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A CFD based Thermo-Hydraulic Performance Analysis of an Artificially Roughened Solar Air Heater Having Circular Ribs on the Absorber Plate

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Abstract - **This article presents the numerical investigation of artificially roughened solar air heater having circular ribs on absorber plate by using computational fluid dynamics (CFD). The input parameter for the analysis is taken as Reynolds no (Re), relative roughness height (e/D) and relative roughness pitch (P/e). A three-dimensional simulation is conducted using k-e turbulence model in ANSYS FLUENT 14.5 code. Due to artificial roughness heat transfer increases as compared to smooth duct. The present investigation shows the effect of input design parameter on various thermal properties like nusselt number and average friction factor. For the range investigated and for this type of rib arrangement maximum value of thermo-hydraulic performance parameter is found to be 1.631.**

Keywords - CFD, Thermo-hydraulic performance parameter, solar air heater, circular ribs.

1. INTRODUCTION

SAH is a solar thermal technology in which the energy from the sun is captured by an absorbing medium and used to heat air. Efficiency of a solar air heater is very poor due to low value of heat transfer coefficient

between the absorber plate and working fluid even for turbulent flow [6], so it became crucial to make SAH more efficient. It can be done by providing artificial roughness on the absorber plate of SAH , which increases the heat transfer capability of a SAH. Till now a number of experiments and analysis have been performed by many researchers found that SAH duct with artificial roughness has more heat transfer coefficient as compared to smooth duct**.** Yadav and Bhagoria [1] performed 2-dimensional CFD analysis of an artificially roughened solar air heater having transverse wire rib roughness on the absorber plate using ANSYS FLUENT 12.1 code as a solver with k-e turbulence model. Maximum value of thermo-hydraulic performance parameter was obtained 1.65 for the range of parameter investigated. Yadav and Bhagoria[2] conducted two dimensional CFD based analysis of an artificially roughened solar air heater having square sectioned ribs on absorber plate. For the range of parameter investigated maximum value of thermo-hydraulic performance parameter was reported to be 1.82 corresponding to relative roughness pitch of 10.71. Chaube[3] carried out two dimensional CFD investigation of an artificially roughened solar air heater having ten different ribs shape viz. rectangular, square, chamfered, triangular etc on absorber plate using ANSYS FLUENT 6.1 code as a solver with k-w turbulence model. Optimum result was found with rectangular rib. Karmare and Tikerkar[4] conducted a numerical analysis of the heat transfer and flow friction characteristics in an artificially roughened solar air heater having arc shaped artificial roughness on the absorber plate. CFD simulation was performed using FLUENT 6.3.26 commercial CFD code as a solver with RNG k-e turbulence model. The maximum value of thermo-hydraulic performance parameter was found at 58^{o} angle of attack. Kumar and Saini [9] performed CFD analysis of artificially roughened solar air heater and got maximum value of thermo-hydraulic performance ratio as 1.7. Bolemtafes and Benzaoui[10] performed the CFD analysis of roughened solar air heater and compared various turbulence models. Singh, hans and Gill[11] has select non uniform cross section ribs for CFD analysis and they found that non uniform cross section results in higher Nusselt number and low friction factor.

Computational fluid dynamics (CFD) is a computer-based simulation method for analyzing fluid flow and heat transfer. This project uses CFD for analysis of flow and heat transfer. Some examples of application areas are: aerodynamic lift and drag (i.e. airplanes), power plant combustion, heating, ventilation, various chemical process and in biomedical engineering such as simulating blood flow through arteries and veins. CFD analyses carried out in the various industries are used in R&D and manufacture of combustion engines and aircraft as well as many other industrial products.

2.CONCEPTS OF ARTIFICIAL ROUGHNESS

It is desirable to make the flow turbulent inside the duct to enhance the heat transfer capability of SAH. This is done by introducing artificial roughness and keeping the height of the roughness element to be small in comparison with the duct dimensions. Turbulent is created by artificial roughness near the wall and thus breaks the laminar sub layer. Therefore artificial roughness plays a vital role in enhancement of heat transfer capability in SAH duct which in turn leads to make SAH more efficient.

Although there are several parameters that characterize the arrangement and shape of the roughness, the roughness element height (e) and pitch (P) are the most important. Theses parameters are usually specified in terms of dimensionless parameters, some of them are relative roughness height (e/D), relative roughness pitch (P/e), angle of attack (α), relative gap position (d/W), relative gap width (g/e), groove position (g/P) etc. The roughness elements can be two-dimensional ribs or three dimensional ribs, angled ribs, continuous or broken ribs etc.

Many experimental and CFD analysis have been carried out to study the flow field and characteristics of heat transfer and friction factor of roughened tubes, annuli and ducts.

3. CFD SIMULATION

The computational domain is simply the physical region having the dimensions of length 640mm, height 20mm and width 100mm. The length consist of three sections, namely, entrance length (L_1=245mm), test section (L_2=280mm) and at last exit section (L_3=115mm) (Fig.1).In this analysis circular ribs is considered as roughened element which enhance the heat transfer in SAH. These ribs are made underside of top plate while other sides are considered as smooth. Maximum and minimum height of ribs are taken as 1.4 and 1 mm respectively, so that the blockage effect of ribs are negligible and pitch are taken in the range of 10-20 mm.

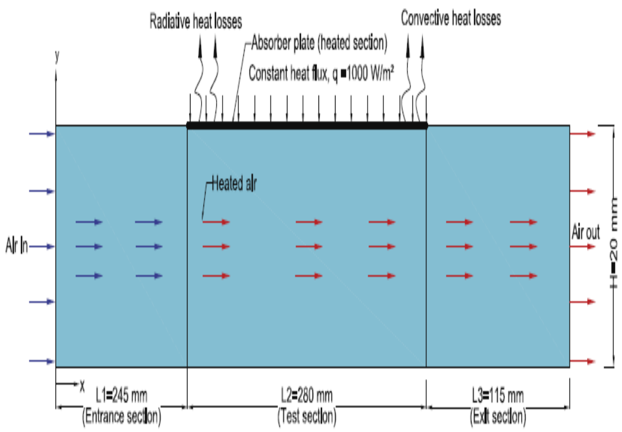


Table 1. Range of operating parameter for CFD

Operating Parameters	Range
Uniform Heat flux I	1000 w/m^2
Reynolds number Re	8000-180000
Prandtl Number Pr	0.7441
Relative roughness pitch P/e	7.14-20
Relative roughness height e/D	0.03-0.042
Hydraulic diameter	33.33

Table2. Thermo-physical properties of working fluid (air) and absorber plate (aluminium) for CFD

Properties	Working fluid (air)	Absorber plate (aluminium)
Density Kg/m^3	1.225	2719
Specific heat C_p ($J\ kg^{-1}k^{-1}$)	1006.43	871
Viscosity	$1.7894e^{-05}$	-
Thermal conductivity k	0.0242	202.4

4. CAD MODELLING

Three-dimensional Model Description

- A 3-dimensional model the shape of a rectangular duct is developed for solar air heater analysis. The model geometry will be created using pre-processor ANSYS DESIGN MODELER. The physical dimensions set to be 640mm length, 100 mm width, and 20 mm height (fig 2). Table 3 shows the geometric parameters of SAH with ribs geometry combinations

- Table 3. Geometric parameters of SAH with ribs geometry combinations

L_1(mm)	L_2(mm)	L_3(mm)	W(mm)
245	280	115	100

H(mm)	D(mm)	e(mm)	P(mm)
20	33.33	1,1.4	10,15,20

- In this CFD analysis six different rib roughness models have been simulated. Each rib model is performed with four combinations of Reynolds number ranging between 8000 to 18000.

- Total twenty-four models have been simulated and results are compared with smooth duct. Main parameters on which we are going to compare the results are relative roughness pitch (P/e) and relative roughness height (e/D).

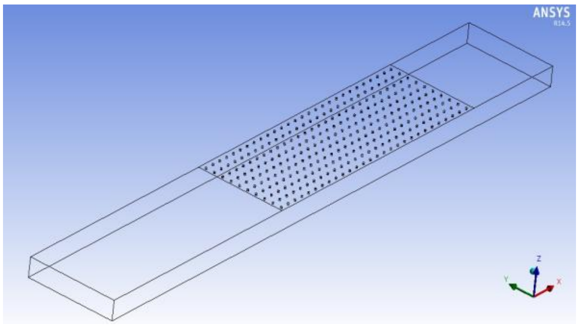


Fig.2. 3-Dimensional domain SAH duct with circular ribs on absorber plate

Meshing

After creating the geometry, meshing was done in which a uniform tetrahedral mesh was selected for the entire domain and a uniform mesh is formed over the entire model. The total numbers of nodes and elements is about 255358 and 515961 respectively. Meshing model of duct is shown in Fig 3.

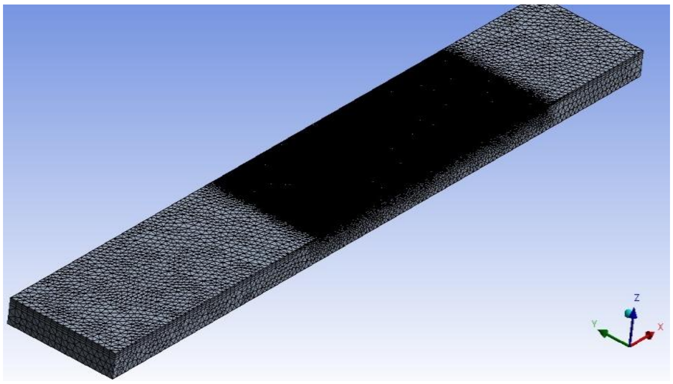


Fig.3 Meshing model SAH duct

Boundary Conditions**:**

Operating Condition**:** Pressure = 101325 Pa

Inlet:

Velocity will vary according to the Reynolds number used

Hydraulic Diameter = 33.33mm

Heat flux at the top of the absorber plate q= 1000 W/m^2

5. RESULT AND DISCUSSION-

Average Nusselt no is defined as

$Nu_r = hD/k$

Where h is convective heat transfer coefficient.

Friction factor is given by

$F_r = (\Delta P)\, D / (2lu^2 p)$

Therm0-hydraullic performance parameter is given by

$THPP = (Nu_r/Nu_s) / (f_r/f_s)^{1/3}$ [8]

Friction factor for smooth plate is given by

$f_s = 0.085\ Re^{-0.25}$

The data collected using ANSYS FLUENT 14.5 included the temperature distribution, pressure distribution and airflow velocity at all node points in the model duct, from which we can see the following results-

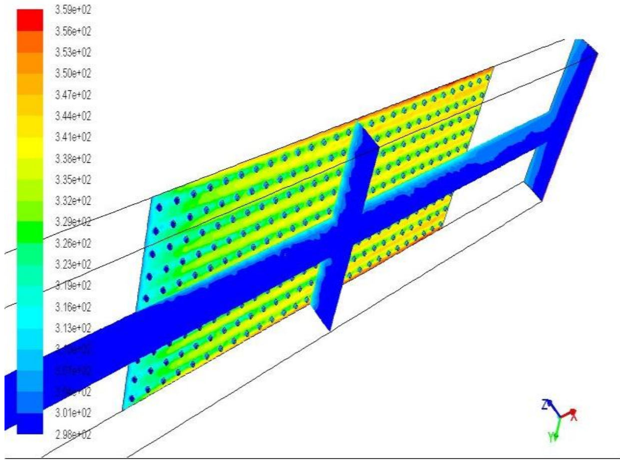


Fig 4 Contour of static temperature of absorber plate corresponds to P=10mm, e= 1.4mm, Re=8000

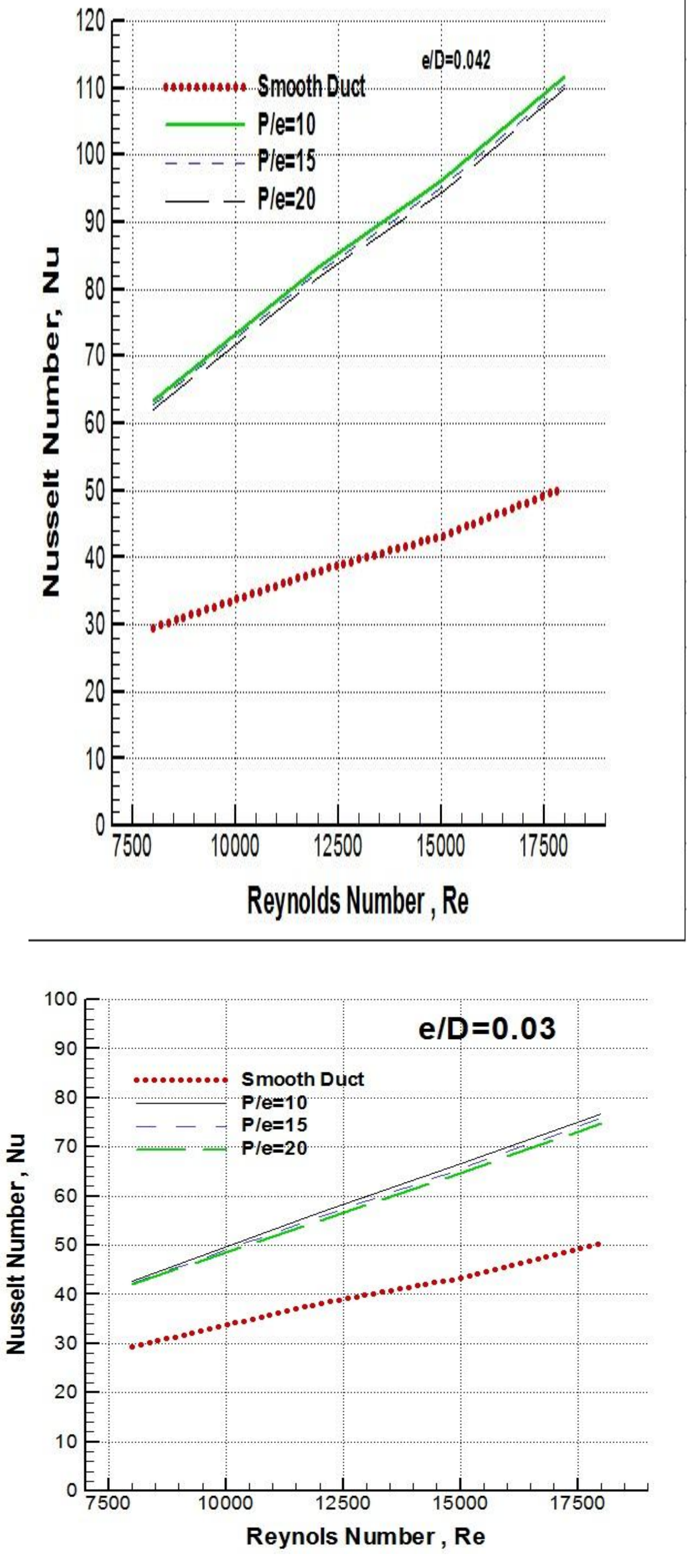


Fig 5 Effect of relative roughness pitch on average Nusselt number for different values of Reynolds number and for fixed value of relative roughness height.

We can see in fig 5 the average nusselt number increases with increase in Reynolds number in all cases for fixed value of relative roughness height.

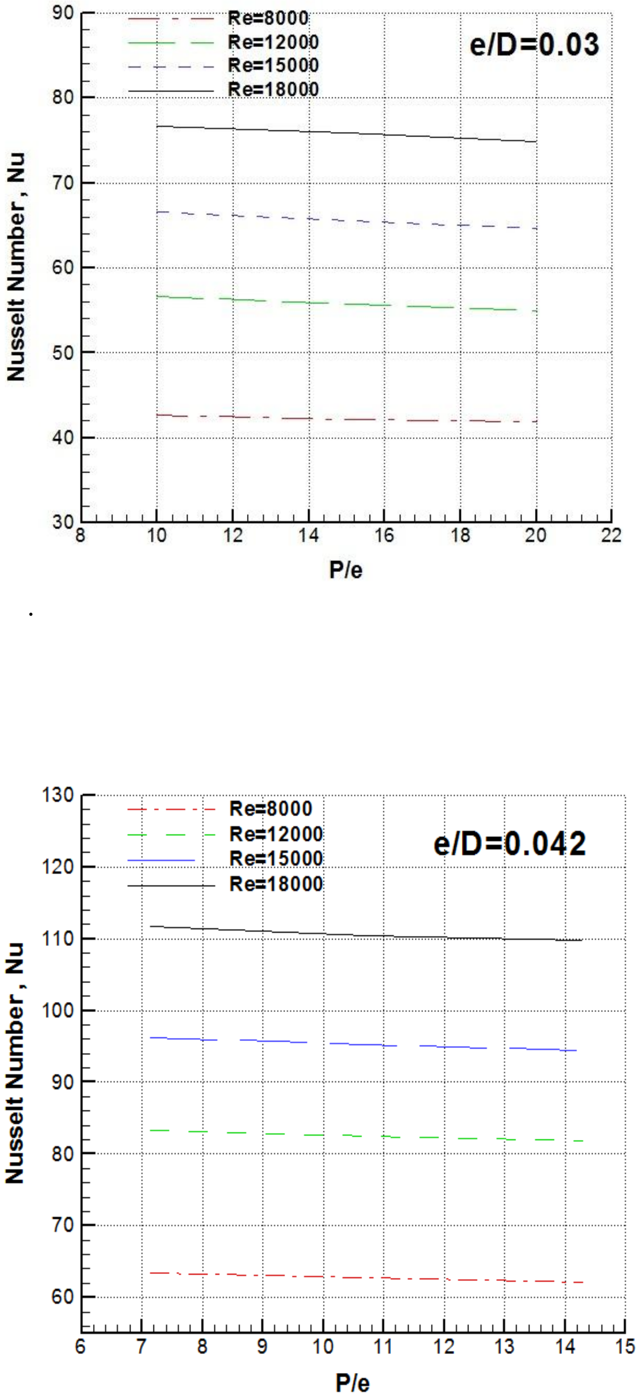
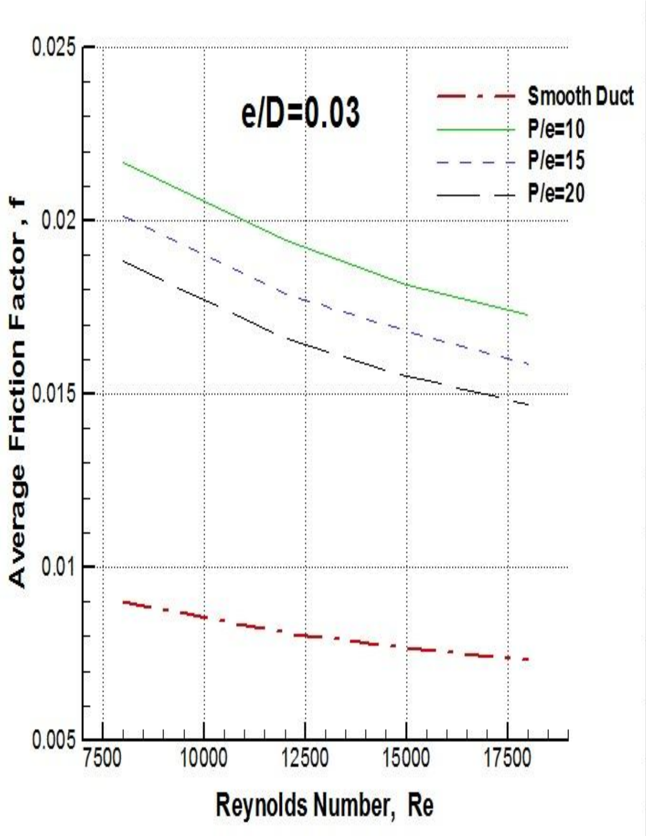


Fig 6 Effect of Reynolds number on average Nusselt number for different values of relative roughness pitch and for fixed value of relative roughness height.

We can see in fig 6 average nusselt number decreases with increases in relative roughness pitch in all cases for fixed value of relative roughness height.



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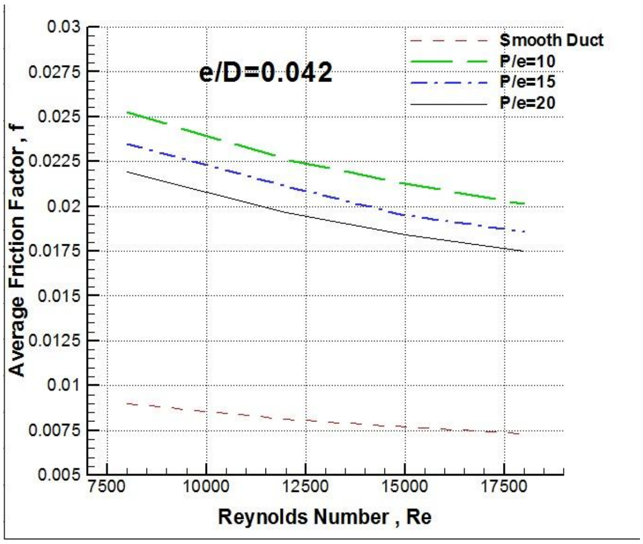

Fig 7 Effect of relative roughness pitch on average friction factor for different values of Reynolds number and for fixed value of relative roughness height.

We can see in fig 7 average friction factor decreases with increase in Reynolds number in all cases.

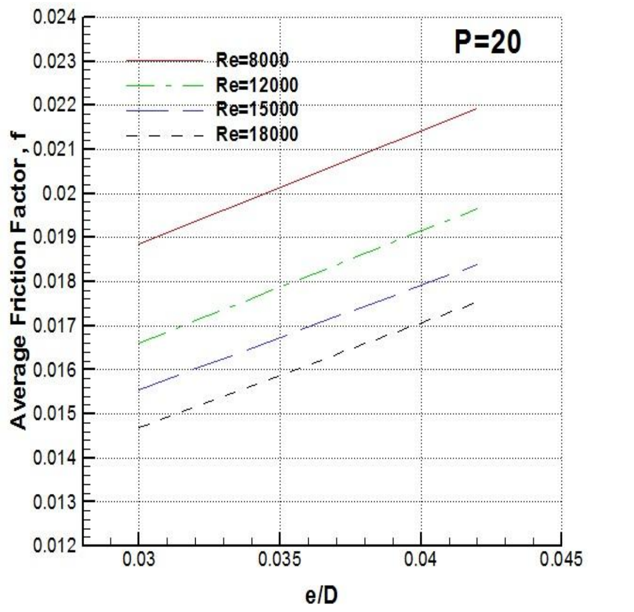

Fig 8 Effect of Reynolds number on average friction factor for different values of relative roughness heights and for fixed value of pitch

We can see in fig 8 average friction factor decreases with increase in relative roughness pitch for relative roughness height and increases with the increase of relative roughness height for fixed value pitch.

Table 4 Nusselt number enhancement ratio

e(mm)	e/D	P(mm)	P/e	Re=8000	Re=12000
1	0.03	10	10	1.452	1.486
		15	20	1.434	1.463
		20	30	1.426	1.443
1.4	0.042	10	7.142	2.154	2.184
		15	10.714	2.133	2.164
		20	14.286	2.113	2.145

e (mm)	**e/D**	**P (mm)**	**P/e**	**Re=15000**	**Re=18000**
1	0.03	10	10	1.539	1.521
		15	20	1.513	1.503
		20	30	1.494	1.483
1.4	0.042	10	7.142	**2.223**	2.213
		15	10.714	2.201	2.191
		20	14.286	2.182	2.177

Table 5 Friction factor enhancement ratio

e(mm)	e/D	P(mm)	P/e	Re=8000	Re=12000
1	0.03	10	10	2.412	2.412
		15	20	2.238	2.238
		20	30	2.097	2.097
1.4	0.042	10	7.142	2.811	2.811
		15	10.714	2.614	2.614
		20	14.286	2.441	2.441

e (mm)	e/D	P (mm)	P/e	Re=15000	Re=18000
1	0.03	10	10	2.365	2.357
		15	20	2.188	2.160
		20	30	2.023	2.003
1.4	0.042	10	7.142	2.769	2.744
		15	10.714	2.541	2.533
		20	14.286	2.395	2.388

6. CONCLUSIONS

- The average nusselt number increases with increase in Reynolds number in all cases for fixed value of relative roughness height.
- The average nusselt number decreases with increases in relative roughness pitch in all cases for fixed value of relative roughness height.
- The average nusselt number increase with increases in relative roughness height in all cases for fixed value of relative roughness pitch.
- Maximum nusselt number has been found to be 2.223 times compared to smooth duct corresponds to relative roughness height (e/D) of 0.042 and relative roughness pitch (P/e) of 7.142 at Reynolds number 15000 in the range of parameter investigated.
- The average friction factor decreases with increase in Reynolds number in all cases.
- The average friction factor decreases with increase in relative roughness pitch for relative roughness height and increases with the increase of relative roughness height for fixed value pitch.
- The value of Thermo-hydraulic performance parameter varies between 1.083 and 1.631 for the parameters investigated.
- Optimum value of Thermo-hydraulic performance parameter, which is 1.631, has been found corresponds to relative roughness height (e/D) of 0.042 and relative roughness pitch (P/e) of 10.714 for the Reynolds number of 15000.

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