertainty in useful heat gain:

$$Q_{u} = \dot{m}_{a}c_{p}\left(T_{o} - T_{i}\right) = \dot{m}_{a}c_{p}\Delta T$$

$$\frac{\delta Q_{u}}{Q_{u}} = \left[\left(\frac{\delta \dot{m}_{a}}{\dot{m}_{a}}\right)^{2} + \left(\frac{\delta c_{p}}{c_{p}}\right)^{2} + \left(\frac{\delta \Delta T}{\Delta T}\right)^{2}\right]^{0.5}$$
(16)

- uncertainty in heat transfer coefficient:

$$h_{t} = \frac{Q_{u}}{A_{p} \left(T_{p} - T_{f}\right)} = \frac{Q_{u}}{A_{p} \Delta T_{f}}$$

$$\frac{\delta h_{t}}{h_{t}} = \left[\left(\frac{\delta Q_{u}}{Q_{u}}\right)^{2} + \left(\frac{\delta A_{p}}{A_{p}}\right)^{2} + \left(\frac{\delta \Delta T_{f}}{\Delta T_{f}}\right)^{2} \right]^{0.5}$$
(17)

- uncertainty in Nusselt number:

$$\operatorname{Nu}_{rs} = \frac{h_t D_H}{K_a}$$
$$\frac{\delta \operatorname{Nu}_{rs}}{\operatorname{Nu}_{rs}} = \left[\left(\frac{\delta D_H}{D_H} \right)^2 + \left(\frac{\delta h_t}{h_t} \right)^2 + \left(\frac{\delta K_a}{K_a} \right)^2 \right]^{0.5}$$
(18)

- uncertainty in Reynolds number:

$$\operatorname{Re} = \frac{VD_{H}}{v_{a}} = \frac{\rho_{a}VD_{H}}{\mu}$$
$$\frac{\delta\operatorname{Re}}{\operatorname{Re}} = \left[\left(\frac{\delta D_{H}}{D_{H}}\right)^{2} + \left(\frac{\delta V}{V}\right)^{2} + \left(\frac{\delta\rho_{a}}{\rho_{a}}\right)^{2} + \left(\frac{\delta\mu}{\mu}\right)^{2} \right]^{0.5}$$
(19)

- uncertainty in friction factor:

$$f_{rs} = \frac{2(\Delta_p)_d D_H}{4\rho_a L_t V^2}$$
$$\frac{\delta f_{rs}}{f_{rs}} = \left[\left(\frac{\delta D_H}{D_H}\right)^2 + \left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta L_t}{L_t}\right)^2 + \left(\frac{\delta \rho_a}{\rho_a}\right)^2 + \left(\frac{\delta(\Delta_p)_d}{(\Delta_p)_d}\right)^2 \right]^{0.5}$$
(20)

- uncertainty in thermohydraulic performance parameter:

$$\eta_{p} = \left(\operatorname{Nu}_{rs} / \operatorname{Nu}_{ss}\right) / \left(f_{rs} / f_{ss}\right)^{0.33}$$
$$\frac{\delta\eta_{p}}{\eta_{p}} = \left[\left(\frac{\delta\operatorname{Nu}_{rs}}{\operatorname{Nu}_{rs}}\right)^{2} + \left(\frac{\delta f_{rs}}{f_{rs}}\right)^{2}\right]^{0.5}$$
(21)

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As the uncertainty calculation was done on a single test run (constant Reynolds number), the uncertainty analysis for complete test run for single geometry (complete set of Reynolds number) was carried out and results are presented in tab. 2 for the experimental data.

Results and discussion

The Nu_{rs} and f_{rs} descriptions of an impingement jet SAP roughened with multiple arcs protrusion ribs, calculated on the sources of investigational data collected for different stream and roughness factors, are discussed.

Validation of experimental set-up

The value of Nu_{ss} and f_{ss} calculated through experimental outcomes for a smooth channel have been compared with the outcomes obtained from the Dittus-Boelter equation, eq. (22), for the Nu_{ss} , and modified Blasius equation, eq. (23), for the Kumar and Kim [1]. The Nu_{ss} for a smooth passage is given by the Dittus-Boelter equation:

$$Nu_{ac} = 0.023 Re^{0.8} Pr^{0.4}$$
(22)

The f_{ss} for a smooth passage is given by the modified Blasius equation:

$$f_{cc} = 0.085 \mathrm{Re}^{-0.25} \tag{23}$$

The comparison of the experimental and estimated outcomes of Nu_{ss} and f_{ss} as a function of the Reynolds number is shown in figs. 4(a) and 4(b), respectively. The average absolute percentage deviation of the experimental Nu_{ss} is 5.78% from the value predicted by eq. (22), and the average absolute percentage deviation of the present experimental f_{ss} is 4.98% from the value predicted by eq. (23). Thus there is a good agreement between the predicted values and the experimental values of the Nu_{ss} and f_{ss} . This ensures the accuracy of the experimental data obtained from the present set-up within reasonable limits.



Heat and fluid-flow

The experimental analysis has been perforated for a blockage SAP with spherical obstacles on an absorber plate, and the results are discussed in this section. The results of D_s/D_H

Table 2.	Range of	of uncerta	inty in the
measure	ment of	essential	parameters

Parameters	Error range [%]	
Heat transfer coefficient	3.98-6.12	
Nusselt number	3.89-6.55	
Friction factor	2.24-4.15	
Thermohydraulic performance parameter	3.45-6.89	

on Nu_{rs} , Nu_{rs}/Nu_{ss} , f_{rs} , and f_{rs}/f_{ss} for air-flow are represented in a SAP. The outcomes have been compared with those obtained in case of without obstacles surface working under similar experimental conditions.

The outcomes of Nu_{rs} have been represents as a function of Reynolds number for the various values of D_s/D_H in fig. 5(a), and for constant values of the other blockage parameters such as $X_s/D_s = 4.04$ and $Y_s/D_s = 4.04$. It has been seen that the Nu_{rs} increase with increase in the D_s/D_H and attains a highest value matching to a D_s/D_H value of 0.195 in the range of the parameters studied. In all cases, the presence of a surface with spherical blockage produces maximum Nu_{rs} compares to the without spehrical blokage passage. The spherical blockage can lead to superior Nu_{rs} performance because of the scondary flow vortices induced by the upper part of spherical blockage. These secondary flow vortices have the form of more than one counter rotating vortices, which carry cold air from the middle core region towards the spherical blockage surfaces. These secondary flow vortices interact with the primary stream, thus affecting the flow reattachment and recirculation between spherical blockage and interrupt the boundary-layer enlargement down ward of the re-attachment regions.

Figure 5(b) presents the values of Nu_{rs} as function of D_S/D_H for the selected Reynolds number values where a superior in the values corresponding to a $D_S/D_H = 0.195$ for all Reynolds number. The outcomes of Nu_{rs}/Nu_{ss} have been represents as a function of Reynolds number for the various values of D_S/D_H in fig. 6(a), and for constant values of the other blockage parameters such as $X_S/D_S = 4.04$ and $Y_S/D_S = 4.04$. It has been seen that the Nu_{rs}/Nu_{ss} increase with increase in the D_S/D_H and attains a highest value matching to a D_S/D_H value of 0.195 in the range of the parameters studied. Figure 6(b) presents the values of Nu_{rs}/Nu_{ss} as function of D_S/D_H for the selected Reynolds number values where a superior in the values corresponding to a $D_S/D_H = 0.195$ for all Reynolds number.



Figure 5. (a) Variation of Nu_{rs} with Reynolds number at different D_S/D_{H} , (b) variation of Nu_{rs} with D_S/D_{H} at selected Reynolds number

The outcomes of f_{rs} have been represents as a function of Reynolds number for the various values of D_s/D_H , in fig. 7(a), and for constant values of the other blockage parameters such as $X_s/D_s = 4.04$ and $Y_s/D_s = 4.04$. It has been seen that the f_{rs} increase with increase in the D_s/D_H and attains a highest value matching to a D_s/D_H value of 0.217 in the range of the parameters studied. In all cases, the presence of a surface with spehrical blockage produces maximum f_{rs} compares to the without spehrical blokage passage. Figure 7(b) presents the values of f_{rs} as function of D_s/D_H for the selected Reynolds number values where a superior in the values corresponding to a $D_s/D_H = 0.217$ for all Reynolds number. The outcomes of of f_{rs}/f_{ss} have been represents as a



Figure 6. (a) Variation of Nu_{rs}/Nu_{ss} with Reynolds number at different D_{s}/D_{H} , (b) variation of Nu_{rs}/Nu_{ss} with D_{s}/D_{H} at selected Reynolds number



Figure 7. (a) Variation of f_{rs} with Reynolds number at different D_S/D_H , (b) variation of f_{rs} with D_S/D_H at selected Reynolds number



Figure 8. (a) Variation of f_{rs}/f_{ss} with Reynolds number at different D_s/D_H , (b) variation of f_{rs}/f_{ss} with D_s/D_H at selected Reynolds number

function of Reynolds number for the various values of D_S/D_H of in fig. 8(a), and for constant values of the other blockage parameters such as $X_S/D_S = 4.04$ and $Y_S/D_S = 4.04$. It has been seen that the f_{rs}/f_{ss} increase D_S/D_H with increase in the D_S/D_H and attains a highest value matching to a D_S/D_H value of 0.217 in the range of the parameters studied. Figure 8(b) presents the values of f_{rs}/f_{ss} as function of D_S/D_H for the selected Reynolds number values where a superior in the values corresponding to a $D_S/D_H = 0.217$ for all Reynolds number.

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Thermal hydraulic performance

The SAP with spherical blockage results in highest Nu_{rs}/Nu_{ss} as well as f_{rs}/f_{ss} compared to without spherical blockage SAP. So a overall thermal performance needs to the calculated





that takes into account both Nurs/Nuss as well as f_{rs}/f_{ss} to evaluate to usefulness. A overall thermal performance parameter based on equal pumping power explained by Webb and Eckert [18] considered both the Nu_{rs}/Nu_{ss} and f_{rs}/f_{ss} enhancement. The outcomes of η_p have been represents as a function of Reynolds number for the various values of D_S/D_H in fig. 9, and for constant values of the other blockage parameters such as $X_S/D_S = 4.04$ and $Y_S/D_S = 4.04$. It has been seen that the η_p increase with increase in the D_S/D_H and attains a highest value matching to a D_S/D_H value of 0.195 in the range of the parameters studied.

Conclusions

A SAP roughened with sphere blockage was experimentally analysis for variation in sphere of diameter. The following conclusions are drawn.

- Attached a sphere type blockage in the inner side of heated plate results in considerable enhancement inn heat transfer of fluid-flow SAP, the enhancement is a strong function of diameter of spherical blockage.
- An increase in heat transfer while decreases in pressure drop with increase in Reynolds number values is observed.
- The highest values of Nu_{rs} and Nu_{rs}/Nu_{ss} are observed for a spherical dimaeter blockage SAP with a $D_s/D_H = 0.195$.
- The maximum values of f_{rs} and f_{rs}/f_{ss} are observed for a spherical diameter blockage SAP with a $D_S/D_H = 0.217$.
- The superior value of overall thermal performance parameter is 2.83 corresponding to D_{S}/D_{H} of 0.195.

Nomenclature

- heated plate surface area, [m²] A_p
- A_o - orifice area, [m²]
- C_{do} - coefficient of discharge
- specific heat of air, [Jkg⁻¹K⁻¹] C_{p}
- \dot{D}_H - hydraulic diameter of channel, [m]
- D_{S} - diameter of sphere, [m]
- D_S/D_H relative sphere diameter
- friction factor of roughened obstacle f_{rs}
- f_{ss} - friction factor without obstacle h_t - convective heat transfer coefficient, $[Wm^{-2}K^{-1}]$
- H_p - height of passage, [m]
- thermal conductivity of air, [Wm⁻¹K⁻¹] K_a
- L_t - length of test section, [m]
- length of passage, [m]

- mass-flow rate of air, [kgs⁻¹] 'n,
- Nu_{rs} - Nusselt number of obstacle surface
- Nu_{ss} Nusselt number of surface without obstacle
- $(\Delta p)_d$ pressure drop across test section, [Pa]
- $(\Delta p)_0$ pressure drop across orifice plate, [Pa]
- useful energy gain, [W] Q_u
- 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 V- plate temperature of air, [K]
- velocity of air, [ms⁻¹]
- W_P/H_P passage aspect ratio
- W_P - width of passage, [m]
- X_S - stream wise spacing, [m]

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 X_S/D_S – relative stream wise spacing

 Y_s – span wise spacing, [m]

 Y_S/D_S – relative span wise spacing

Greek symbols

 β_o – open area ratio, [%]

β_R – ratio of orifice meter to pipe diameter, dimensionless ρ_a – air density, [kgm⁻¹]

- v_a kinematic viscosity of air, $[m^2s^{-1}]$
- η_p thermal hydraulic performance

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