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Enhancing Heat Transfer in Porous Media Systems through Finned Cylinders: An Experimental Investigation

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ABSTRACT

The present study shows finned cylinders increase porous medium heat transport. To promote heat dissipation, a porous material region with air-carrying tubes and internal heating devices evaluates different tube shapes and fin patterns. A study found that fins increase thermal exchange surface area, improving heat transfer. Additionally, staggered tube layouts function better than in-line ones. Fluid velocity, or Reynolds number, affects convective heat transfer efficiency, especially with fins. Comparing experimental methods and outcomes to previous studies proves reliability. The work gives us insights into heat transfer in porous materials and enhances industrial thermal management systems. Fins boost heat transmission by 55% in-line and 26% in staggered structures at a fixed Reynolds number. At low heat flux, the fins improve heat transfer by 71% for in-line designs and 139% for staggered designs. High heat flux reduces efficacy.

1. Introduction

Heat transfer is a fundamental topic in thermodynamics that has important ramifications in several sectors, including automotive and electronics [1]. The effectiveness of heat transfer processes has a direct impact on the performance, energy use, and sustainability of systems. This study investigates the improvement of heat transmission by strategically using cylinders with fins and incorporating porous media, with the goal of optimizing thermal management in various applications [2,3]. Enhancing heat transmission is essential for optimizing the efficiency and performance of thermal systems [4]. The idea of using finned cylinders as a means to augment the surface area for heat transfer, hence improving the rate at which heat is released [5]. Now day's investigations examine the possibilities of using cylinders with fins in situations including forced and natural convection. It emphasizes the significance of fin design, material selection, and positioning in order to achieve best performance [6].

Porous media give an extra dimension to improving heat transmission because of their intricate structure packed with pores or empty spaces [7]. The interplay between the movement of fluid and

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the presence of porous structures amplifies the contact area and generates turbulence, hence intensifying the combined impacts of convection and conduction heat transfer mechanisms[8]. Comprehending the fundamental principles of heat transmission processes, especially inside porous materials, is crucial for many applications such as extracting geothermal energy and achieving effective cooling in electronic equipment [9]. The importance of effective heat transfer in industry is emphasized, particularly in relation to its crucial role in energy generation, cooling of electronics, and automotive systems [10].

In systems that use fins inside porous media, the primary focus of improving heat transmission is centered on the mechanics of conduction and convection. Conduction is essential in these setups since it enables the flow of heat energy via the solid components of the system, namely the fins and the porous medium's matrix [11]. Fins, usually composed of materials with high thermal conductivity, efficiently disperse heat from heated surfaces towards cooler regions. The porous media facilitates this process by efficiently transferring heat through its solid matrix, which is influenced by its material composition [12]. The conduction is significantly increased at the interface where the fins are connected to the porous matrix, highlighting the crucial role of material selection and design in optimizing heat transfer efficiency [13]. Convection, however, is greatly affected by the fluid's flow through the porous medium and its movement around the fins. As the fluid passes through the system, it comes into contact with the fins and the porous structure, resulting in enhanced heat transfer. Fins cause turbulence in the flow, which reduces the thickness of the thermal boundary layer - a thin layer of fluid at the surface that functions as an insulator [14]. The decrease in the thickness of the boundary layer increases the convective heat transfer coefficient, resulting in improved efficiency in removing heat from the surface. In addition, the complex network of channels in the porous medium enhances the interaction between the fluid and the surface, hence intensifying the convective heat transfer process. The combination of conduction and convection in finned porous media systems work together to enhance heat dissipation, making them essential for designing effective thermal management solutions [15].

The experimental work explores heat transmission in an air duct system with a porous media zone and finned tubes with internal heaters. The study examines how in-line and staggered tube layouts and fins effect heat transfer coefficient under varied heat flux values and Reynolds numbers. This involves examining how fins on tubes improve heat transfer in various operational circumstances. The study also examines how Reynolds number-varying airflow dynamics affect heat transfer efficiency. Porosity of the medium affects the equilibrium between conductive and convective heat transfer processes in the system. This study aims to understand the parameters that optimize heat transmission in designed thermal systems to improve industrial design and operation. This study investigates the impact of Reynolds number (Re), heat flux, and pipe arrangement (in-line and staggered) on the performance of finned and non-finned tubes in porous media. The validation of the current work and its comparison to earlier work is also mentioned.

2. Methodology

The experimental setup, seen in Figure 1, includes a porous media zone that has a cross-sectional area of 0.4 m by 0.4 m and a length of 0.4 m. The air duct, through which the fluid air travels, has identical cross-sectional dimensions but is extended to a length of 1.2 m. This indicates that the porous medium occupies one-third of the duct's length. The tubes, with a diameter of 6 mm, are probably located within the porous media area and are fitted with fins and internal heaters. The inclusion of finned tubes with internal heaters inside the porous medium is essential for the heat transmission mechanism. The fins augment the surface area that encounters the air and the porous

medium, hence intensifying heat transfer. Thermal energy is produced within the tubes and transferred via the metal of the fins and tubes to the surrounding gravel and air. Heat transmission via convection is initiated by the temperature differential between the hot surfaces of the tubes and the colder air.

The gravel has a porosity of 0.42, which permits considerable but not unrestricted airflow across the porous zone. This implies that while there is extensive air-gravel interaction, the flow is somewhat limited, which may impact heat transfer rates. The heated air transmits thermal energy as it flows through the duct, ultimately departing at a greater temperature than the incoming air. The determination of the heat transfer coefficient, denoted as h, in this system requires considering the fin and porous medium shape, together with the air flow parameters. The flow regime inside the duct may vary from transitional to turbulent, depending on the selected Reynolds numbers, which range from 28063 to 14032. This variation has an impact on the efficiency of convective heat transfer. At higher Reynolds numbers, the heat transfer rate is increased owing to enhanced turbulence and air mixing. The given heat flux numbers (20700, 36713, 55069, 74973) indicate the quantity of heat energy delivered per unit area of the heaters. These numbers represent the system's ability to transfer thermal energy into the porous material under different operating circumstances. As the heat flow increases, there is a larger possibility for heat transmission, provided that the air can efficiently absorb and remove the heat.

Heat transfer coefficient h can be determined from the following expression [16]:

$$h = \frac{q}{T_w - T_b} \quad (1)$$

where the q is heat flux, T_w is finned tube wall temperature, T_b is bulk fluid temperature.

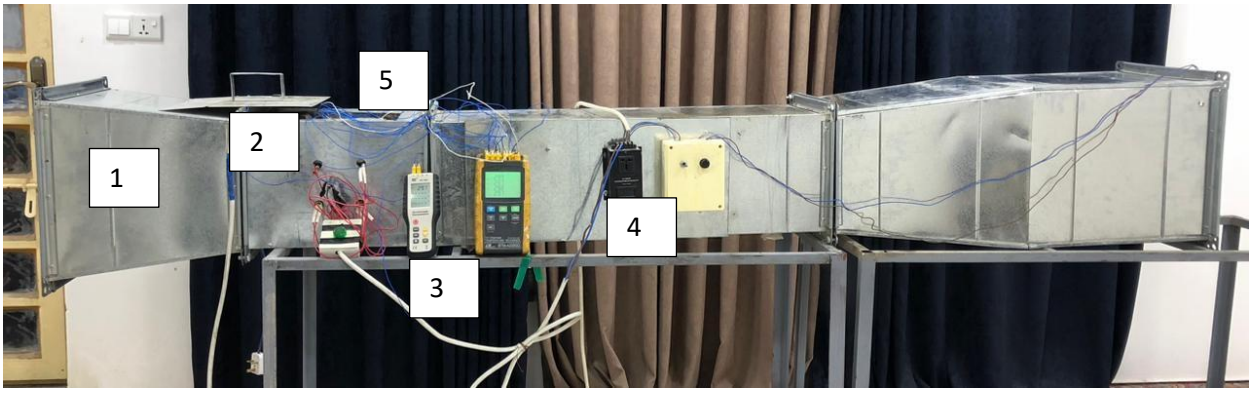
Reynolds number of fluid can be calculated as following:

$$Re = \frac{\rho\, Le\, U}{\mu} \quad (2)$$

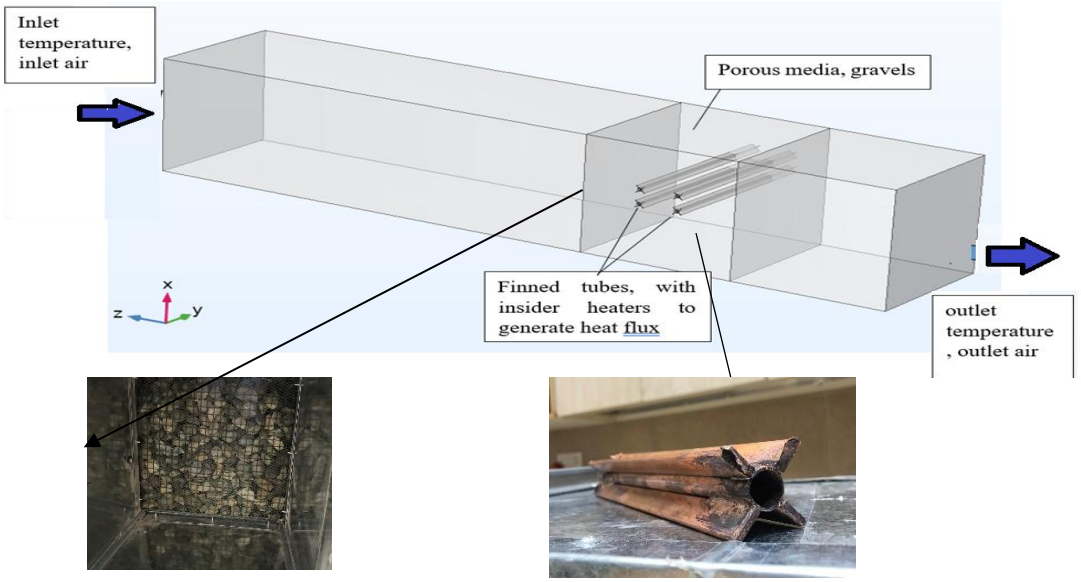
Where ρ and μ are air density and viscosity in film temperature, Le is duct diameter (square diameter), U is air flow velocity.

Where is the film temperature is:

$$T_f = \frac{T_w + T_b}{2} \quad (3)$$



a. Rig setup: 1. Air duct, 2. Porous media zone, 3. Temperature records and measurement devices , 4. Electric control device, 5. Thermocouples.



b. Flow diagram of preset work system.

Fig. 1. Experimental work setup

3. Results and Discussion

3.1 The Effect on Tubes Configurations

Figures 2 and 3 illustrate the correlation between the heat transfer coefficient (h, measured in W/m^2 K) and heat flux (measured in W/m^2) for tube geometries with and without fins, both at a Reynolds number (Re) of 18709. Figure 2 illustrates a situation without fins, where two configurations are being compared: in-line and staggered. Both arrangements exhibit a correlation in which the heat transfer coefficient rises in tandem with the heat flux. This suggests that as the amount of heat delivered increases, the tubes become more proficient in transmitting it. The staggered arrangement consistently exhibits a better heat transfer coefficient compared to the in-line design at the same heat flux, indicating that the staggered structure improves heat transmission. Figure 3 depicts the same connection, although with the inclusion of fins in the configurations. Additionally, the presence of fins has a positive correlation with the heat transfer coefficient, indicating a rise in its value as the heat flow increases. Compared to the situation when there are no fins, the staggered arrangement performs better than the in-line arrangement in terms of all observed heat flow values, resulting in a greater heat transfer coefficient. By including fins, the accessible surface area for heat transmission is augmented, leading to an overall increase in the heat transfer coefficient. The comparison of the vertical scales of Figures 2 and 3 reveals that the heat transfer coefficients in Figure 3 are often greater than those in Figure 2. This suggests that the presence of fins improves the heat transfer capacity of the tubes.

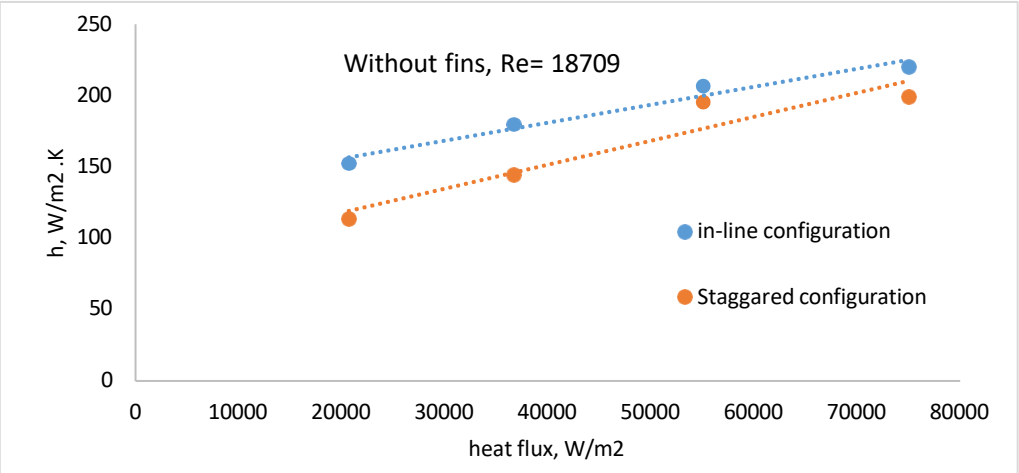


Fig. 2. Heat transfer coefficient vs. heat flux for various tubes configuration without using fins

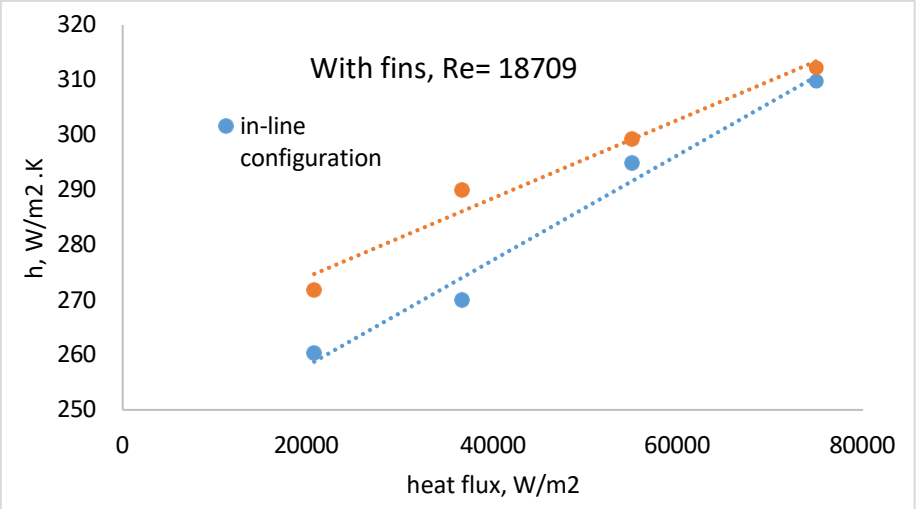


Fig. 3. Heat transfer coefficient vs. heat flux for various tubes configuration with using fins

The greatest improvement in heat transfer achieved by increasing the heat flow for each scenario is as follows:

- The addition of fins in the in-line design leads to an estimated 55% enhancement in the heat transfer coefficient.
- The addition of fins in the staggered design leads to a significant enhancement of around 26% in the heat transfer coefficient.

3.2 The Effect on Tubes Fins

Figure 4 depicts the percentage enhancement in heat transfer resulting from the use of fins on tubes, in comparison to a baseline configuration without fins, that extend a range of heat flux values. The data is shown for two distinct tube designs, namely in-line and staggered, while maintaining a constant Reynolds number. At lower heat flux levels, both layouts initially show a substantial increase in heat transfer, as demonstrated by the high percentages. This indicates that fins are more efficient when dealing with lower levels of thermal loads, most likely because they enhance the available surface area for heat transmission. As the heat flow rises, the effectiveness of fins starts to diminish for both layouts. This phenomenon may be explained by several variables, including the diminished influence of extra surface area in situations of intense heat flow or the thermal saturation of the

fins. The staggered structure consistently exhibits a greater improvement than the in-line configuration over the whole range of heat flux investigated. The superiority of the staggered configuration in terms of performance may be attributed to its improved fluid mixing and turbulence, resulting in enhanced efficacy of convective heat transfer. At higher heat flux levels, the improvement percentages for both designs come together, indicating that the fins become less effective as the heat flux rises. This phenomenon may occur when the heat transfer process is primarily influenced by the thermal characteristics of the fluid and the material of the tubes, rather than the surface area given by the fins. In the in-line design, the greatest improvement is seen at the lowest heat flux value of 20700 W/m^2, resulting in a 71% boost. As the heat flow rises, the percentage of improvement drops, suggesting that the in-line design is most advantageous for using fins at lower heat fluxes. In the staggered design, the greatest improvement is shown at the lowest heat flux of 20700 W/m^2, with a notably greater increase of 139%. The enhancement drops as the heat flow rises, but the staggered arrangement maintains an enhancement over 50% until a heat flux of 55069 W/m^2. After that, it marginally increases to 57% at a heat flux of 74973 W/m^2.

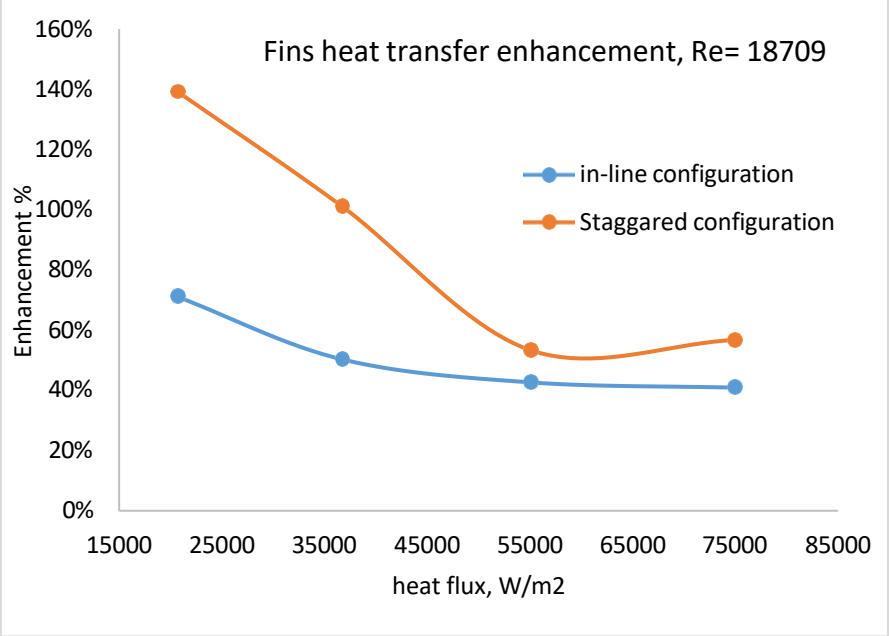


Fig. 4. Fins aid heat transfer enhancement vs. heat flux for various tubes configuration with using fins

3.3 The Effect on Rynolds Number

Figures 5 and 6 depict the relationship between the heat transfer coefficient and the Reynolds number for tube designs without and with fins, respectively. These figures are based on a constant heat flux of 55069 W/m^2. Both pictures depict curves for in-line and staggered setups. In Figure 5, Without fins, both layouts exhibit a rise in the heat transfer coefficient with increasing Reynolds number. Nevertheless, the pace of growth is very gradual. This outcome is anticipated because higher Reynolds numbers correspond to increased fluid velocities, which typically augment the convective heat transfer. The staggered form exhibits a somewhat elevated heat transfer coefficient in comparison to the in-line configuration, most likely because to the enhanced fluid turbulence around the tubes, hence augmenting the convective heat transfer. In figure 6, As the Reynolds number rises, the heat transfer coefficient for both designs experiences a more significant enhancement with the addition of fins. Once again, the staggered arrangement demonstrates greater heat transfer coefficients compared to the in-line arrangement when Reynolds numbers are equal. This suggests

that fins greatly improve the transmission of heat, particularly as the speed of the fluid rises. This observation aligns with the idea that fins provide more surface area for heat transfer. The significant rise in the heat transfer coefficient, as depicted in Figure 6, is related to the heightened turbulence intensity linked to high Reynolds number values. The relationship highlights the direct influence of higher fluid velocity on turbulence in the system, resulting in a substantial enhancement of heat transfer efficiency.

This behavior indicates the existence of a porous media in the system. This shows that at low velocities, heat transmission is primarily regulated by conduction inside the porous medium. Porous media may augment heat transfer at lower fluid velocities by increasing the available surface area and promoting localized mixing. This can offset the diminished convective effects seen at lower Reynolds numbers. Therefore, it is possible that we will not see a significant variation in the heat transfer coefficient at lower Reynolds numbers in both figures. In Figure 5, the absence of fins and the inclusion of porous media might explain the comparatively flat curves seen at lower Reynolds numbers. The heat transmission is mostly influenced by the conduction through the solid matrix of the porous medium, rather than the fluid velocity. Figure 6 demonstrates that the presence of fins leads to a significant improvement, yet the underlying idea remains same. The fins are expected to extend into the porous medium, so enhancing the effective surface area for conduction and consequently the total heat transfer coefficient, irrespective of the rise in fluid velocity as indicated by the Reynolds number. Overall, both data sets indicate that when a porous medium is present, the impact of fluid velocity on heat transfer is less significant at lower Reynolds numbers. At elevated Reynolds numbers, the augmented fluid velocity and the existence of fins have a substantial impact on the convective heat transfer, as seen by the more pronounced inclines of the curves in Figure 6. The staggered arrangement consistently performs better than the in-line arrangement at the same Reynolds numbers, regardless of the presence of fins. This is because the staggered structure promotes improved mixing and turbulence.

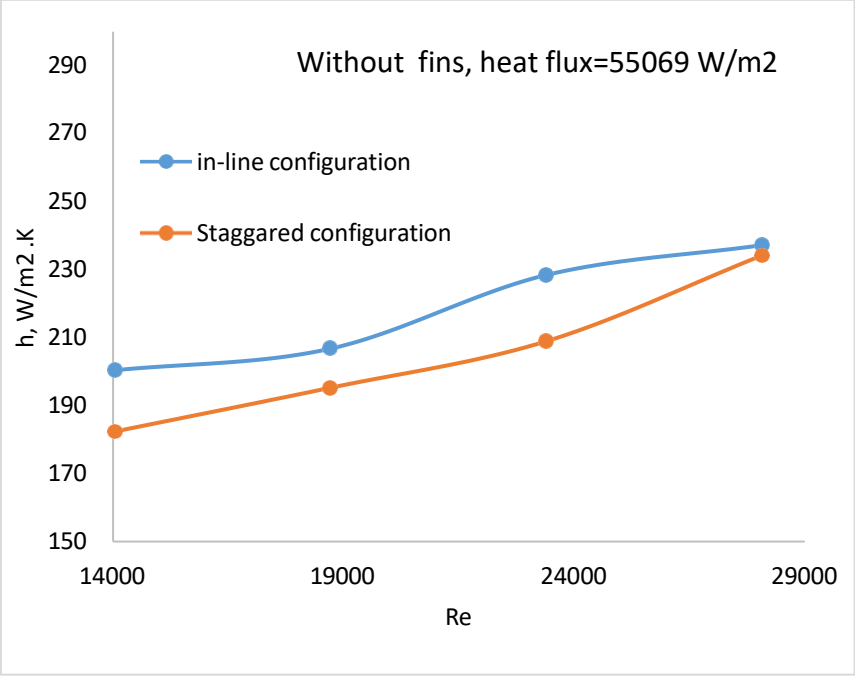


Fig. 5. Heat transfer coefficient vs. Reynolds number for various tubes configuration without using fins

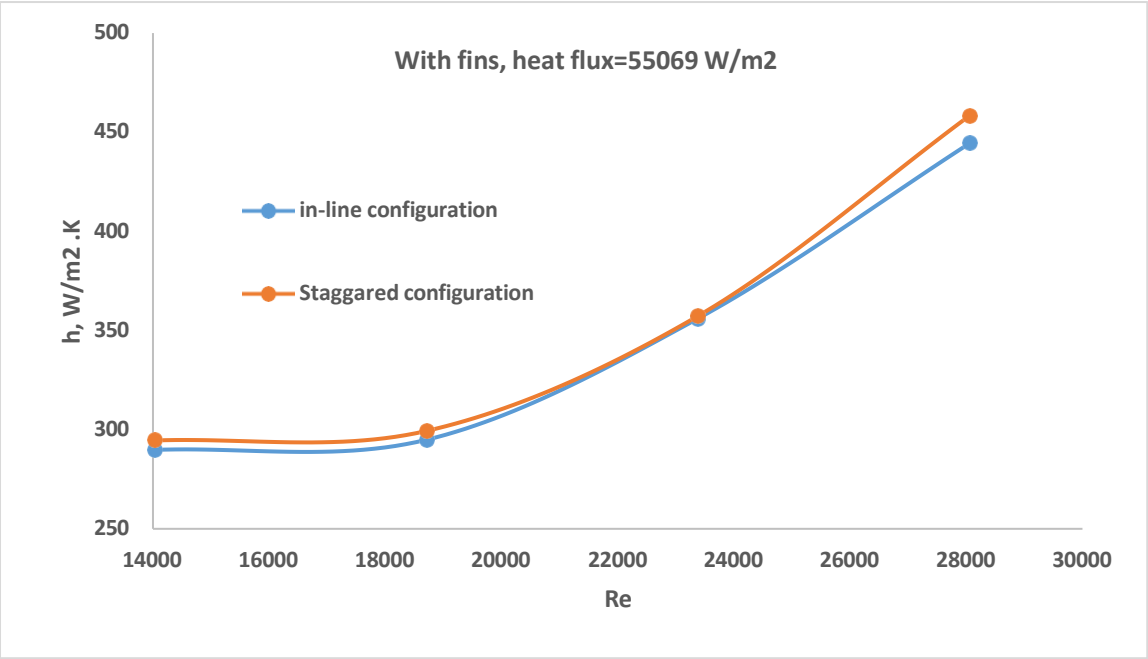


Fig. 6. Heat transfer coefficient vs. Reynolds number for various tubes configuration with using fins

Figure 7 illustrates a comparative examination of the improvement in heat transfer caused by fins at different Reynolds numbers for in-line and staggered tube arrangements, with a constant heat flux of 55069 W/m^2. The graph clearly illustrates a clear pattern: initially, as the Reynolds number grows, there is a significant drop in improvement for both configurations, which may be ascribed to a change in the dynamics of the flow. This indicates that at lower speeds, the fins greatly enhance heat transmission by increasing the surface area. As the fluid velocity increases, the turbulence and chaotic mixing of the fluid reduce the relative effectiveness of the fins, resulting in a decrease in enhancement. As the Reynolds number increases, the heat transfer improvement for both designs starts to increase, suggesting a renewed effectiveness of the fins. The increase in fluid velocities leads to a positive effect where the fins work along with the turbulent flow to improve the transfer of heat by convection, thus compensating for the initial decrease.

The staggered layout regularly demonstrates higher enhancement percentages compared to the in-line configuration over the entire range of Reynolds numbers. The difference is most evident in the intermediate region of the Reynolds numbers, highlighting the staggered configuration's ability to use turbulence caused by the fins to enhance heat transmission. At higher Reynolds numbers, the curves for both designs seem to come together. This trend indicates that at high fluid velocities, the difference in fin performance across tube arrangements becomes less significant. This might be because the fluid turbulence is already at its maximum, reducing the impact of the tube arrangement.

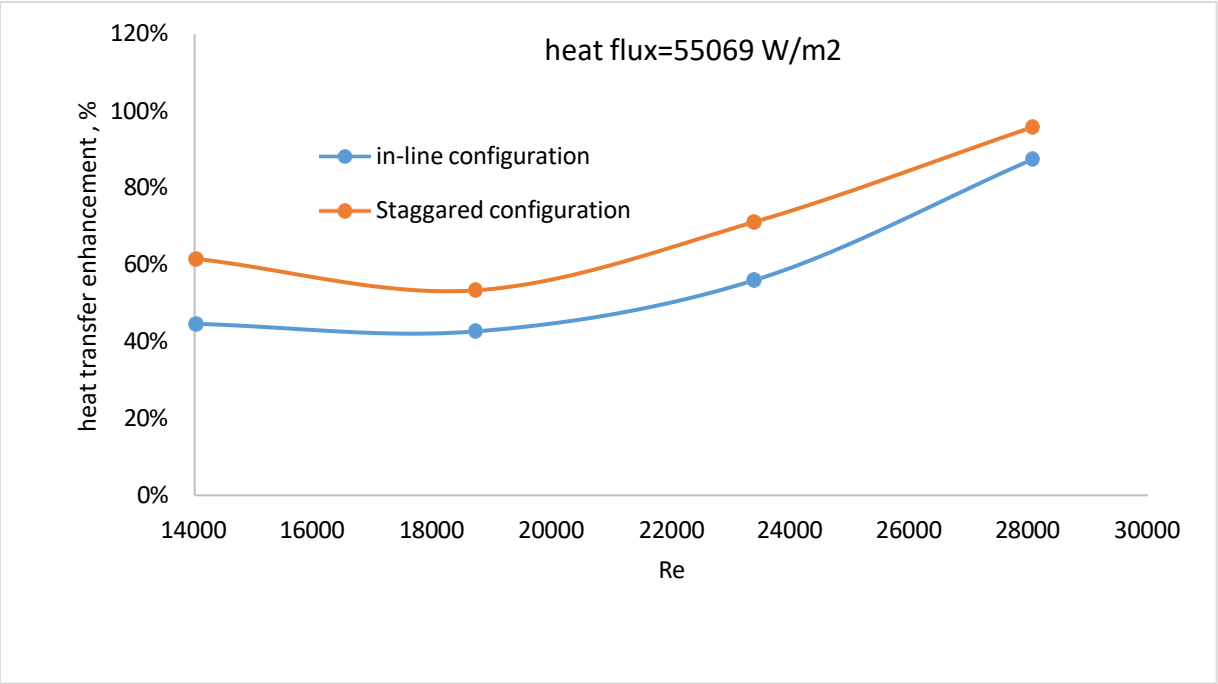


Fig. 7. Fins aid heat transfer enhancement vs. Rynolds Number for various tubes configuration with using fins

The highest increase of heat transmission resulting from the increase in Reynolds number (Re) for each configuration is as follows:

- When using fins in the in-line design, the heat transfer coefficient experiences a significant rise of roughly 74.07% at the maximum Reynolds number.
- At the greatest Reynolds number, the heat transfer coefficient for the staggered arrangement with fins experiences a 100% rise.

3.4 The Effect of Porosity

The heat transfer properties of a medium are greatly affected by its porosity, since it changes the equilibrium between conduction and convection processes. A higher porosity often results in a larger surface area inside the medium, allowing more contact between the fluid and the solid structure. This increased contact may improve the pace at which heat is transferred. The presence of voids in porous medium enhances fluid flow, leading to increased convective heat transfer when the flow breaks the thermal boundary layers. Additionally, the gaps contribute to a greater surface area across which heat may be transferred. In addition, the intricate paths created by the porous structure may generate localized turbulence and thermal dispersion, so enhancing fluid mixing and perhaps increasing the effective thermal conductivity. The impact of porosity on the total heat transfer coefficient depends on several aspects, such as the shape of the porous material, characteristics of the fluid, flow circumstances, and the particular porosity range being studied. In order to effectively measure this connection, it is necessary to conduct thorough experimental investigations or computer simulations that are specifically designed for the specific configurations of the heat transfer system being studied.

3.5 Previous Work Validation

Figures 8 and 9 provide a graphic depiction of a comparison analysis, showing the current work alongside previous work[16]. The results for a staggered layout, as shown in Figure 8, provide a

significant level of concurrence with previous work, particularly evident at lower heat fluxes. This indicates that even subjected to less intense temperature conditions, the staggered design in the current study maintains the patterns found by Ali. In contrast, Figure 9, illustrating the in-line layout, portrays a connection that is more divergent. The level of agreement varies over the range of heat flux. At lower levels, the current study's results seem to agree with Ali's, as seen by the overlapping data points. Nevertheless, when the heat flow intensifies, the divergence becomes more evident, suggesting possible inconsistencies that may be attributable to several variables, including experimental circumstances, measurement accuracy, or disparities in material characteristics and configuration. The high level of agreement obtained in the staggered layout may be due to the increased mixing effects and turbulence often associated with such arrangements. These factors improve the predictability of the heat transfer mechanism, aligning it closely with earlier research. On the other hand, the in-line structure, which usually leads to a smoother flow, may be more responsive to small changes in experimental or simulation circumstances, resulting in the increased variability seen at higher heat fluxes.

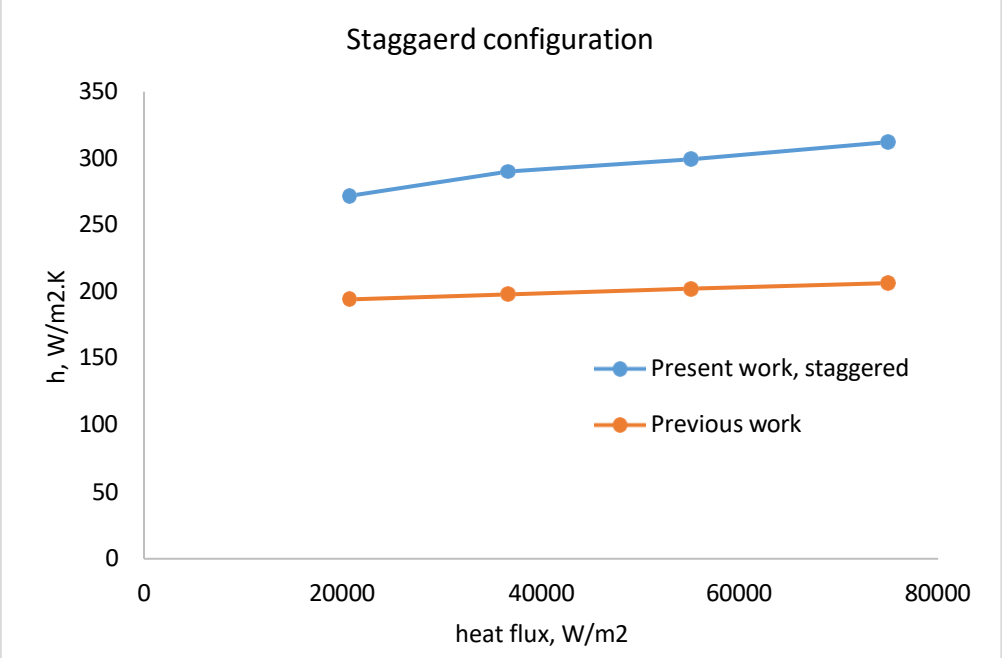


Fig. 8. The validation of present work with previous work [16] , staggered configuration

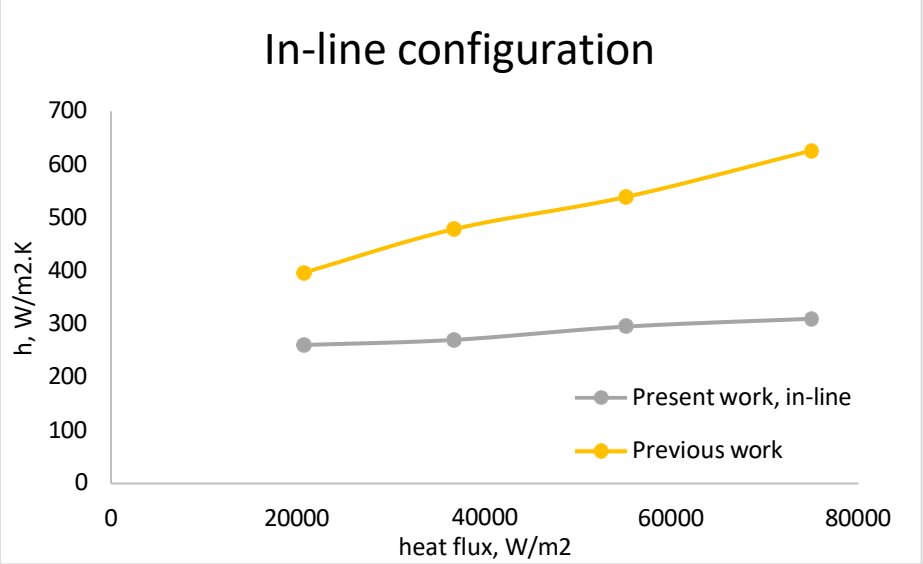


Fig. 9. The validation of present work with previous work [16], in-line configuration

4. Conclusions

This experimental study investigates the impact of tube shapes, the addition of fins, and variations in Reynolds numbers on heat transfer within a system incorporating a porous media zone connected to an air duct. The key findings are:

1. **Presence of Fins**: Fins significantly enhance heat transfer by increasing the surface area available for thermal exchange. This enhancement is more pronounced with staggered tube layouts as opposed to in-line arrangements, indicating a higher effectiveness in heat transfer.
2. **Staggered vs. In-Line Layouts**: Staggered layouts consistently outperform in-line setups in terms of heat transfer efficiency, regardless of the heat flux levels. The staggered design, with its superior fluid mixing and turbulence, demonstrates better performance, especially when fins are present.
3. **Effect of Reynolds Numbers**: The heat transfer coefficient increases with Reynolds numbers in both in-line and staggered configurations, regardless of the presence of fins. The increase is more pronounced in systems with fins, highlighting the synergistic effect of higher fluid velocity and the thermal benefits of fins.
4. **Impact of Porous Media**: The inclusion of a porous medium proves crucial, particularly at lower fluid velocities indicated by Reynolds numbers. It enhances heat transmission at lower velocities by increasing the surface area and promoting localized mixing, which compensates for the reduced convective effects seen at lower Reynolds numbers.
5. **Comparative Review**: A comparison with previous research confirms the superior performance of staggered layouts, particularly at lower heat flow levels, suggesting that these designs enhance mixing effects and turbulence, resulting in more reliable and consistent heat transfer. Conversely, in-line structures show more variation, especially at higher heat flow levels, possibly due to their sensitivity to experimental conditions or other variables.

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