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Thermal Hydraulic Performance of Solar Air Heater with Roughness: A Numerical Analysis

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ABSTRACT

Solar air heaters are indispensable in several industries, encompassing industrial environments, agricultural product dehydration, material conditioning, and residential heating. Nevertheless, inadequate convective transfer can hinder their effectiveness. The enhancements in thermal hydraulic performance and friction factor characteristics have significantly increased the efficiency of solar energy utilization. Additional research and development efforts have the potential to enhance the utilization of clean and sustainable energy sources. This paper achieved a heat transfer rate that was more than higher than the maximum value, and the thermal performances surpassed a value of 1.1.

Keywords: Solar air heater; Thermal performance; Nusselt number; Friction factor; Fluid flow; Vorticity; Heat transfer; Fan roughness; CFD.

1. Introduction

Solar energy does, however, have certain limitations. For example, it is a diluted source and rarely produces more than 1 kW/m^2 in the hottest places. With a maximum radiation of 7 kW/m^2 per day, this technology has minimal demand. Large setups are needed to properly supply energy demands, because solar energy is impacted by Earth's seasons and day-night cycle. One kind of solar thermal system involves a solar air heater, which heats airflow in a collector before transferring it into an interior room with an enclosed container like something bin. With the help of solar panels, ambient warmth flows inside a room using solar air heaters.

The impact of several types of ribs that researchers have employed on solar heater panels, emphasizing the placement & shape of these ribs. A table of review outlining the findings is included with the review, in addition to experimental setups and numerical investigation outcomes. Dry air and nanofluids were the working fluids employed; techniques (Momin et al. [1]). In comparison with inclined ribs with flat plates, the research indicated that V-shaped ribs raised their Nusselt number between 1.14% and 2.30% with a roughness height of 0.034 at an angle of attack of 60̊.

Sukhmeet Singh et al. [2] in this paper, an experiment was conducted to study heat transfer and friction within rectangular ducts [3] that were roughened alongside an innovative arrangement. At this position, the Nu was 2.88 times higher and the Fr was 3.03 times higher compared to smooth ducts. Technology greatly improves the TH efficiency of solar air heaters (Muluwork et al. [4]). Through employing math to figure out how temperature as well as fluid moves through a duct over V-shaped solar air heaters [5], the highest thermal efficiency rating of 1.93 has been obtained. Anil K. Patil et al. [6], the heating efficiency of a solar air heater is significantly enhanced by making the surface surrounding the absorbent rougher than it naturally is. In turn, this speeds up the passage of heat as well as raises the Nusselt number from 1.77 to 3.18 (Deo et al. [7]). The study looked at thermo-hydraulic efficiency, heat transmission, & friction when considering a rectangular passageway having multi-gap V-down ribs & artificial roughness. The Nusselt number increased by 3.34 times as the THP indicators of performance increased by 2.45 times, according to the data. Rajesh Maithani et al. [8] in a research conducted on improving coefficient of a SAH [9] by using artificially roughened air ducts, specifically V-ribs, discovered that the enhancement reached a maximum compared of smooth channel at 3.6 times. Additionally, the friction factor experienced a 3.67-fold rise. Anil Kumar et al. [10], in this work, A maximum improvement was discovered in improving factor of a SAH utilizing deliberately roughened ducts for air, notably V-ribs featuring asymmetrical intervals. Mukesh Kumar Sahu et al. [11] in this work, an analysis was used as the exegetic effectiveness of a solar-powered air conditioner having arc-shaped wiring rib. The modified solar-powered air heater was previously reported to achieve a maximum increase in exergetic efficiency of 56% comparing w.r.t smooth duct. This improvement corresponds to an approximate smoothness height (e/D) for 0.0422 (Alperen et al. [12]). The study aims was obtaining the effectiveness of transfer of heat rectangular ducts by utilizing roughened hybrid ribs [13]. The channels have been exposed to three separate rib roughness in order to quantify the frictional and heat components. The rectangular channels were created with specific measurements: a length of 320mm and a height of 120mm. throughout the experiment, there have been changes in both the heat transfer & friction factors. Andallib Tariq et al. [14], the study analysed the enhancement for fermentation by utilizing a mounted slit rib on a simulated surface. The results demonstrated a significant enhancement of 10, 20, 30, 40, and 50 percent in comparison to the entire rib area, taking into account the downstream flow and heat transfer rate.

Prashant Singh [15] examined the enhancement of heat transport in a square channel with internal ribs. The research made use of a square channel containing two opposing walls that had several rib ruggedness arrangements, including simple pierced rectangle, & perforation elliptical ribbing. Mohsen Sheikholeslami et al. [16], through the use for three-dimensional modeling of a rectangular rib channel, it was demonstrated possible to achieve the highest possible heat transfer coefficient while yet preserving a constant heat flux. The duct measured 570 mm in height & 120 mm by 120 mm in cross-section. The fluid moved down the conduit in the x-direction at a Reynolds number of three thanks to the placement of three rectangular transverse ribs on the ground. The Reynolds numbers have been determined employing data on the physical properties of air at 25°C & 100 KPa, as well as the intake speed. Ganesh Kumar [13] was assigned the task of conducting research on a Review paper about a square channel that is installed in a circular tube.

1.1. Study Objectives

1. To study CFD Analysis; 2. To study Heat transfer rate; 3. To study Nusselt Number; 4. To study Friction factor; 5. To study Dittus-Boelter comparison; 6. To study Thermal performance.

2. Methodology of Solar Air Heater (SAH)

This section expresses the methodology of the solar air heater (SAH) which is design of rectangular channel. The rectangular channel design is sketched by computational fluid dynamics (CFD). This chapter deals with the roughness method of multiple Fan shaped mounted on the solar rectangular channel. The main motive is to generate the heat transfer rate more than smooth rectangular channel. The Geometric model of smooth rectangular duct is shown in figures 1 and 2. In the figure, the rectangular channel has total length of L= 650 mm with effective height and width of 25 mm and 250 mm respectively and these parameters taken from the research paper as reference

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values of design model. After this solution in case of smooth, we mounted Fan shaped roughness with constant gap and with different height rib roughness, e = 1.49–3.88 mm and for multiple Fan shaped rib roughness some variations are taken as gaps in the rib roughness which is shown in parameters range section.

The complete design of multiple Fan shaped roughness with gap mounted on smooth channel at different Pitch ratio (P/e = 6-14) are given in the following below figures and these all the geometrics are designed in ANSYS FLUENT.

Figure 1. Design of Smooth rectangular channel

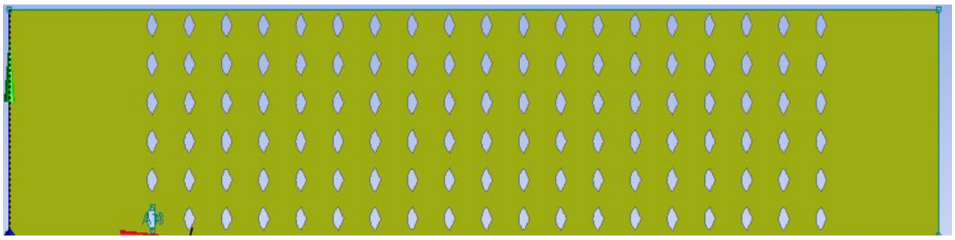

Figure 2. Design of multiple Fan shaped solar air heater with gap

The variables are categorized as the mathematical design variables that are taken into account and used for the absorber surface of the for example, relative pitch roughness, variables with Reynolds numbers Re = 3000–18000 are some dimensionless parameters employed in the project. Because roughness is a key technique for generating heat for an air or working flue, all characteristics are employed in the section to design a useful model that will increase the thermal performance of solar air heaters.

2.1. Mesh generation for multiple Fan shaped SAH

In this section, second step is taken for meshing of the design model and Ansys meshing is a general method in the production of high efficiency of the rectangular solar air heater (SAH) with multiple Fan shaped roughness as shown in Table 1.

Table 1. Grid test for Rectangular channel

S. No.	Elements of mesh grid	Results
1	45452	13.56651
2	55353	28.35421
3	876653	27.61512
4	958544	28.08461
5	978644	41.65647

2.2. Assumption

Numerous assumptions are made in this section regarding the solar rectangular duct's thermal performance, pressure drop, transition model, and heat transfer rate. There are a few frequent presumptions that are made in the rectangle solar heater duct.

Illustrated assumptions are assumed for multiple Fan shaped roughness SAH.

(1) Steady flows.

(2) Pressure variation in y direction is zero.

(3) Shear force in y direction is zero.

(4) Body force due to gravity has been neglected.

(5) Incompressible flow.

(6) At the inlet of test section, the flow has been flow fully formed.

3. Results and Discussion

In this chapter, the design model is analyzed by use of the CFD program. The design model is simulated in setup format after the meshing process. In the setup format of CFD, we have to find the importance of the parameters of the design model and find all the results at different parameters. The importance of roughness manipulates for increase capacity of SAH and decrease friction factors for life of solar air heater. This air system is most attractive in solar thermal power system and we had discussed number of the system had been used but our system is only system with huge number of changes in pitch ratio (P/e = 6-14) of each arm of multiple Fan shaped roughness. It is based on the natural circulation of air and our motive is to use the air for heat transfer rate at any situation.

3.1. Results of Dittus-Boelter Correlation and Smooth rectangular channel

Figure 3 depicts a comparison between the smooth duct and the dittus-Boelter equation. This comparison is used to demonstrate the effectiveness of the heat transfer coefficient in a smooth rectangular duct devoid of several Fan-shaped roughnesses.

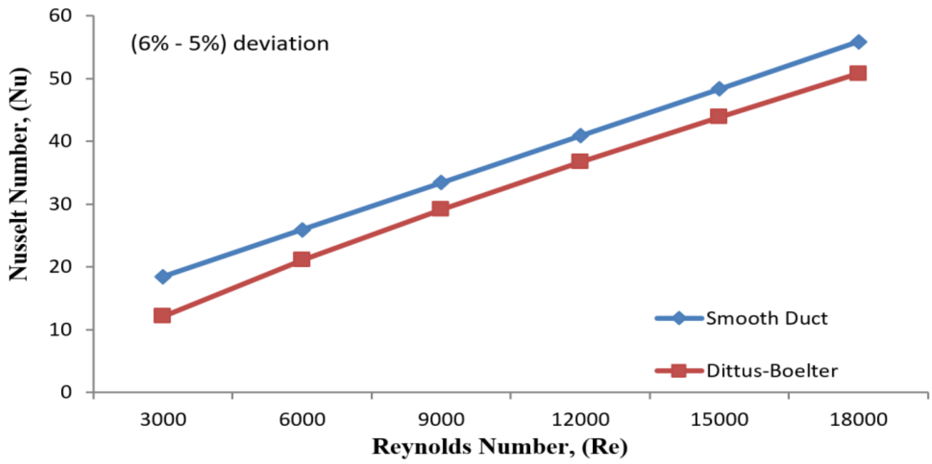

Figure 3. Expressed the heat transfer rate

3.2. Results and discussion of the variations in the solar rectangular duct with Multiple fan shape roughness

In this section, all the results are discussed which are calculated by the Ansys fluent. Thermal efficiency based on the applied situation with roughness and without roughness. The heat transfer results of the solar rectangular duct manipulated on the basic of variations of the roughness and we are taking variations for the roughness's height e = 1.5, 2.1, 2.7, 3.3, and 3.9 mm because of the height, fluid circulated and increased reattachment zone around the roughness.

3.2.1. Velocity Contour of Solar Rectangular Channel

Multiple-Fan shaped roughness is being utilized in this model with the intention of improving the effectiveness of solar air heaters. This is due to the fact that smooth ducts tend to be more productive than a single smooth duct. Enhancing thermal performance is another benefit of mass flow rate as shown in Figure 4.

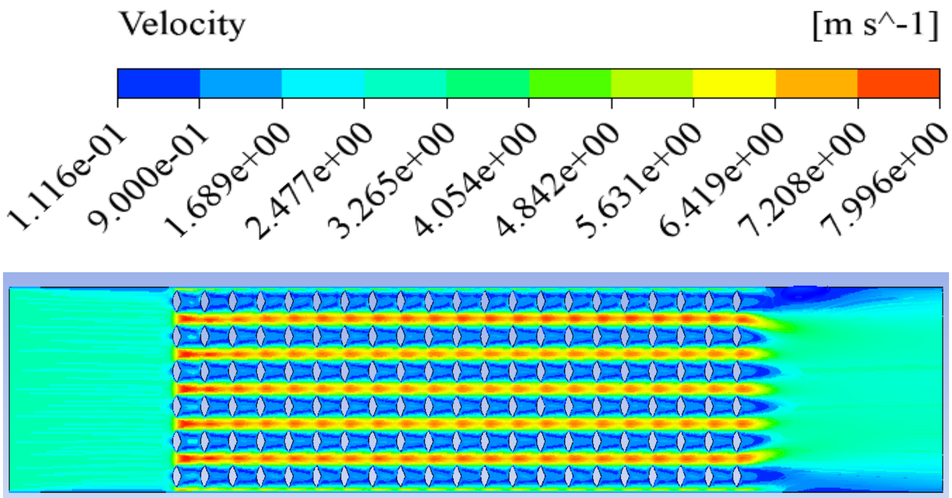

Figure 4. Velocity contour at P/e = 6

3.3. Reynolds Number, a Relative Roughness Pitch, and Multiple Fan Shaped Roughness Analysis's Effects

All of the numerical analyses is investigated and studies are presented in the section in which heat transfer characteristic was man motive to describe by figures. All the problems were solved like the energy-containing turbulent eddies by the large computer process as Ansys Fluent workbench [17].

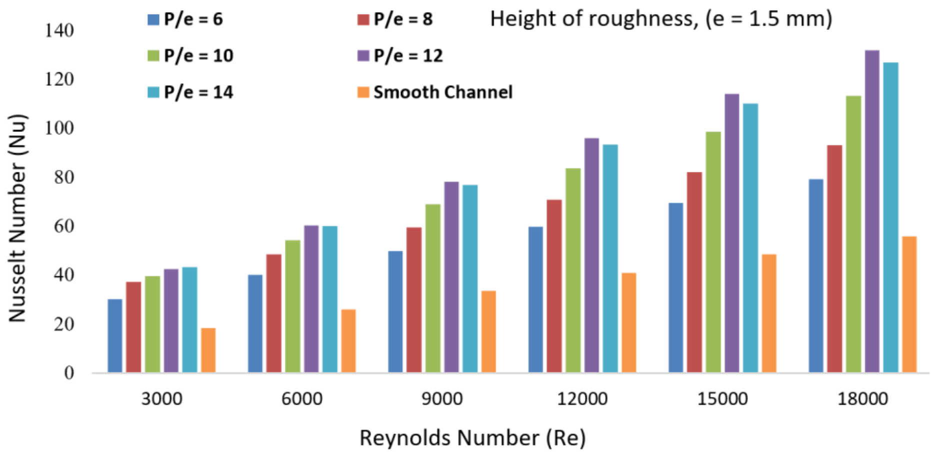

Figure 5. The heat transfer rate of multiple Fan shaped roughness

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There are a lot of effects are examined or calculated like heat transfer rate in the form of Nusselt numbers, friction factors as improvement of the model, thermal performance under overall results. Now we can explain that Nusselt number effects on the solar air heater to increase the capacity of the thermal power from natural energy and faction factor effects used to maintain eddies due to the turbulent flow

Figures 5, 6, 7, 8, 9, and 10, expressed the increased heat transfer rate with increasing Reynolds number Re = 3000 – 18000. Conduction heat of the multiple Fan shaped with gap rib is transferred to the air in the form of convection so in the figure variations in the values of p/e = 6 – 14.

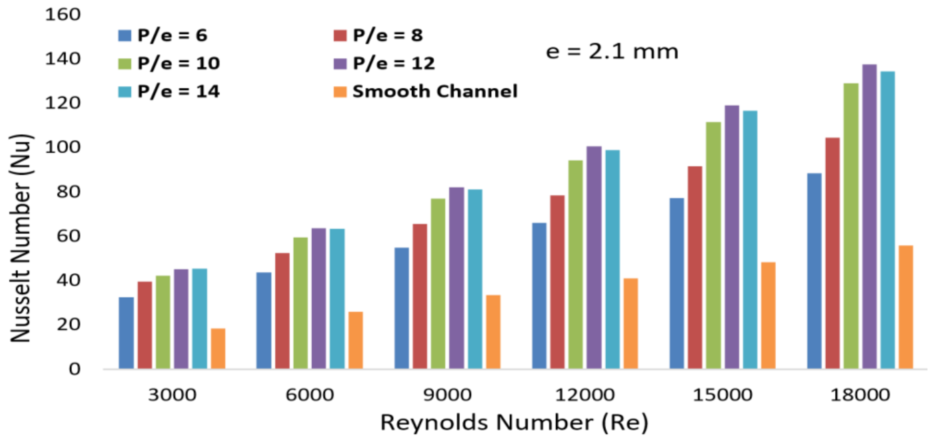

Figure 6. Expressed the Nusselt number for g = 2.1 mm

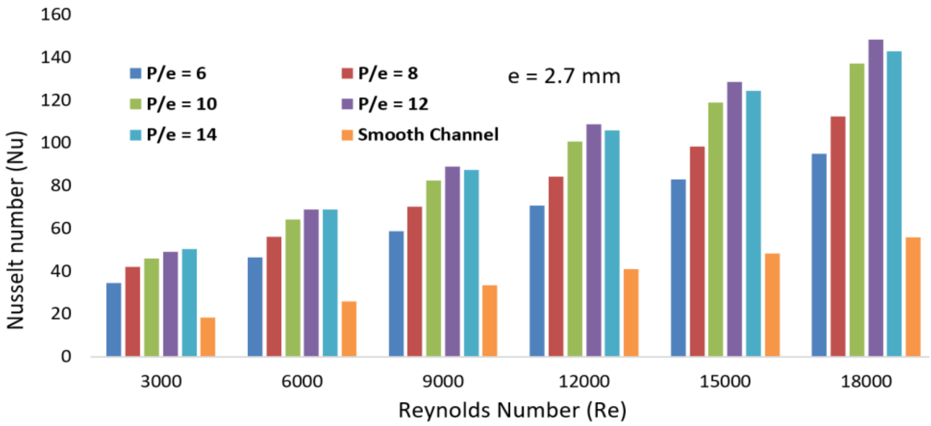

Figure 7. Obtained variations of Nusselt number at e = 2.7 mm

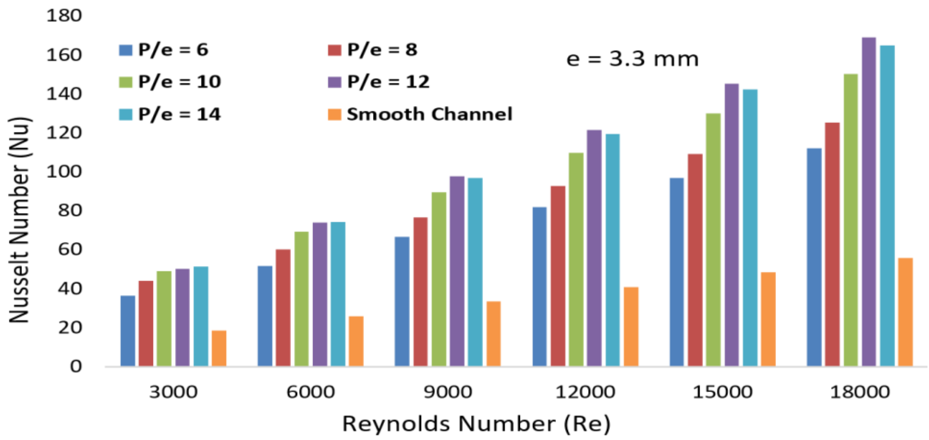

Figure 8. Obtained variations of Nusselt number at e = 3.3 mm

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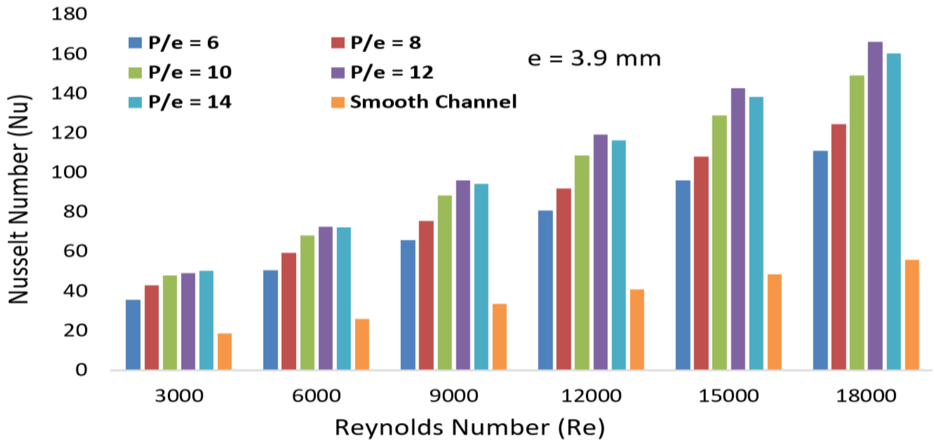

Figure 9. Obtained variations of Nusselt number at e = 3.9 mm

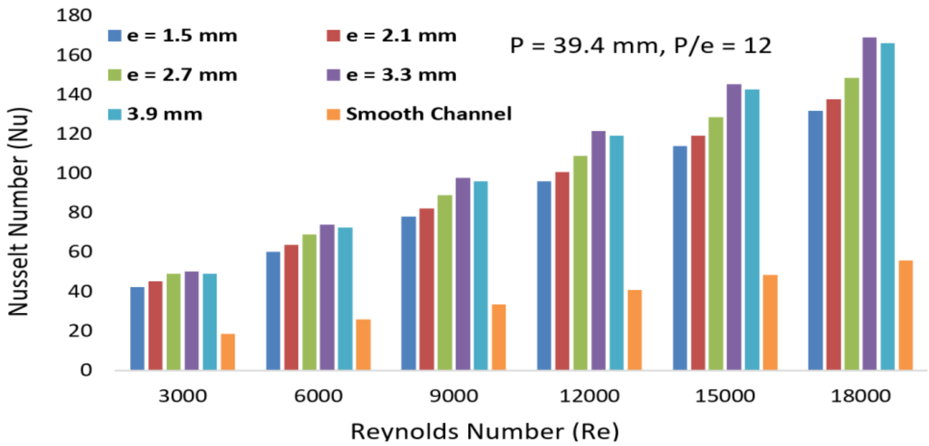

Figure 10. Obtained variations of Nusselt number at P = 39.6 mm

3.4. Friction Factor of Rectangular Duct

In the segment, friction factors are presented for use of multiple Fan shaped type solar heater's absorption frame's harshness, which would be dependent upon changes in coarseness with intervals. The friction factors are based on the turbulent flow due to irregular fluctuations fluid in the solar rectangular duct with high velocity that is transferred into high heat transfer enhancement and increased in the friction factor. In Figure 11, the friction factors depend upon the variation of the Reynolds number Re = 3000 - 18,000 and relative pitch roughness P/e = 6 – 14.

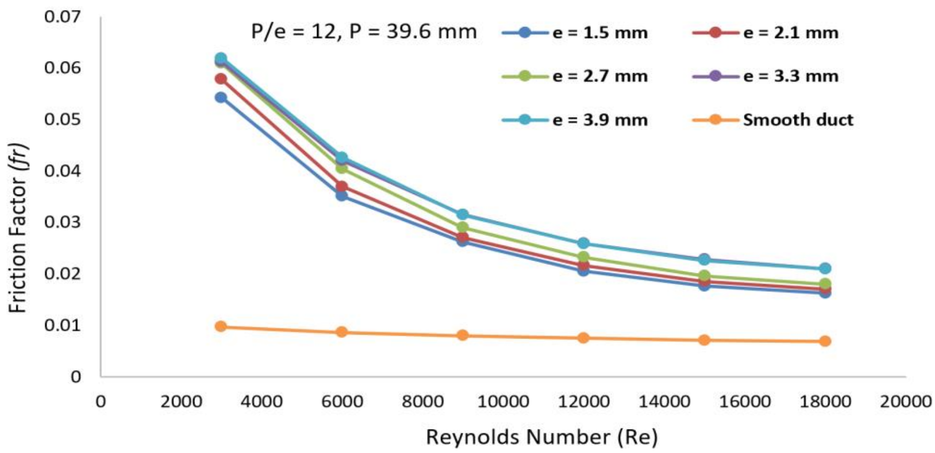

Figure 11. Expressed the friction factors at p/e = 12

4. Thermal-hydraulic Efficiency

Through the utilization of quantitative examination of heat exchange findings and friction variables, the objective of this study is to analyze the thermal hydraulic performance of a rectangular duct.

The operating fluid's turbulence fluctuating flow—increased overall hydrodynamic and thermal efficiency. The thermal performance graph has an important advantages to locate the condition that how much heat transfer rate is required to change the natural power into thermal performance and to reduce the global warming and this hydraulic also depends upon the circulation of the air around solar air heater with slit rib roughness for more effective process.

From this solution the thermal hydraulic performance is observed for p/e = 12 and at e = 3.3 mm, Re = 18000, and P = 39.6 mm, and multiple Fan shaped roughness. The above results we can see that when pitch spacing between the roughness increased then the Nusselt number also increased and now this design and its parameters are reasonable to obtain the maximum thermal performance η_{max} = 1.84 in figure 12.

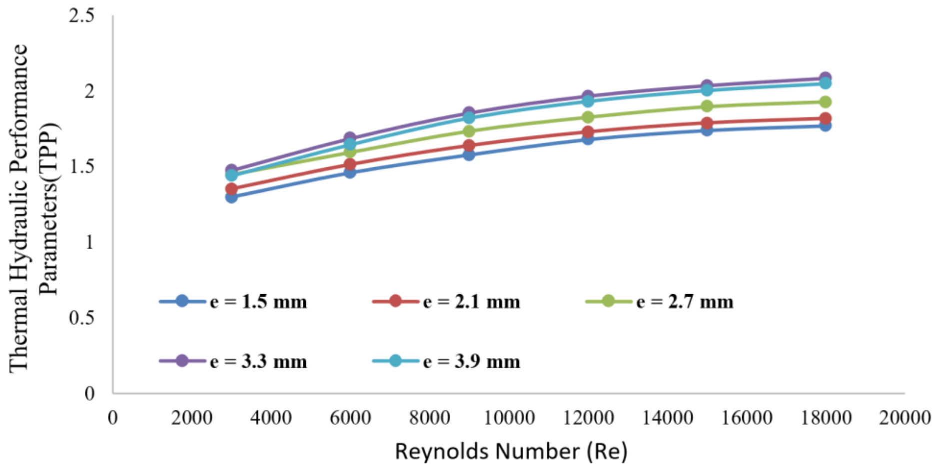

Figure 12. THP of Solar air heater with Roughness

5. Conclusion

The design and results of the solar rectangular channel are examined with the multiple Fan shaped roughness by the help of the computational fluid dynamics software that is called Ansys fluent. In the chapter conclusion is taken from the above numerical investigation and examined results, which is dependent on how many differences there were in the multiple Fan roughness and Reynolds number Re = 3000–18,000 are indeed the comparative pitch roughness values.

(1) The study of the solar rectangular channel is designed in the k-e model which provided more effective and accurate results near the boundary wall.

(2) All the results with efficiency of a duct improve as the fraction factor of roughness, Nusselt number, average fraction factors, or thermal efficiency.

(3) The Nusselt number increases with respect to the smooth channel at the increasing in the gap g = 17 mm, Re = 18,000, P/e = 12 and e/D=0.13.

(4) The conditions of mm P/e=7, with Re = 18000 and observed the minimum friction coefficient Fr=0.01664997.

(5) The highest thermal performance THPP = 1.849884051 at P/e = 12. P= 38.4 mm and Re=18,000.

5.1. Future Scope

1. Variations of Pitch space between roughnesses can be improved; 2. Heat transfer rate and focus on analyzing the full life cycle of solar air heater; 3. Systems and identifying ways to reduce their environmental footprint; 4. Thermal performance of HET can be maintained; 5. Friction factors can be decreased by using of variations in gaps of roughness 4s; 6. The number of gaps can be improved the rate of energy transfer.

Declarations

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This study did not receive any grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing Interests Statement

The authors declare no competing financial, professional, or personal interests.

Consent for publication

The authors declare that they consented to the publication of this study.

References

[1] Momin, A.M.E., Saini, J.S., & Solanki, S.C. (2002). Heat transfer and friction in solar air heater duct with V-shaped rib roughness on absorber plate. International Journal of Heat and Mass Transfer, 45(16): 3383–3396. https://doi.org/10.1016/s0017-9310(02)00046-7.

[2] Singh, S., Chander, S., & Saini, J.S. (2011). Heat transfer and friction factor of discrete V-down rib roughened solar air heater ducts. Journal of Renewable and Sustainable Energy, 3(1). https://doi.org/10.1063/1.3558865.

[3] Singh, H., Singh, H., & Kishore, C. (2022). CFD numerical investigation of Heat transfer characteristics of Y-shaped solar air heater. Materials Today: Proceedings, 52: 2003–2013. https://doi.org/10.1016/j.matpr.2021.12.007.

[4] Singh, H., Chavadaki, S., Kishore, C., Kumar, K.N., & Avikal, S. (2021). Numerical analysis of roughened solar air heater with arc and fan shape roughness to understand heat transfer and fluid flow characteristics. Materials Today: Proceedings, 46: 10662–10667. https://doi.org/10.1016/j.matpr.2021.01.399.

[5] Singh, H., Singh, H., Bahuguna, R., & Kishore, C. (2022). CFD analysis of heat transfer characteristics of rectangular solar air heater with kite shaped roughness. Materials Today: Proceedings, 52: 2014–2025. https://doi.org/10.1016/j.matpr.2021.12.008.

[6] Patil, A.K., Saini, J.S., & Kumar, K. (2012). Heat transfer and friction characteristics of solar air heater duct roughened by broken V-shape ribs combined with staggered rib piece. Journal of Renewable and Sustainable Energy, 4(1). https://doi.org/10.1063/1.3682072.

[7] Deo, N.S., Chander, S., & Saini, J.S. (2016). Performance analysis of solar air heater duct roughened with multigap V-down ribs combined with staggered ribs. Renewable Energy, 91: 484–500. https://doi.org/10.1016/j.renene.2016.01.067.

[8] Maithani, R., & Saini, J.S. (2016). Heat transfer and friction factor correlations for a solar air heater duct roughened artificially with V-ribs with symmetrical gaps. Experimental Thermal and Fluid Science, 70: 220–227. https://doi.org/10.1016/j.expthermflusci.2015.09.010.

[9] Singh, H., Kishore, C., Chamoli, S., & Joshi, A. (2024). Enhancing heat transfer in rectangular solar air heater channels: a numerical exploration of multiple Boomerang-shaped roughness elements with variable gaps. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 46(1): 6696–6712. https://doi.org/10.1080/15567036.2024.2354506.

[10] Kumar, A., Saini, R.P., & Saini, J.S. (2012). Experimental investigation on heat transfer and fluid flow characteristics of air flow in a rectangular duct with Multi v-shaped rib with gap roughness on the heated plate. Solar Energy, 86(6): 1733–1749. https://doi.org/10.1016/j.solener.2012.03.014.

[11] Sahu, M.K., & Prasad, R.K. (2016). Exergy based performance evaluation of solar air heater with arc-shaped wire roughened absorber plate. Renewable Energy, 96: 233–243. https://doi.org/10.1016/j.renene.2016.04.083.

[12] Alperen, Y., & Sertac, C. (2020). Multi objective optimization of a micro-channel heat sink through genetic algorithm. International Journal of Heat and Mass Transfer, 146: 118847. https://doi.org/10.1016/j.ijheatmasstransfer.2019.118847.

[13] Singh, H., Singh, D.P., Bahuguna, R., & Kishore, C. (2022). CFD simulation of thermal hydraulic performance of rectangular solar air heater with combination of boot rib roughness. Materials Today: Proceedings, 65: 3860–3865. https://doi.org/10.1016/j.matpr.2022.07.071.

[14] Tariq, A., Panigrahi, P.K., &Muralidhar, K. (2004). Flow and heat transfer in the wake of a surface-mounted rib with a slit. Experiments in Fluids, 37: 701–719. https://doi.org/10.1007/s00348-004-0861-8.

[15] Singh, P., Ji, Y., & Ekkad, S.V. (2018). Experimental and numerical investigation of heat and fluid flow in a square duct featuring criss-cross rib patterns. Applied Thermal Engineering, 128: 415–425. https://doi.org/10.1016/j.applthermaleng.2017.09.036.

[16] Sheikholeslami, M., Gorji-Bandpy, M., & Ganji, D.D. (2015). Review of heat transfer enhancement methods: Focus on passive methods using swirl flow devices. Renewable and Sustainable Energy Reviews, 49: 444–469. https://doi.org/10.1016/j.rser.2015.04.113

[17] Singh, H., Kishore, C., Chamoli, S., & Bhattacharya, S. (2024). Enhancing heat transfer in heat exchanger tube using four-shape cutting cone (FSCC) inserts: A numerical analysis. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 46(1): 52–74. https://doi.org/10.1080/15567036.2024.2382326.