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CFD BASED PERFORMANCE INVESTIGATION OF SOLAR AIR HEATER HAVING ROUGHNESS ELEMENTS AS A COMBINATION OF TRANSVERSE AND V-UP RIBS ON THE ABSORBER PLATE

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ABSTRACT

A CFD (Computational Fluid Dynamics) based investigation has been carried out to study the heat transfer and friction characteristics by using a combination of transverse as well as V-up ribs on the absorber plate of solar air heater duct for a range of system and operating parameters. It has been observed that roughened absorber plate results augmented heat transfer coefficient at the cost of frictional penalty. In order to predict performance of the system, Nusselt number and friction factor correlations have been developed by using the data generated under CFD based investigation.

Keywords: Artificial roughness, CFD, friction factor, Nusselt number and Solar air heater.

I. INTRODUCTION

Energy is a crucial input in the process of economic, social and industrial development of any nation. During past several decades, energy demand of the world has been increasing continuously at an alarming rate due to increase in population, industrialization, transportation etc. Continuous use of fossil fuels have resulted energy crisis and environment degradation at global level. On the many alternatives, solar energy is an important renewable energy resource that has the potential of fulfilling all energy needs. Some important applications of solar energy are solar water heating, solar space heating/cooling, solar cooking, solar crop drying, solar power generation etc. Simplest method to utilize solar radiation is to convert it into thermal energy for heating applications by using solar collectors. Solar air heaters because of their inherent simplicity are cheap and are used for many domestic and commercial applications like space heating, crop drying, wood seasoning etc. Thermal energy of hot air flowing from solar air heater can be stored to use the same in absence of solar radiation for various applications as has been reported by Singh et al. [1]. Thermal efficiency of solar air heaters is generally considered poor because of low heat transfer capability between absorber plate and air flowing in the duct. In order to make solar air heaters economically viable, their thermal efficiency needs to be improved by enhancing the heat transfer coefficient. In order to attain higher heat transfer coefficient, it is desirable that laminar sub-layer formed during flow of air on surface of absorber plate should be broken and flow at the heat transferring surface is made turbulent. This can be achieved by providing artificial roughness on the surface of absorber plate. Artificial roughness can be produced by several methods such as by wire fixation in the form of transverse continuous ribs, transverse broken ribs, inclined and V-shaped or staggered ribs, rib formation by machining process in the form of chamfered ribs, wedge shaped ribs, combination of different integral rib roughness elements and by using expanded wire mesh. Many experimental investigations have been carried out involving roughness elements of different shapes, sizes and orientations with respect to flow direction. Hans et al. [2], Bhushan and Singh [3], Kumar et al. [4] and Lanjewar et al. [5] carried out a review of different geometries used for creating artificial roughness on absorber plate of solar air heater. Several investigations have been carried out to study the effect of artificial roughness on heat transfer and fluid flow characteristics used in compact heat exchangers by Webb et al. [6], Hwang et al. [7], Xie et al. [8], Liu et al. [9]. Prasad and Mullick [10] reported the effect of thin wires in transverse direction to increase the heat transfer co-efficient. Authors compared the Nusselt number, friction factor and plate efficiency factor of roughened corrugated and plane absorber plates with that of plane corrugated and smooth absorber plates. Prasad and Saini [11] reported the effect of small diameters protrusions wires fixed on absorber plate of solar air heater. An enhancement in Nusselt number (Nu) and friction factor (f) was observed over smooth duct of the order of 2.38 and 4.25 times respectively. Muluwork et al. [12] compared thermal performance of transverse discrete ribs with discrete V-up and V-down ribs as roughness geometry. Heat transfer coefficient and friction factor attained maximum values for an angle of attack (α) 60^o and 70^o respectively. Momin et al. [13] investigated effect of geometrical parameters on heat transfer and fluid flow characteristics of rectangular duct of solar air heater having absorber plate roughened with V-shape rib roughness geometry. Authors reported that V-shape ribs with an angle of attack (α) of 60^o enhanced Nusselt number by 1.14 and 2.30 times and friction factor by 2.30 and 2.8 times over inclined ribs and smooth duct respectively. Karwa [14] investigated the effect of inclined continuous and discrete ribs on performance of solar air heater. It is reported that the enhancement in Stanton number over the smooth duct was reported to be in range of 102-137%, 110-147%, 93-134% and 102-142% for V-up continuous, V-down continuous, V-up discrete and V-down discrete respectively. Hans et al. [15] reported an experimental investigation on heat transfer and friction characteristics of solar air heater duct having multiple v-ribs roughness geometry. Maximum enhancement in Nusselt number and friction factor was observed to be 6 and 5 times respectively as compared to smooth duct for the range of parameters considered. Singh et al. [16] reported an experimental investigation on heat transfer and flow characteristics of rectangular duct having its one broad wall heated and roughened with periodic discrete V-down ribs. Kumar et al. [17] studied the effect of multi v-shaped rib with gap roughness on heat transfer and friction characteristics of rectangular solar air heater. The enhancement of Nusselt number and friction factor was reported to be of order 6.74 and 6.37 times respectively over smooth duct. Singh et al. [18] experimentally investigated the effect of multiple arc shaped ribs on the heat transfer and friction characteristics of rectangular solar air heater. The maximum enhancement in Nusselt number and friction factor is 5.07 and 3.71 times respectively as compared to smooth duct. Layek et al. [19] reported experimental investigation on heat transfer and friction characteristics of solar air heater duct having roughness geometry. Authors reported that Nusselt number and friction factor increased by 3.24 times and 3.78 times respectively as compared to smooth duct. Saini and Saini [20] reported experimental investigation on expended metal mesh type of roughness geometry. Maximum enhancement in Nusselt number and friction factor was reported of the order of 4 and 5 times respectively as compared to smooth duct. Bhushan and Singh [21] investigated heat transfer and friction characteristics of a roughened duct having protruded roughness provided on absorber plate. It is reported that maximum enhancement of Nusselt number and friction factor of 3.8 and 2.2 times respectively in comparison to smooth duct. Yadav et al. [22] reported experimental investigation on heat transfer and friction characteristics of solar air heater duct having circular protrusions arranged in angular arc as roughness elements on absorber plate. Authors reported that heat transfer and friction factor is 2.89 and 2.93 times as compared with smooth duct in the investigated range of parameters. Application of artificial roughness to increase heat transfer coefficient has also been investigated using Computational Fluid Dynamics (CFD) by various investigators. Use of CFD in analysis of artificially roughened solar air heater has been attempted by few investigators. Yadav and Bhagoria [23] carried out a review of the literature that deals with the applications of CFD in the design of solar air heater. Chaube et al. [24] carried out CFD based analysis for prediction of heat transfer and friction characteristics in high aspect ratio rib roughened rectangular air duct. 2-D models were run for various types of roughness geometry. Shear stress transport (SST) k-ω turbulent model available in FLUENT software was selected by comparing the predictions of different turbulence models with experimental results available in the literature. A detailed analysis of heat transfer variations within inter rib region was done by using the selected turbulence model. Miyazaki et al. [25] conducted CFD based investigation on the performance of a solar chimney. Hahne and Chen [26] conducted numerical investigation on heat transfer and flow characteristics in a cylindrical hot water store during the charging process under adiabatic thermal boundary conditions. Kumar and Saini [27] carried out a numerical investigation to study CFD based performance of a solar air heater duct provided with artificial roughness in the form of thin circular wire in arc shaped geometry. It has been observed that heat transfer and pressure drop data for K-shaped (combination of transverse and V-up) roughness geometry have not been reported in the literature. In the present paper, CFD based investigation has been reported, in which effect of K-shaped roughness geometry on heat transfer and friction characteristics of artificial roughened duct has been investigated. CFD data have been utilized to develop Nusselt number and friction factor correlations for predicting performance of the system.

II. CFD MODEL AND INVESTIGATION PROCEDURE

In order to carry out present CFD based analysis, duct model was designed as per guidelines proposed in ASHARE standard [28]. Conventional solar air heater and CFD model of solar air heater duct are shown in Fig. (1) and (2) respectively. Length (L), height (H) and width (W) of rectangular duct are 2400, 30 and 300 mm respectively. Length of entry, test and exit sections were kept 900 mm, 1000 mm and 500 mm respectively. Absorber plate has been assumed made of GI sheet of thickness 0.9 mm as shown in Fig.3 (a) & (b). 2D plane flow analysis of heat transfer and fluid flow through a rectangular duct roughened with K-shaped ribs has been carried out using Flow Simulation module available in SolidWorks software. 2D computational domain and grid were selected. Non-uniform meshing was generated over the duct. In order to examine the heat transfer and flow, finer meshing was done in the inter ribs regions. In other regions, meshing level was kept normal. The total numbers of cells (fluid, solid and partial) were varied depending upon the roughness height. Static pressure and air velocity were considered as inlet and outlet boundary conditions in order to have pressure drop in test section of the duct. As flow of air takes place within selected geometry, heat transfer and flow were simulated in two dimensional planes. A uniform heat flux of 500 W/m^2 was given on surface of absorber plate as heat source.

In order to carry out CFD analysis in two dimensional planes, following assumptions were made;

i. Flow is fully turbulent.

ii. Thermal conductivity of the duct wall and roughness element does not change with temperature.

iii. Material of the duct and ribs is homogenous and isotropic.

iv. The working fluid i.e. air is incompressible.

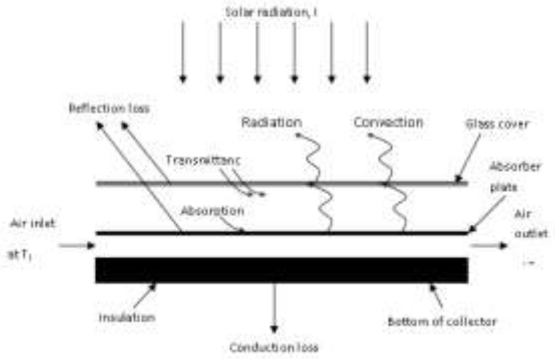


Fig.1: Conventional Solar Air Heater

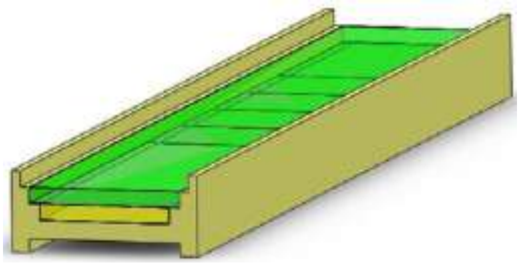


Fig. 2: CFD Model of Solar Air Heater Duct.

Accuracy of CFD data collected in the present investigation was verified by conducting CFD analysis of conventional smooth duct. Nusselt number and friction factor data were obtained and compared with the values obtained from the following Dittus and Boelter Nusselt number correlation and modified Blasius friction factor correlation as reported by Saini and Saini [20] for rectangular smooth duct.

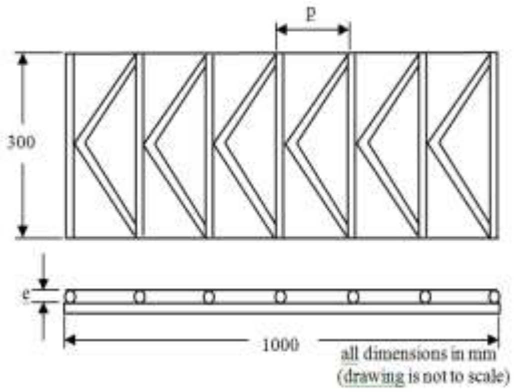


Fig.3: (a) Schematic of Roughened Absorber Plate.

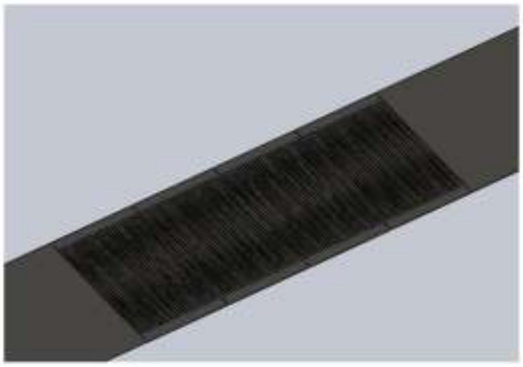


Fig.3: (b) Photographic View of Roughened Absorber Plate.

$$Nu = 0.024\, Re^{0.8} Pr^{0.4} \tag{1}$$

$$f = 0.085\, Re^{-0.25} \tag{2}$$

III. DATA REDUCTION

Following equations were used for calculating heat transfer rate (q), heat transfer coefficient (h), velocity of air (V), Nusselt number (Nu) and friction factor (f):

$$q = \dot{m} C_p \,(T_o - T_i) \tag{3}$$

$$q = hA\left(T_{pm} - T_{am}\right) \tag{4}$$

Therefore, from Eqs. (3) and (4)

$$h = \frac{\dot{m} C_p \,(T_o - T_i)}{A\left(T_{pm} - T_{am}\right)} \tag{5}$$

where T_{pm} and T_{am} are mean temperature of absorber plate and air. These were determined from temperature values obtained for absorber plate and air at different locations along test section of the duct. Reynolds number, Nusselt number and friction factor values were evaluated by using the following relationships:

$$Re = \frac{\rho VD}{\mu} \quad (6)$$

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

$$f = \frac{2\Delta PD}{4\rho LV^2} \quad (8)$$

Table 1: Range/value of system and operating parameters.

S.No.	Parameter	Range/value
1	Reynolds number (Re)	4000-16000
2	Relative roughness pitch (p/e)	7.5-10.7
3	Relative roughness height (e/D)	0.025-0.036
4	Hydraulic diameter of duct (D)	54.54 mm
5	Duct aspect ratio (W/H)	10

Figs.4 and 5 show comparison of CFD and predicted data of Nusselt number and friction factor for smooth absorber plate. A reasonably good agreement between CFD data and predicted data ensures accuracy of the data being collected from CFD based investigation of solar air heater duct.

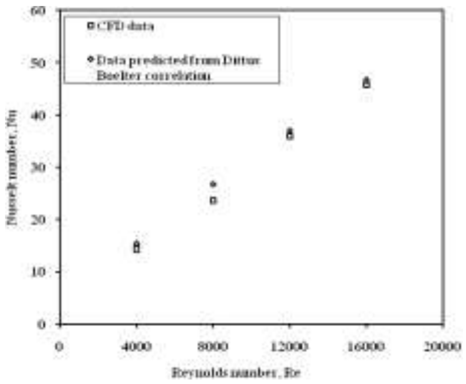


Fig. 4: Comparison of CFD and predicted data of Nusselt number for smooth absorber plate.

IV. RESULTS AND DISCUSSION

Heat transfer and flow characteristics of the duct get affected in the direction of air flow due to ribs provided in the form of artificial roughness. Effect of flow and roughness parameters on heat transfer and friction characteristics has been investigated and results have been reported and discussed in the present section. Fig. 6 represents variation of Nusselt number with Reynolds number. In this set, relative roughness height (e/D) was kept fixed while relative roughness pitch (p/e) was varied. It can be observed that for a given type of artificial roughness, Nusselt number increases with an increase in Reynolds number for smooth as well as roughened plate. It may happen due to separation of flow at the rib and reattachment does not occur for relative roughness (p/e) less than 8 as reported by Prasad and saini [11]. With increase in relative roughness pitch from 7.5 to 8.3, Nusselt number increases and is maximum at p/e of 8.3.

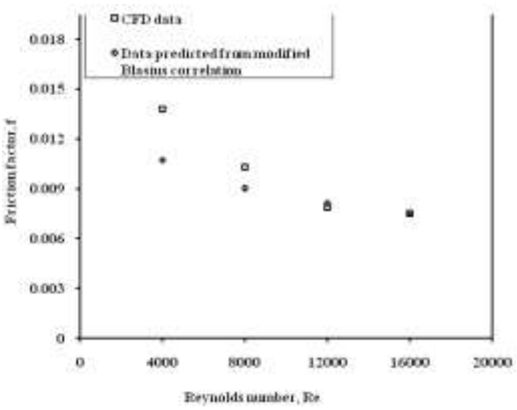


Fig. 5: Comparison of CFD and predicted data of friction factor for smooth absorber plate.

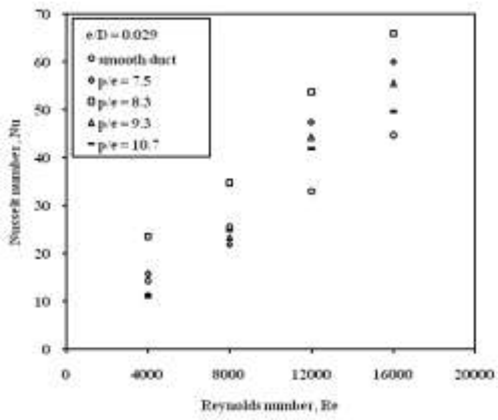


Fig. 6: Variation of Nusselt number as a function of Reynolds number for range of relative roughness pitch (p/e).

Fig. 7 represents variation of Nusselt number with Reynolds number. In this set, relative roughness pitch (p/e) was kept fixed while relative roughness pitch (e/D) was varied. It can be observed that Nusselt number increases monotonously with an increase in Reynolds number for smooth and roughened duct. It can be also observed that larger relative roughness height (e/D) may be produced the same effect as that of relative roughness pitch (p/e) less than 8 as reported by Prasad and Saini [11].

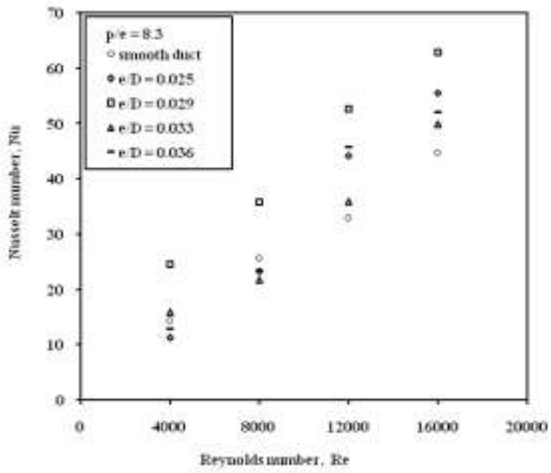


Fig. 7: Variation of Nusselt number as a function of Reynolds number for range of relative roughness height (e/D).

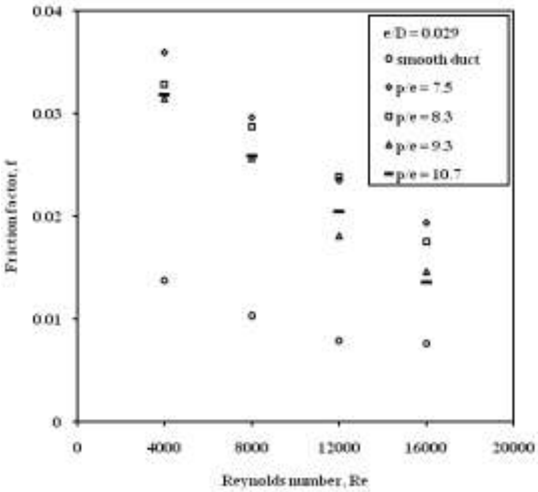


Fig. 8: Variation of Friction factor as a function of Reynolds number for range of relative roughness pitch (p/e).

Fig. 8 shows the variation of friction factor with Reynolds number for the range of relative roughness pitch. It can be observed that friction factor decreases with an increase in Reynolds number for smooth and roughened duct. Similar effect has also been reported by Hans et al. [15]. Fig.9 shows variation of friction factor with Reynolds number for range of relative roughness height. It can be observed that friction factor decreases with an increase in Reynolds number. Similar variation has also been reported by Prasad and Saini [11]. It can be also observed that increase in relative roughness height (e/D) results in an increase in friction factor at a given value of Reynolds number.

V. DEVELOPMENT OF NUSSELT NUMBER AND FRICTION FACTOR CORRELATIONS

It has been observed that Nusselt number and friction factor are strong functions of Reynolds number (Re) and relative roughness pitch (p/e). Functional relationships for Nusselt number and friction factor can therefore be written as:

$$Nu = f\,(Re, p/e, e/D) \tag{9}$$

$$f = f\,(Re, p/e, e/D) \tag{10}$$

As per procedure described by Singh et al. [29] and using Sigma plot software following Nusselt number and friction factor correlations were developed corresponding to CFD data as shown in Figs. (6,7) and (8,9) respectively.

$$Nu = 1.62 \times 10^{-8} (Re)^{0.98} (p/e)^{5.7} (e/D)^{6.03} \exp[-7.13\{\log(p/e)\}^2] \exp[-7.3\{\log(e/D)\}^2] \tag{11}$$

$$f = 0.182\,(Re)^{-0.25} (p/e)^{-0.64} (e/D)^{0.19} \tag{12}$$

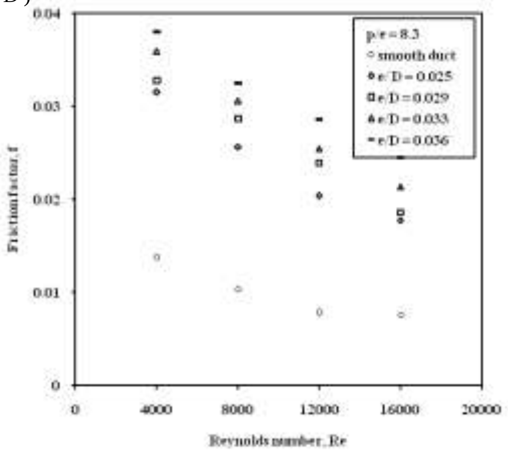
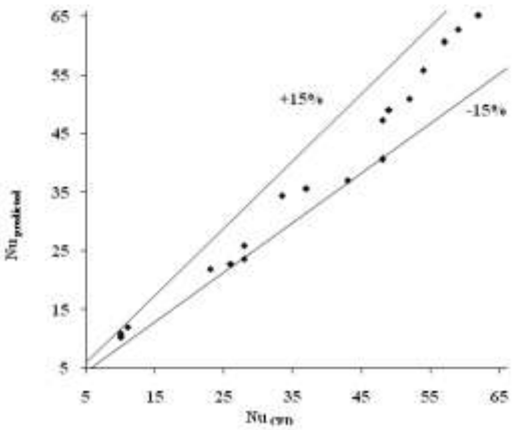


Fig. 9: Variation of friction factor as a function of Reynolds number for range of relative roughness height (e/D).

Figs.10 and 11 show comparison of CFD data and that predicted from above developed Nusselt number and friction factor correlations for roughened absorber plate. Average absolute percentage deviations between CFD and predicted values of Nusselt number and friction factor for K-shaped ribs have been found to be ±15 % and ±20 % respectively.



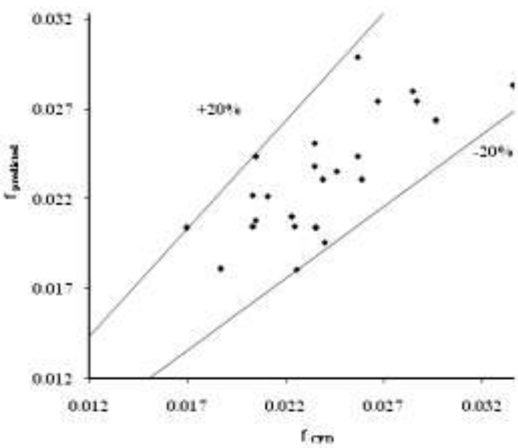


Fig. 10: Comparison of CFD and predicted data of Nusselt number.

Fig. 11: Comparison of CFD and predicted data of friction factor.

VI. CONCLUSIONS

CFD based investigation has been reported in the present paper in order to study heat transfer and friction characteristics of artificially roughened duct. Effect of roughness elements on heat transfer and friction has been investigated for Reynolds number range of 4000–16000. It has been observed that roughened absorber plate results into higher heat transfer coefficient at the cost of frictional penalty. In order to predict performance of the system Nusselt number and friction factor correlations have been developed by utilizing CFD data.

VII. NOMENCLATURE

A cross-sectional area of duct, m^2
C_p specific heat of the air, J kg^{-1} K^{-1}
D hydraulic diameter of duct, m
e height of roughness element, m
f friction factor (dimensionless)
H height of the duct, m
h heat transfer coefficient, W m^{-2} K^{-1}
k thermal conductivity of air, W m^{-1} K^{-1}
L length of duct test section, m
M mass flow rate of air, kg s^{-1}
Nu Nusselt number (dimensionless)
p pitch of roughness element, m
Pr Prandlt number (dimensionless)
ΔP pressure drop in duct test section, N m^{-2}
q heat transfer rate, W
Re Reynolds number (dimensionless)
T_i inlet air temperature of duct test section, K
T_o outlet air temperature of duct test section,
T_{am} mean temperature of air, K
T_{pm} mean temperature of absorber plate, K
V velocity of air, m s^{-1}
W width of the duct, m
T_{am} *mean* temperature of air, K
Greek letters
ρ density of air, kg m^{-3}
μ dynamic viscosity of air, kg/s-m

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