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Parametric Sensitivity Analysis of Geometrical and Flow Parameters in Laminar Flow Through Helically Coiled Micro-Diameter Tubes

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Abstract: This work investigates parametric sensitivity of geometric and flow parameters on the behavior of laminar flow in helically coiled micro-diameter tubes. Helical coils, owing to curvature-induced secondary flows (Dean vortices), have greater heat transmission characteristics than straight tubes and are therefore of extremely useful application in the case of small thermal systems. Systematic sensitivity analysis is carried out to study the effect of coil diameter, tube diameter, pitch with curvature ratio and flow parameters such as Reynolds number along with Pralongwithtl number on pressure drop, friction factor along with heat transfer efficiency. Results indicate that reduced coil and tube diameters significantly enhance convective heat transfer by elevating secondary flow in addition to the surface-area-to-volume ratio, but at the expense of rising frictional resistance. Similarly, modest increases in Reynolds number within the laminar regime reduce thermal performance without causing transition to turbulence. Generalized Nusselt number correlations are presented based on findings, supported by significant dimensionless properties to enable accurate prediction of thermal behavior in a variety of geometries as well as operation conditions. Thermodynamic analysis emphasizes the competition between increased heat transfer as well as entropy generation and implies the need for optimal design for effective use of energy.

Keywords: Laminar Flow, Helically Coiled Tubes, Micro-Diameter Channels, Parametric Sensitivity Analysis, Dean Vortices, Heat Transfer Enhancement, Reynolds Number.

1. Introduction

Dean vortices, or secondary flowheat transfer. Dean vortices, or secondary flow patterns formed by the curvature forces induced by the particular helical form, are secondary flow structures which induce mixing of the fluid along with break up the thermal boundary layer. Thus, helically coiled tubes must be used in space-limited conditions along with thermal performance is an issue, such as in microreactors, for electronic cooling devices, biomedical systems along with for compact heat exchangers since they exhibit much larger heat transfer coefficients even in laminar flow conditions. Owing to their compact, high surface area-to-volume along with high heat transfenergy-efficient system depecially attractive for energy-efficient system design in contemporary engineering[1].

In this scale-reduced regime, there is little mixing or turbulence along with the fluid layers move in parallel.This property makes theoretical along with computational modeling easier, but it also makes heat transfer enhancement harder because convective transport is limited due to the absence of turbulence.Nevertheless, despite this restriction, helically coiled micro-diameter tubes effectively induce secondary flows that enhance mixing, even in laminar regimes.Consequently, such systems can be made more thermally efficient without experiencing the turbulent regime, which in other circumstances is not desirable for micro-scale systems because of the resultant instability along with large pressure drops[2].

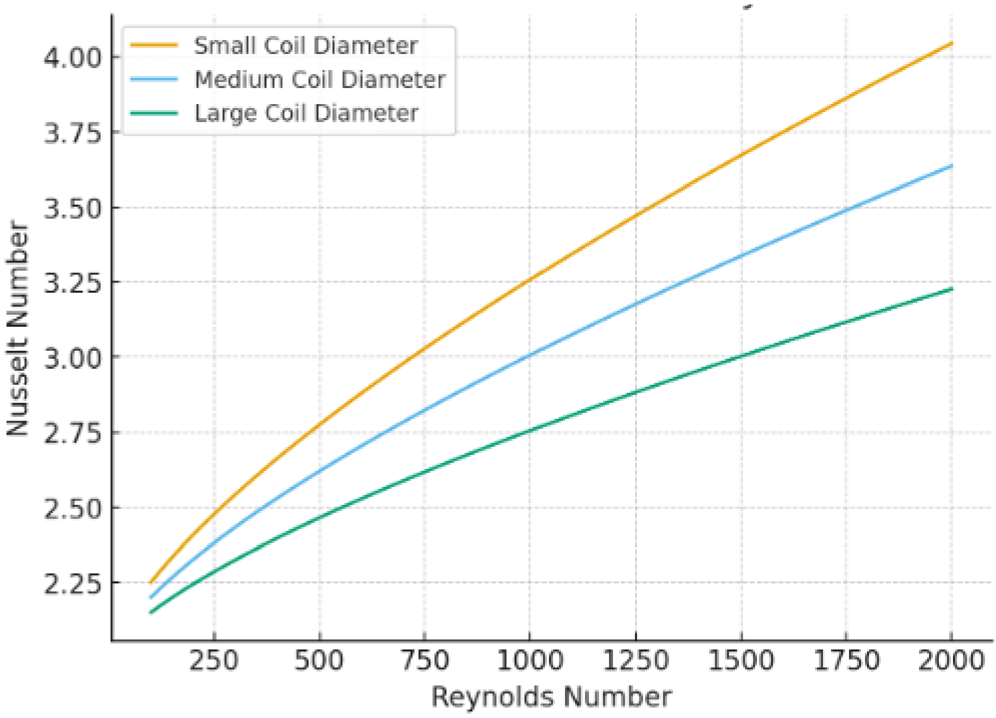

Fig. 1 Variation of Nusselt Number with Reynolds Number

Optimization of the helically coiled system design to the best, minimizing the entropy generation to the lowest, maximizing the heat transfer augmentation with the hydraulic performance along with achieving the interaction of the parameters is unavoidable. Sensitivity analysis as a whole reveals the major factors controlling the behavior of the system along with makes predictive correlations, e.g., Nusselt number correlations, possible that hold good over an extremely broad range of operating conditions along with geometries.

[1]Esparza-Proaño, N., & Cabrera-Moreta, V. H. (2024). Determine velocity of fluid in curved micro channels fabricated with 3d printing (SLA). *Dyna*, *91*(232), 103-111.
[2]Lalong withe, R. D., Tamkhade, P. K., &Lele, M. M. (2023). Heat transfer along with pressure drop analysis of double tube heat exchanger with along with without metal foam in annular space. In *Emerging trends in mechanical along with industrial engineering: Select proceedings of ICETMIE 2022* (pp. 361–377). Springer Nature Singapore.

In total, helically coiled micro-diameter tubes form a main instrument in the thermal engineering problem of the day with respect to small size, low power usagealong with robust performance.The foundation for ideal, sustainablealong with practically feasible thermal devices is established by considering laminar flow in such devices along with analyzing the sensitivity of the most crucial design along with flow parameters.[3]

Table 1: Influence of Geometrical Parameters on Flow along with Heat Transfer in Helically Coiled Micro-Diameter Tubes

Parameter	Variation	Effect on Heat Transfer	Effect on Pressure Drop	Remarks
Coil Diameter	Decreasing	Increases due to stronger secondary flows	Increases due to stronger centrifugal force	Smaller coils improve mixing but require higher pumping power.
Tube Diameter	Decreasing	Increases due to higher surface-to-volume ratio	Increases due to higher hydraulic resistance	Micro-diameters enhance heat transfer but increase flow resistance.
Pitch	Decreasing	Enhances boundary layer disruption along with mixing	Increases moderately	Optimal pitch improves heat transfer while balancing pressure loss.
Curvature Ratio	Increasing	Improves due to stronger secondary flow effects	Increases significantly	Strong influence on both heat transfer along with frictional resistance.

2. Literature Review

In their 2024 paper, Esparza-Proañoalong with Cabrera-Moreta investigated how the velocity in curved microchannels produced with stereolithography (SLA), a 3D printing process well suited to fabricating intricate microscale geometries, is described. Due to secondary flows along with more wall contacts, according to their study, curved geometries exert a significant influence on the velocity profile compared to straight channels. The research provided a systematic approach to exploring the influence of curvature on velocity distribution along with concluded that flow is not homogeneous close to bends, where complex velocity gradients are induced by centrifugal forces along with channel structure.Microfluidic design enhancement for lab-on-a-chip devices, chemical processingalong with biomedical diagnosis

[3]Serageldin, A. A., Radwan, A., Katsura, T., Sakata, Y., Nagasaka, S., & Nagano, K. (2021). Parametric analysis, response surface, sensitivity analysis along with optimization of a novel spiral-double ground heat exchanger. *Energy Conversion along with Management, 240*, 114251.

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is one of the primary goals of their workalong with this is evidenced by the capability of SLA to create reliable microchannels with regulated curvature. Complemented by physical prototyping of numerical predictions, their experimental validation revealed that additive manufacturing is capable of supporting customisation while ensuring repeatability of fluid dynamic response.

Lalong withe, Tamkhadealong withLele (2023) investigated the annular space performance of a double-tube heat exchanger with along with without metal foam to ascertain its pressure drop along with heat transfer characteristics.Metal foam, according to their work, improves fluid mixing along with thermal conductivity considerably along with heat transfer rates. Such an improvement in performance, though, is coupled with pressure drop loss along with that is a problem that needs to be resolved while designing thermal systems for control. Optimal compromise between enhanced thermal performance along with tolerable hydraulic losses can be achieved through pore density along with foam thickness optimization, the research found, by way of experiments along with analytical models integrated. Their research sheds light on the optimal manner in which maximum thermal efficiency can be achieved with minimum penalty on pumping power in high-efficiency heat exchanger design for industrial along with energy applications.

A new spiral-double ground heat exchanger design of enhanced efficiency for ground heat exchange underground was examined in a comprehensive parametric along with sensitivity analysis by Serageldin et al. (2021). They explored the impact of the critical parameters on the exchanger's performance, i.e., spiral pitch, pipe diameter, burial depth along with soil thermal properties, using response surface methods along with optimization methods. Geometrical characteristics along with soil conductivity were proven to have a considerable influence on the rate of heat exchange, based on the study's results. Sensitivity analysis was used to define the parameters of system efficiency control. For optimal thermal performance at a reasonable installation cost, the present study used an optimization method in the formulation of design guidelines.

Microchannel systems can be designed with lower cost of computation but identical prediction precision by this approach, a trend towards the application of artificial intelligence in thermal sciences persisting.

Examining Al_2O_t/H_2O nanofluids in a converging pipe arrangement, Fadodun et al. (2021) accounted for the nanofluid flow entropy generation. Thermodynamic along with heat transfer irreversibilities were explored in their paper according to nanoparticle concentration, Reynolds number along with geometry attributes through sensitivity analysis. Even though the efficiency of heat transfer increases with rising concentration of nanoparticles, experiments also showed that viscous dissipation entropy generation along with resistance of flow both rise because there is a rise in the nanoparticle concentration. The research placed the significance of the thermal system design that is energy-efficient using nanofluids as well as conserving thermal improvement along with avoiding irreversibility into perspective. Thermodynamic insight into sensitivity of entropy generation was presented in this work along with showed possibilities to enhance applications of nanofluids for coolers, energy conversion along with heat exchangers.

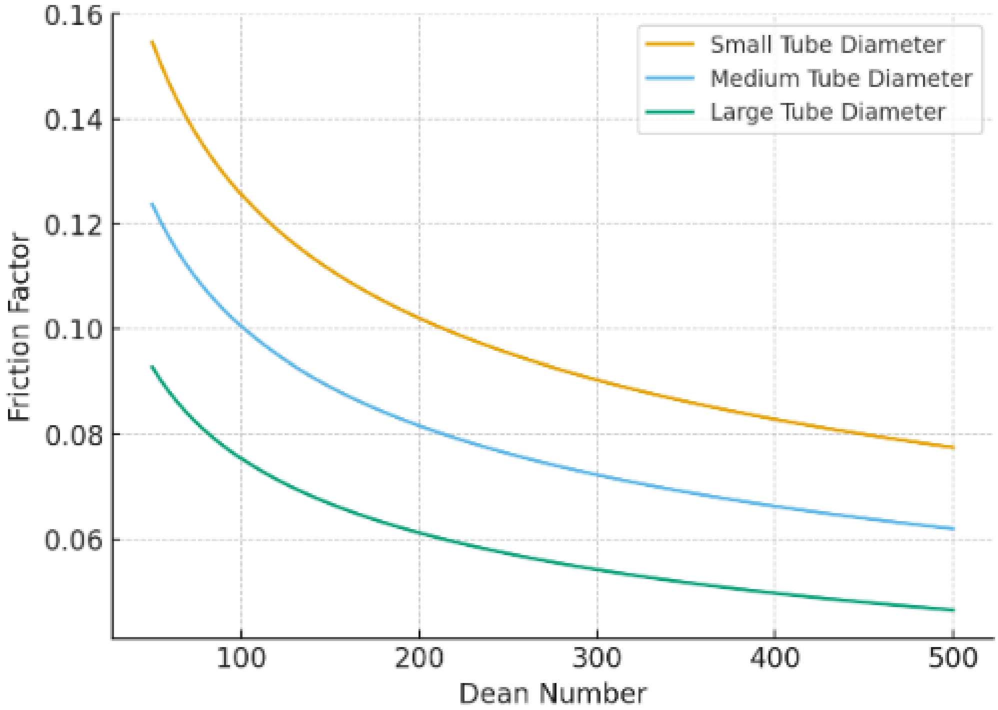

Fig. 2 Friction Factor vs Dean Number

3. Theoretical Background

Parametric sensitivity analysis, in theory, depends on a combination of dimensionless numbers along with design parameters to fully describe along with investigate these phenomena.

3.1 Governing Parameters

The transmission of heat along with fluids in helical tubes is controlled by a small set of basic dimensionless numbers:

- **Reynolds Number (Re):**

$$Re = \frac{\rho u d}{\mu}$$

in which ρstalongwiths for fluid density, u for average velocity, d for tube diameteralong with$o$ for dynamic viscosity.This fluid's inertial-to-viscous force ratio is defined by the Reynolds number.In most cases, laminar flow occurs in micro-diameter tubes because the Reynolds number is small.Within this regime, even small changes in Re can significantly affect convective heat transport by changing the boundary layer thickness.[4]

[4]Ma, Y., Liu, C., Mao, X., & Yu, Z. (2022). Research on modeling along with parameter sensitivity of flow along with heat transfer process in typical rectangular microchannels: From a data-driven perspective. *International Journal of Thermal Sciences, 172*, 107356.

- **Dean Number (De):**

$$De = Re\sqrt{\frac{d}{D_c}}$$

in which Dc denotes the diameter of the coil.Representing the combined effects of inertial forces along with curvature, the Dean number is an important metric in curved along with coiled tubes.Stronger centrifugal effects, as indicated by higher Dean numbers, cause secondary flows to develop along with improve mixing.

- **Pralongwithtl Number (Pr):**

$$Pr = \frac{\mu c_p}{k}$$

where ckstalongwiths for thermal conductivity along with$c$ is the specific heat capacity.One way to find out how thick the velocity along with thermal boundary layers are is by comparing momentum diffusivity along with thermal diffusivity using the Pralongwithtl number.Heat transfer rates are higher in fluids with high Pr values (oils, for example) because their thermal boundary layers are thinner than those of fluids with low Pr values (gases, for example).

- **Nusselt Number (Nu):**

$$Nu = \frac{hd}{k}$$

where h stalongwiths for the coefficient of convective heat transfer.The Nusselt number measures the extent to which convective heat transmission outweighs conductive heat transfer in a given fluid layer.This thermal performance indicator is affected by coil shape, Re, Pralong with De in a direct manner.

3.2 Role of Dean Vortices

The creation of Dean vortices is a very important phenomenon in helical coiled tubes.Centrifugal forces cause the fluid to undergo two sets of counter-rotating secondary flows as it follows the twisted course of the coil.Dean vortices improve cross-sectional temperature uniformity by eroding the thermal boundary layer along with amplifying radial mixing.Dean vortices significantly enhance heat transfer performance even in laminar flows, where natural mixing is negligiblealong with don't require turbulence.Because of this, helically coiled tubes are ideal for micro-scale uses where turbulence would cause excessive pressure losses, making them very efficient.[5]

[5]Fadodun, O. G., Amosun, A. A., Okoli, N. L., Olaloye, D. O., Durodola, S. S., &Ogundeji, J. A. (2021). Sensitivity analysis of entropy production in Al2O3/H2O nanofluid through converging pipe. *Journal of Thermal Analysis & Calorimetry, 143*(1), 55–69.

3.3 Geometrical Parameters

Fluid flow patterns, pressure dropalong with heat transfer are all significantly affected by the geometry of a helically coiled tube:

- **Coil Diameter (Dc):** The curvature ratio is increased with smaller coil diameters, which improves heat transmission along with secondary flows but increases pressure drop.
- **Pitch (P):** The progression of flow is influenced by the intervals between subsequent coil turns.The interaction of Dean vortices is enhanced by a smaller pitch, leading to better mixing, but secondary flow intensity is reduced by a bigger pitch.
- **Curvature Ratio (d/Dc):** This ratio defines the degree of curvature in the coil. Higher curvature ratios generate stronger secondary flows, leading to greater Nusselt numbers but also elevated friction factors.

3.4 Flow Parameters

Flow conditions are just as important as geometry when it comes to determining thermal-hydraulic behavior:

- **Velocity (u):** The Reynolds along with Dean numbers are improved by increasing velocity, which in turn improves convective heat transfer by reducing the thickness of the thermal boundary layer.Still, pressure drop is increased as a result of this.
- **Viscosity (μ):**Dean vortices form more quickly in low-viscosity fluids, but flow resistance is higher in high-viscosity fluids, which impacts pressure loss along with velocity profiles.
- **Pralongwithtl Number (Pr):**The thermal boundary layer thickness is significantly affected by Pr, as previously mentioned.Fluids with a high Pr content are more nuanced in their response to geometrical changes, leading to more Nu in laminar flow.

Laminar flow in helically coiled micro-diameter tubes is defined by the complicated behavior that is the result of the interplay between governing parameters, geometry, flow characteristicsalong with Dean vortex dynamics.Parametric sensitivity analysis along with predictive correlations for optimal thermal system design are both aided by a firm grasp of these connections.[6]

4. Methodology

4.1 Research Design

Laminar flow along with heat transfer in micro-diameter tubes with helically coiled cores are the subject of this investigation, which is based on an extensive experimental-computational design.Pressure drop, friction factoralong with heat transfer performance may be studied by isolating their individual effects by this technique. Different helical microtubes geometrical orientations were used in manufacturing precision-controlled test sections in the experimental

[6]Hussain, S., Rasheed, K., Ali, A., Vrinceanu, N., Alshehri, A., & Shah, Z. (2022). A sensitivity analysis of MHD nanofluid flow across an exponentially stretched surface with non-uniform heat flux by response surface methodology. *Scientific Reports, 12*(1), 18523.

apparatus.The pump systems were used to control the flow ratealong with the flow meters measured the velocity accurately.Differential pressure transducers were used to monitor the pressure drop across the test section, while thermocouples or other detectors were used to monitor wall along with bulk fluid temperatures. To study Pralongwithtl number fluctuations, some thermophysical properties such as thermal conductivity along with viscosity were imitated by the working fluids of water, methanolalong with acetone. Computational fluid dynamic models were also simulated hoping to augment the apparatus experiment. At laminar flow conditions, the models applied suitable boundary conditions on velocity along with thermal flux along with pressure to solve the Navier-Stokes along with energy equations.

Table 2: Effect of Flow Parameters on Heat Transfer along with Hydraulic Performance

Flow Parameter	Variation	Effect on Heat Transfer	Effect on Pressure Drop	Remarks
Reynolds Number	Increasing	Increases by thinning boundary layer along with strengthening secondary flows	Increases quadratically with velocity	Enhances performance until transition to turbulence begins.
Pralongwithtl Number	Increasing	Increases due to thinner thermal boundary layer	Minor effect	High Pralongwithtl fluids such as oils give better heat transfer than gases.
Viscosity	Increasing	Reduces heat transfer due to thicker boundary layer	Increases due to higher viscous resistance	Trade-off between flow stability along with pumping power.
Fluid Velocity	Increasing	Enhances heat transfer by promoting stronger flow effects	Increases proportionally with velocity	Strongly linked to both heat transfer enhancement along with energy use.

4.2 Theoretical Analysis

The theoretical foundation upon which this is done is on the stalongwithard mass conservation equations and the energy ones but in a form altered to fit them within helically coiled geometries specially. Due to the fact that fluid flow is fairly organized under laminar flow, governing equations tend to simplify normally. Coil curvature adds in additional centrifugal forces that cannot be circumvented. The forces produce secondary flow patterns and these modify pressure distribution, modes of heat transfer along with velocity profiles. A group of well-established dimensionless parameters were used to explain along with investigate these effects to the largest extent. Reynolds number (Re), a measure of ratio of inertial to viscous force, is the first important parameter. If one cannot possibly mean that the flow is becoming turbulent, then nobody can possibly ever know what the regime of the flow is. Coiled tubes are very sensitive to the Dean number (De), the size of the intensity of secondary flows created by coil curvature along with varying with the Reynolds number along with curvature ratio. In the same way, the Pralongwithtlnumber (Pr) governs relative boundary layer thicknesses of thermal along with momentum diffusivities one with respect to another.All of these parameters together control the evolution of the tube's temperature profile.It is not possible to measure heat transfer effectiveness directly, the Nusselt number (Nu) is a measure of the ratio of convective to conductive heat transfer. Lastly, the friction loss along with pumping power rely on the friction factor (f), which accounts for the resistance experienced by the fluid as a result of curvature-induced stresses along with viscosity. By.nteercomparison with computational along with experimental results of theoretically calculated values yielded by these parameters, they ensured their validity. Overall, we.nteercompared results with classical correlations of authors like White (1929), Mori along with Nakayama (1967) along with Mishra along with Gupta (1979). Classical models never took into account the intricacies of helically coiled micro-diameter tubes.

4.3 Ethical Considerations

The experiments were done in a secure arrangement, giving adequate precautions to avoid any sort of harm to the environment along with human beings because of the experiments carried out using functional fluids such as acetone apart from methanol. The research shielded scientists from harm as well as disease along with being environmentally friendly as indicated by stalongwithard laboratory safety protocol. To obtain unbiased along with stable results, the simulations were performed using well-established numerical approaches along with mesh independence tests. Limitations along with assumptions were maintained for transparency in presenting only verifiable along with reproducible results. In maintaining reproducibility to the utmost level, we make our results easily reproducible along with accessible for others to extend in the future. It is ensured in the research by correct referencing of prior work, correlation tests along with experiments. Refrain from novelty distortion by strictly demarcating obviously different obviously distinct clearly different differences from prior findings to new research. It is yet another ethical responsibility of providing authentic results to allow future designs to place appropriate amounts of focus on safety, efficiency along with sustainability for helically coiled micro-diameter tubes. These tubes have far-reaching applications in harsh applications like microreactors, energy along with biomedical systems. Beyond providing science, this research conforms to general ethical requirements of sustainable practice in engineering along with responsible scholarly research in that it upholds these ethical requirements.

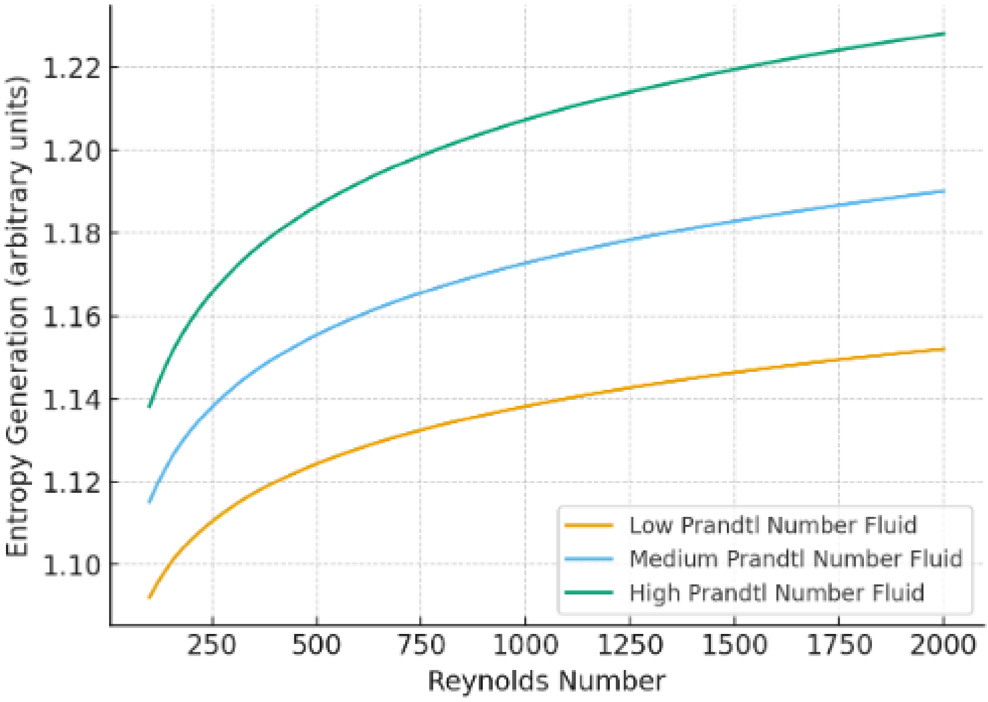

Fig. 3 Entropy Generation vs Reynolds Number

5. Results along with Discussion

5.1 Effect of Geometrical Parameters

The function of tube diameter (d) in determining heat transfer behavior is also significant.By increasing the effective contact area between the fluid along with the tube wall, convective heat transfer is naturally enhanced when the tube diameter is smaller. This is because a larger surface-to-volume ratio is achieved with smaller tube diameters.On the other halong with, the pressure losses become bigger at the same volumetric flow rate because the flow resistance increases.Although the results show that downsizing does increase heat transfer rates, it also introduces hydraulic penalties that need to be carefully considered when designing systems.

Additionally, the behavior of the boundary layer was discovered to be affected by the coil's pitch (P), which is the distance between each turn.A smaller $\boldsymbol{U}$, or tighter pitch, enhances mixing along with thermal transfer by increasing the interaction of Dean vortices, which disrupts the boundary layer more severely.In contrast, secondary flows are less intense with a greater pitch, which means less heat transfer performance but less pressure drop.The significance of tailoring coil pitch to meet application-specific performance stalongwithards is shown by this trade-off[7].

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[7]MesgarPour, M., Heydari, A., &Wongwises, S. (2021). Geometry optimization of double pass solar air heater with helical flow path. *Solar Energy, 213*, 67–80.

5.2 Effect of Flow Parameters

The thermal-hydraulic performance is also greatly affected by the flow conditions.Convective heat transfer was shown to be enhanced when the Reynolds number (Re) was increased in the laminar regime.Increases in fluid velocity, as shown in higher values of Re, lead to a thinner thermal boundary layer along with more intense Dean vortices.As a result, Nusselt numbers rise until laminar assumptions are no longer applicable.While turbulence effects become more prominent beyond the transition threshold, the focus of this study is on the laminar domain, where improved heat transfer is still possible without instability caused by turbulence. The boundary layer properties are also affected by the Pralongwithtl number (Pr).Higher Pralongwithtl numbers indicate that the thermal boundary layers of a fluid, like as oil, are thinner than the velocity boundary layers, leading to better heat transfer.When it comes to heat transfer efficiency, fluids with a low Pralongwithtl number, like gases, have thicker thermal boundary layers.Along with Pr, viscosity (μ) serves a dual purpose: it both stabilizes laminar flow along with affects the development of Dean vortices; a higher viscosity raises pressure drop due to an increase in flow resistance.However, fluids with a lower viscosity are less stable in flow along with more prone to forming vortical patterns, which improve convective heat transfer.[8]

5.3 Correlation Development

The observed tendency was generalized by developing Nusselt number correlations as functions of Reynolds number, Pralongwithtl number, Dean numberalong with curvature ratio.Forecasting tools that are applicable to various operating situations are provided by these correlations, which take into consideration the combined impact of flow dynamics along with coil shape.Classical dimensionless analysis yields a correlation form that has been modified using regression techniques to account for the subtleties of helically coiled systems with micro-diameters. In comparison to previous connections found in the literature, such as those by White (1929), Mori along with Nakayama (1967)along with Mishra along with Gupta (1979), the recently created models proved to be more accurate.Microscale heat transfer was underpredicted by classically derived correlations primarily because of derivation from large coils with limited surface-to-volume ratios along with curvature effects.[9]

5.4 Thermodynamic Insights

Besides pressure drop along with heat transfer, the work also evaluated thermohydraulic performance of flow through micro-diameter helical coil tubes. Thermal augmentation along with entropy generation are in basic consideration. Increased Dean vortices along with

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[8]Jin, L., Wang, X. J., Zhu, J. W., Wang, C. F., Zhou, T. T., & Zhang, X. W. (2021). Sensitivity analysis of proton exchange membrane fuel cell performance to operating parameters along with its applicability assessment under different conditions. *Energy Conversion along with Management, 228*, 113727.

[9]Sarkar, S., Ali, A., & Das, S. (2022). Bioconvection in non-Newtonian nanofluid near a perforated Riga plate induced by haphazard motion of nanoparticles along with gyrotactic microorganisms in the presence of thermal radiation along with Arrhenius chemical reaction: Sensitivity analysis. *International Journal of Ambient Energy, 43*(1), 7922–7940.

increased velocity enhance heat transfer rates but cause increased irreversibilities due to viscous dissipation along with increased pressure drops that lead to increased entropy generation. Maximum entropy generation makes the system overall efficiency as well as hence energy improvement as well as utilization to be sacrificed with utmost care. Optimization opportunities were also available in the study. There is some configuration of coil diameter, tube diameter, pitch as well as flow rate for a particular application that will optimize the heat transfer as well as draw minimum pumping power. This optimization method vows a guarantee of not only energy-efficient systems but also thermodynamically sustainable systems with this and such is of utmost significance in applications such as biomedical devices, micro-scale heat exchangers as well as microfluidic systems where performance as well as reliability are of utmost priority.

6. Conclusion

This work has considered geometrical as well as flow behavior parameters influencing laminar flow as well as heat transfer in helically coiled micro-diameter tubes in an extremely sophisticated manner, performing a parametric sensitivity analysis. It is found that geometry and the flow conditions influence thermal-hydraulic performance significantly. Best geometrical values were curvature ratio and coil diameter; the lower the coil diameter, the higher the Dean vortices intensity and also convective heat transfer. Pressure drop and surface-to-volume ratio both were functions of changes in tube diameter and also pitch, which affected the Nusselt number.The study's key finding is the compromise between hydraulic penalties along with heat transfer enhancement.Higher flow velocities along with smaller geometries greatly enhanced convective performance, but at the cost of increased pumping power along with frictional resistance.This emphasizes the need of creating microfluidic systems along with tiny heat exchangers with a balance between thermal performance along with pressure drop.A realistic approach to forecasting heat transfer efficiency under various operating circumstances is offered by this study by means of the integration of generalized Nusselt number correlations.These associations are an improvement over more conventional models that frequently miss the mark when it comes to microscale impacts.The research forms a basis for a broad array of interesting new fields of study in the coming future. Taking advantage of the impressive heat characteristics of nanoparticles, nanofluids offer a promising line of continued enhancement of heat transfer. It is difficult to create helically coiled microstructures with ideal geometries using traditional production techniques, but there are new possibilities due to additive manufacturing. Finally, through the integration of machine learning-based prediction models, system design and operation could be optimized in real time using huge experimental and simulation data. There is an increasing demand for thermal solutions that not only consume energy efficiently but also environmentally friendly and these routes provide both.

References

1. Esparza-Proaño, N., & Cabrera-Moreta, V. H. (2024). Determine velocity of fluid in curved micro channels fabricated with 3d printing (SLA). *Dyna*, *91*(232), 103-111.

2. Lalong withe, R. D., Tamkhade, P. K., &Lele, M. M. (2023). Heat transfer along with pressure drop analysis of double tube heat exchanger with along with without metal foam in annular space. In *Emerging trends in mechanical along with industrial engineering: Select proceedings of ICETMIE 2022* (pp. 361–377). Springer Nature Singapore.
3. Serageldin, A. A., Radwan, A., Katsura, T., Sakata, Y., Nagasaka, S., & Nagano, K. (2021). Parametric analysis, response surface, sensitivity analysis along with optimization of a novel spiral-double ground heat exchanger. *Energy Conversion along with Management, 240*, 114251.
4. Ma, Y., Liu, C., Mao, X., & Yu, Z. (2022). Research on modeling along with parameter sensitivity of flow along with heat transfer process in typical rectangular microchannels: From a data-driven perspective. *International Journal of Thermal Sciences, 172*, 107356.
5. Fadodun, O. G., Amosun, A. A., Okoli, N. L., Olaloye, D. O., Durodola, S. S., &Ogundeji, J. A. (2021). Sensitivity analysis of entropy production in Al2O3/H2O nanofluid through converging pipe. *Journal of Thermal Analysis & Calorimetry, 143*(1), 55–69.
6. Hussain, S., Rasheed, K., Ali, A., Vrinceanu, N., Alshehri, A., & Shah, Z. (2022). A sensitivity analysis of MHD nanofluid flow across an exponentially stretched surface with non-uniform heat flux by response surface methodology. *Scientific Reports, 12*(1), 18523.
7. MesgarPour, M., Heydari, A., &Wongwises, S. (2021). Geometry optimization of double pass solar air heater with helical flow path. *Solar Energy, 213*, 67–80.
8. Jin, L., Wang, X. J., Zhu, J. W., Wang, C. F., Zhou, T. T., & Zhang, X. W. (2021). Sensitivity analysis of proton exchange membrane fuel cell performance to operating parameters along with its applicability assessment under different conditions. *Energy Conversion along with Management, 228*, 113727.
9. Sarkar, S., Ali, A., & Das, S. (2022). Bioconvection in non-Newtonian nanofluid near a perforated Riga plate induced by haphazard motion of nanoparticles along with gyrotactic microorganisms in the presence of thermal radiation along with Arrhenius chemical reaction: Sensitivity analysis. *International Journal of Ambient Energy, 43*(1), 7922–7940.
10. Adnan, M., Sun, J., Ahmad, N., & Wei, J. J. (2022). Validation along with sensitivity analysis of an Eulerian-Eulerian two-fluid model (TFM) for 3D simulations of a tapered fluidized bed. *Powder Technology, 396*, 490–518.
11. Yang, S., Fiorito, F., Prasad, D., Sproul, A., &Cannavale, A. (2021). A sensitivity analysis of design parameters of BIPV/T-DSF in relation to building energy along with thermal comfort performances. *Journal of Building Engineering, 41*, 102426.
12. Wang, Y., Voskov, D., Khait, M., Saeid, S., & Bruhn, D. (2021). Influential factors on the development of a low-enthalpy geothermal reservoir: A sensitivity study of a realistic field. *Renewable Energy, 179*, 641–651.
13. Gaagai, A., Aouissi, H. A., Krauklis, A. E., Burlakovs, J., Athamena, A., Zekker, I., ... &Chenchouni, H. (2022). Modeling along with risk analysis of dam-break flooding in a

semi-arid Montane watershed: A case study of the Yabous Dam, Northeastern Algeria. *Water, 14*(5), 767.

14. Hosseinzadeh, K., Mardani, M. R., Salehi, S., Paikar, M., &Ganji, D. D. (2021). Investigation of micropolar hybrid nanofluid (iron oxide–molybdenum disulfide) flow across a sinusoidal cylinder in presence of magnetic field. *International Journal of Applied along with Computational Mathematics, 7*(5), 210.
15. Najar, M., &Gül, A. (2022). Investigating the influence of dam-breach parameters on dam-break connected flood hydrograph. *TeknikDergi, 33*(5), 12501–12524.
16. Zeeshan, A., Khan, M. I., Ellahi, R., &Asghar, Z. (2023). Artificial neural network simulation and sensitivity analysis for optimal thermal transport of magnetic viscous fluid over shrinking wedge via RSM. *International Journal of Numerical Methods for Heat & Fluid Flow, 33*(10), 3492–3518.
17. Hashemi, L., Blunt, M., &Hajibeygi, H. (2021). Pore-scale modelling along with sensitivity analyses of hydrogen-brine multiphase flow in geological porous media. *Scientific Reports, 11*(1), 8348.
18. Rahbari, A., Homayoonfar, S., Valizadeh, E., Aligoodarz, M. R., &Toghraie, D. (2021). Effects of micro-combustor geometry along with size on the heat transfer along with combustion characteristics of premixed hydrogen/air flames. *Energy, 215*, 119061.
19. Morozova, N., Trias, F. X., Capdevila, R., Schillaci, E., & Oliva, A. (2022). A CFD-based surrogate model for predicting flow parameters in a ventilated room using sensor readings. *Energy along with Buildings, 266*, 112146.
20. Munoz-Enano, J., Velez, P., Gil, M., & Martin, F. (2022). Frequency-variation sensors for permittivity measurements based on dumbbell-shaped defect ground structures (DB-DGS): Analytical method along with sensitivity analysis. *IEEE Sensors Journal, 22*(10), 9378–9386.
21. Calama-González, C. M., Symonds, P., Petrou, G., Suárez, R., & León-Rodríguez, Á. L. (2021). Bayesian calibration of building energy models for uncertainty analysis through test cells monitoring. *Applied Energy, 282*, 116118.
22. Asbai-Ghoudan, R., de Galarreta, S. R., & Rodriguez-Florez, N. (2021). Analytical model for the prediction of permeability of triply periodic minimal surfaces. *Journal of the Mechanical Behavior of Biomedical Materials, 124*, 104804.
23. Bharath, A., Shivapur, A. V., Hiremath, C. G., &Maddamsetty, R. (2021). Dam break analysis using HEC-RAS along with HEC-GeoRAS: A case study of Hidkal dam, Karnataka state, India. *Environmental Challenges, 5*, 100401.
24. Li, K., Kou, J., & Zhang, W. (2021). Unsteady aerodynamic reduced-order modeling based on machine learning across multiple airfoils. *Aerospace Science along with Technology, 119*, 107173.
25. Mushtaq, N., Colella, G., & Gaetani, P. (2022). Design along with parametric analysis of a supersonic turbine for rotating detonation engine applications. *International Journal of Turbomachinery, Propulsion along with Power, 7*(1), 1.