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The influence of flow velocity and turbulence on heat exchange processes and the uniformity of heat transfer fluid heating in solar water heating collectors

Abstract: Enhancing the thermal efficiency and operational stability of solar water heating collectors necessitates optimizing heat transfer and ensuring uniform heating of the working fluid. This study examines the impact of flow velocity and turbulence on heat exchange processes and temperature distribution within the ribbed tubes of a solar collector. The problem is significant for maximizing solar energy utilization and minimizing auxiliary energy losses. Based on a review of recent advances in thermal-fluid modeling, the study aimed to identify optimal flow regimes that balance heat transfer enhancement with energy efficiency. Numerical simulations were conducted using

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the finite difference method, assuming steady-state turbulent flow in a 1.2 m ribbed tube with a 0.02 m internal diameter, wall temperature of 360 K, and inlet water temperature of 300 K. Thermophysical properties of water were set at 330 K. Results showed that an optimal flow velocity range of 3–4 m/s ensured efficient heat transfer and minimized energy losses. At 3.5 m/s, the outlet temperature reached 348 K, while the heat transfer coefficient peaked at 520 W/m^2·K. The uniform heating coefficient Ru decreased from 0.0135 at 0.5 m/s to 0.0095 at 3.5 m/s, indicating significant improvement in temperature homogeneity. Ribbed surfaces enhanced the heat transfer coefficient by 25–35% compared to smooth tubes, even at moderate velocities. The study successfully implemented its objective and offered practical recommendations for optimizing the design and operation of solar thermal systems to ensure stable and energy-efficient performance.

Keywords: working fluid dynamics, uniform temperature distribution, ribbed surfaces, numerical modeling, pressure losses in solar collectors

Introduction

Modern trends in energy are increasingly focused on enhancing the use of renewable energy sources, among which solar water heating collectors hold a significant position. Given the growing demand for energy and the drive to minimize adverse environmental impacts, improving the efficiency of these collectors has become a key challenge. In particular, attention is directed towards heat transfer processes, as they determine how effectively the system can convert solar energy into thermal energy. Important parameters in this regard include the flow rate of the heat transfer fluid and the flow regime within the collector tubes (Temirbaeva et al. 2024).

The flow rate and turbulence are key factors affecting the uniformity of heating and the efficiency of heat transfer (Blinov et. al. 2004). While the laminar flow regime, typical of low flow rates, is limited by the thermal conductivity of the fluid, turbulent flow enhances the heat exchange process due to intensified mixing of fluid layers. However, determining the role of flow rate in ensuring uniform heat transfer and identifying the optimal flow rate that maximizes the system's energy efficiency remains a key challenge (Kovalenko and Khandogina 2022).

The analysis of the influence of flow velocity and turbulence on heat transfer and the uniformity of heating of the heat transfer fluid in solar water heating collector tubes is a relevant task, given the increasing demands for energy efficiency and stability in the operation of such systems.

Numerous studies have been conducted to enhance heat transfer efficiency in solar water heating collectors. Douvi et al. (2021) examined the integration of phase change materials, focusing on their potential for thermal energy storage and release. Xiong et al. (2021) investigated the role of hybrid nanofluids in improving thermal conductivity and heat absorption in solar thermal systems. Kumar and Abraham (2024) analyzed pulsating heat pipes, exploring how their geometric and operational parameters influence heat transfer in compact configurations. Haeri et al. (2024) assessed the thermophysical behavior and stability of titanium nitride-based nanofluids, which are increasingly considered for solar harvesting. Rahman et al. (2022) reviewed both passive and active strategies for thermal enhancement in latent heat storage systems. In the area of concentrated solar power, Gallardo et al. (2025) evaluated the impact of nanofluid use on system efficiency, while Hou et al. (2024) synthesized data on heat transfer characteristics in supercritical fluid heat exchangers under non-uniform thermal boundary conditions. Xu et al. (2022) investigated the coupling of heat flux distribution and buoyancy effects in parabolic-trough collectors using supercritical CO_2, and Yang et al. (2025) carried out numerical simulations of supercritical CO_2 flow in horizontally heated tubes.

Despite the variety of approaches and working media considered, previous research has paid limited attention to the specific influence of flow velocity and turbulence on both the intensity of heat transfer and the uniformity of working fluid heating in the tubes of solar water heating collectors. In particular, there is a lack of detailed quantitative analysis that integrates velocity-dependent turbulence effects, tube geometry (such as ribbed surfaces), and their joint impact on heat transfer coefficient and temperature distribution. This study addresses the research gap by examining these interdependent variables through numerical modeling, thereby providing practical insights into optimizing flow parameters for improved thermal efficiency and system stability in solar water heating applications.

The objective of this study was to investigate the impact of flow rate and turbulence on heat transfer processes and the uniformity of heating in the tubes of a solar water heating collector, with the aim of identifying optimal operating conditions for the system. To achieve this objective, the following tasks are set:

1. Perform a comprehensive analysis of theoretical aspects related to the influence of flow rate and turbulence on heat transfer processes in tubes, taking into account their design features and geometric configuration.

2. Develop a mathematical model that can adequately describe the temperature profile along the tube at various flow rates.

3. Conduct numerical modeling of heat transfer processes to determine the dependence of the heat transfer coefficient on the flow rate.

1. Materials and methods

Numerical modeling of heat transfer processes in this study was carried out to provide a detailed analysis of the functioning of a solar water heating collector under turbulent flow conditions, particularly in tubes equipped with ribbed surfaces. By employing differential equations of heat transfer, the temperature dynamics and heat exchange intensity at various flow rates of the heat carrier were described.

The modeling enabled an investigation into the influence of flow velocity on heat transfer parameters, revealing characteristic dependencies between the heat transfer coefficient and the geometry of the tubes. The primary focus was on the numerical solution of equations that included calculating both the heat transfer coefficient and the temperature profile distribution along the entire length of the tubes. This approach made it possible to account for the complex interactions occurring under conditions of enhanced turbulence, which, in turn, affected the uniformity of heat carrier heating and allowed the identification of key aspects for optimizing collector performance.

To solve the system of equations governing convective heat transfer, a finite difference method (FDM) was applied (1). The differential equation (7), which describes the temperature profile along the tube, was discretized using a first-order upwind scheme for spatial derivatives. The temperature at position was calculated iteratively:

$$T_f(x_{i+1}) = T_f(x_i) + \frac{hp\Delta x}{Gc_p}(T_f(x_i) - T_{wall}) \tag{1}$$

where: Δx is the distance between adjacent points. The Reynolds number (Eq. 5) and the effective Reynolds number (Eq. 4) were recalculated at each iteration based on the updated fluid temperature and viscosity. An adaptive algorithm adjusted the step size Δx based on local temperature gradients to enhance accuracy in high-gradient zones, particularly near the inlet region.

For the numerical solution of the problem of investigating the influence of flow velocity and tube geometry on the efficiency and uniformity of heating the heat transfer fluid, the general heat transfer equation is used, taking into account turbulence and the ribbed tube structure. Consider the heat flux transferred from the tube walls to the heat transfer fluid (2):

$$Q = h \cdot A \cdot \Delta T \tag{2}$$

where:

- Q – heat flux [W],
- h – heat transfer coefficient [W/m^2·K],
- A – heat transfer surface area of the tube [m^2],
- ΔT – temperature difference between the tube wall and the heat transfer fluid [K].

The heat transfer coefficient h in the turbulent flow regime, considering the ribbed surface, can be expressed as (3):

$$h = \frac{k \cdot \left(\mathrm{Re}_{eff}\right)^n \cdot \mathrm{Pr}^{1/3}}{D} \tag{3}$$

where:

- k – empirical coefficient depending on the tube material and conditions,
- Re_{eff} – effective Reynolds number considering the ribbed structure,

n – coefficient equal to 0.8 for the turbulent regime,
Pr – Prandtl number describing the properties of the heat carrier,
D – the diameter of the tube [m].

The effective Reynolds number considering the ribbed structure (4, 5):

$$Re_{eff} = Re \cdot \left(1 + \beta \cdot rib_{height} \cdot rib_{density}\right) \tag{4}$$

where:
Re – Reynolds number,
β – empirical coefficient depending on the rib shape,
rib_{height} – rib height,
$rib_{density}$ – rib arrangement density. The Reynolds number (Re) is a dimensionless quantity that determines the flow regime (laminar or turbulent).

$$Re = \frac{\rho \cdot \vartheta \cdot D}{\mu} \tag{5}$$

where:
ρ – density of water [kg/m^3],
D – the diameter of the tube [m],
ϑ – denotes the mean velocity of the working fluid in the tube [m/s],
μ – dynamic viscosity of water [Pa·s].

The Prandtl number, which describes the ratio of the kinematic viscosity of a fluid to its thermal conductivity (6):

$$Pr = \frac{c_p \cdot \mu}{\lambda} \tag{6}$$

where:
c_p – specific heat capacity of the heat transfer fluid [J/kg·K],
λ – thermal conductivity of the heat transfer fluid [W/m·K].

The temperature profile along the length of the tube is described by the following equation (7):

$$\frac{dT_f(x)}{dx} = \frac{h \cdot p \cdot \left(T_f(x) - T_{wall}\right)}{G \cdot c_p} \tag{7}$$

where:
$T_f(x)$ – temperature of the heat carrier at point x_i along the tube [K],
p – perimeter of the tube's cross-section [m],

G – mass flow rate of the heat carrier [kg/s],
T_{wall} – temperature of the tube wall [K].

To assess the uniformity of heating of the heat carrier, a uniformity coefficient (Ru) can be introduced, which will depend on the standard deviation of the temperature profile (8):

$$R_u = \frac{\sigma_T}{\bar{T}_f} \tag{8}$$

where:
σ_T – standard deviation of temperature along the tube,
$\bar{T}_f$ – average temperature of the heat carrier along the entire length of the tube.

The standard deviation is calculated using the following formulas. The average temperature $\bar{T}_f$ along the length of the tube (9):

$$\bar{T}_f = \frac{1}{N}\sum_{(i=1)}^{N} T_f(x_i) \tag{9}$$

where:
$T_f(x_i)$ – represents the temperature of the heat carrier at point x_i along the tube,
N – number of temperature measurement points along the tube.

The standard deviation of temperature, σ_T (10):

$$\sigma_T = \frac{1}{N}\sum_{i=1}^{N}\left(T_f(x_i) - \bar{T}_f\right)^2 \tag{10}$$

Empirical coefficients were used in the analysis to determine changes in the effective Reynolds number, taking into account the ribbed structure, which contributed to a more accurate description of turbulent vortices and increased heat transfer intensity at various flow rates.

Initial data used for numerical modeling included the following values for the working fluid (water) and system geometry:

- Tube diameter $D = 0.2$ m
- Tube length $L = 1.2$ m
- Wall temperature $T_{wall} = 360$ K (assumed constant based on solar heating)
- Inlet fluid temperature $T_{in} = 300$ K
- Heat transfer fluid properties at 330 K:
  - $\rho = 995$ kg/m^3
  - $c_p = 4182$ J/kg\cdotpK
  - $\mu = 7.8\times10^{-4}$ Pa\cdotps
  - $\lambda = 0.63$ W/m\cdotpK
- Ribbed tube characteristics:
  - Rib height = 0.5 mm
  - Rib density = 10 ribs/cm

- Empirical coefficient β = 1.2 (based on experimental calibration)
- Empirical constant $k = 0.023$ (based on Nusselt correlation for turbulent flow)

These parameters ensured the full reproducibility of the simulation process and the validity of the numerical results presented in Figures 1 and 2.

To determine the effect of changes in water flow velocity and tube geometry on the efficiency and uniformity of heating the heat transfer fluid in a solar water heating collector, two key aspects were considered: heat transfer efficiency and heating uniformity. To analyze the impact of water flow velocity and tube geometry on the efficiency and uniformity of heating the heat transfer fluid in a solar water heating collector, two key aspects were considered: heat transfer efficiency and temperature uniformity.

2. Results

The effect of water flow velocity on heat transfer is closely related to the flow regime inside the tube. In a laminar flow regime, characterized by Reynolds numbers below 2300, the heat transfer fluid moves in distinct layers with minimal mixing. This results in inefficient heat exchange, as the dominant mode of heat transfer is limited by the thermal conductivity of the fluid. The temperature profile along the tube varies significantly, leading to non-uniform heating. Conversely, when the flow velocity increases and the Reynolds number exceeds 4000, the fluid transitions into a turbulent flow regime (Avargani et al. 2023). This shift significantly enhances heat transfer by intensifying the mixing of fluid layers, thereby facilitating a more efficient exchange of thermal energy between the tube walls and the heat carrier. As a result, turbulence not only improves heat transfer efficiency but also contributes to a more uniform temperature distribution along the tube. However, when the velocity becomes excessively high, pressure losses increase significantly, which can negatively affect the system’s overall energy efficiency.

The geometry of the tube also plays a crucial role in determining heat transfer efficiency (Zvorykin et. al. 2016). In a smooth-walled tube, turbulence is induced primarily by the velocity of the fluid flow, and the overall efficiency is strongly dependent on the flow regime. In laminar conditions, the temperature gradient along the tube remains pronounced, resulting in non-uniform heating (Redko et al. 2018). On the other hand, the introduction of ribbed surfaces on the inner walls of the tube creates additional turbulence, even at relatively low flow velocities. This effect arises from the specific characteristics of the ribs, including their height, spacing (or density), and geometric shape (such as trapezoidal or semicircular). The orientation of the ribs relative to the flow direction also plays a critical role, as it determines the formation of vortices and zones of local flow separation, thereby enhancing convective heat transfer. These ribbed structures enhance heat transfer by increasing the effective heat exchange surface area and intensifying turbulent eddies (Havrylenko et. al. 2021). As a result, heat transfer efficiency improves, and temperature distribution becomes more homogeneous along the tube. Moreover, the ribbed design allows for efficient heat transfer without requiring excessively high flow velocities, which helps to mitigate pressure losses while maintaining system performance (Zhangabay et. al. 2023).

From a numerical perspective, heat transfer efficiency is closely tied to the heat transfer coefficient, which increases as the flow velocity increases. The Reynolds number, which represents the ratio of inertial to viscous forces in the fluid, plays a key role in determining the heat transfer characteristics (Golyshev 2003). In the turbulent regime, a ribbed tube surface further amplifies this effect, increasing the heat transfer coefficient by generating additional vortex structures. As flow velocity increases and turbulence intensifies, decreases, confirming that a controlled increase in velocity contributes to better thermal homogeneity.

By solving a set of governing equations (2–10), including those describing heat flux, convective heat transfer coefficients, and temperature profiles, the study identified optimal operating conditions for maximizing heat transfer while minimizing energy losses. To determine the optimal operating parameters, a multi-objective optimization approach was applied, balancing thermal efficiency and energy losses. The objective function Φ was defined as (11):

$$\Phi = \omega_1 \left(\frac{Q}{\Delta P} \right) - \omega_2 R_u \tag{11}$$

where:

- Q – the heat flux (from Eq. 2),
- ΔP – the pressure loss estimated from Darcy-Weisbach equation,
- R_u – the uniform heating coefficient (Eq. 8),
- ω_1 and ω_2 – weighting factors (e.g., 0.6 and 0.4) reflecting the priority of efficiency over uniformity.

Optimization was conducted by scanning the flow velocity from 1 to 5 m/s in 0.5 m/s increments, evaluating Φ at each step. The maximum of Φ indicated the most effective operational point under given geometric and fluid properties.

The results demonstrated that an optimal velocity range exists, typically between 3 and 4 m/s, where the heat transfer coefficient reaches its peak efficiency while avoiding excessive pressure losses. At lower velocities, such as 1 m/s, heat transfer is significantly less efficient, and temperature gradients remain large. In contrast, at higher velocities exceeding 5 m/s, pressure losses become a limiting factor, outweighing the benefits of improved heat transfer. In contrast, at higher velocities exceeding 5 m/s, pressure losses become a limiting factor, outweighing the benefits of improved heat transfer. These pressure losses encompass both significant losses resulting from friction between the fluid and the tube walls along the flow path and minor losses associated with local flow disturbances, such as entrance effects, bends, fittings, and particularly increased turbulence around ribbed structures. As velocity rises, these losses grow nonlinearly due to intensified shear forces and vortex formation, leading to a substantial increase in the energy required for fluid pumping.

The numerical analysis also showed that at an optimal velocity of 3.5 m/s, the temperature of the working fluid stabilized near 350 K, minimizing fluctuations along the tube. R_u, decreased from 0.0135 at 0.5 m/s to 0.0095 at 3.5 m/s, confirming that increasing flow velocity contributes to a more uniform temperature distribution. The introduction of ribbed surfaces further improved heat transfer, increasing the effective heat transfer coefficient by 25–35% compared to smooth tubes. This finding underscores the significance of tube geometry in enhancing heat exchange processes in solar water heating systems.

Overall, the study highlights the importance of striking a balance between flow velocity and system efficiency to achieve optimal performance in solar collectors. While increasing velocity enhances heat transfer and thermal uniformity, excessive velocities lead to increased energy consumption and pressure losses (Pasichnyk et al. 2024). The results provide valuable insights into the design and operational parameters of solar water heating collectors, offering guidelines for optimizing efficiency while minimizing energy costs.

By simultaneously solving equations (2–10), the temperature profile along the tube for different flow velocities and the dependence of , on the water flow velocity (which is related to the intensity of heat transfer) in the tube, taking into account the ribbed surface, are determined. Figure 1 illustrates the temperature profile of water along the tube for different flow velocities, ranging from 1 to 5 m/s.

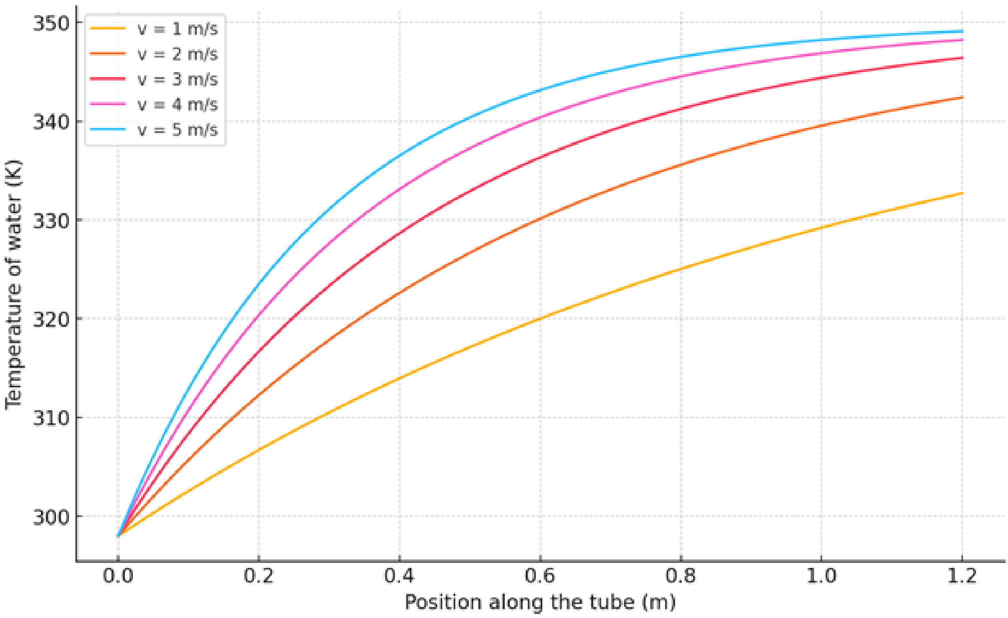

Fig. 1. Influence of flow rate on the water heating process in a solar water heating collector
Source: created by the authors

Rys. 1. Wpływ natężenia przepływu na proces podgrzewania wody w kolektorze słonecznym

The simulations were conducted under the following fixed conditions: the tube length was set to 1.2 m, and the internal diameter was set to 0.02 m. The initial water temperature at the tube inlet was 300 K, while the tube wall temperature was maintained at 360 K. The fluid used in the model was water, with thermophysical properties taken at 330 K: density ρ = 995 kg/m^3, dynamic viscosity $\mu = 7.8 \times 10^{-4}$ Pa\cdotps, specific heat capacity c_p = 4,182 J/kg\cdotpK, and thermal conductivity λ = 0.63 W/m\cdotpK. The internal surface of the tube was ribbed with ribs of 0.5 mm in height and a density of 10 ribs per centimeter. The enhancement of turbulence due to these ribs was accounted for by introducing an empirical correction factor β = 1.2, and the convective heat transfer coefficient was evaluated using a constant k = 0.023 based on Nusselt number correlations for turbulent flow. The numerical solution was carried out using a finite difference method with an upwind scheme, where the spatial discretization step was adapted based on the local temperature gradient to improve accuracy near steep changes in the thermal profile.

At a flow velocity of 1 m/s, the water temperature rises slowly, reaching approximately 320 K at the outlet (1.2 m). This highlights the limited heat transfer efficiency associated with the laminar flow regime, where the fluid layers move in a stratified manner and lack sufficient mixing to enhance thermal exchange. In contrast, as the flow velocity increases to 3 m/s, the outlet temperature rises significantly to 340 K, demonstrating a notable improvement in heat transfer due to the onset of turbulence. At a maximum velocity of 5 m/s, the temperature approaches 350 K, closely matching the temperature of the tube wall. This occurs because turbulence intensifies mixing within the fluid layers, allowing for more effective thermal interaction between the tube wall and the heat transfer fluid.

The temperature profiles exhibit an apparent nonlinearity, especially in the initial section of the tube near the water inlet. At all flow velocities, a steep temperature rise is observed within the first 0.3 to 0.6 meters of the tube. For instance, at a velocity of 3 m/s, the water temperature increases rapidly from 300 K to 330 K within the first 0.6 meters. However, the rate of temperature increase slows significantly beyond this point as the water approaches the temperature of the tube wall. This behavior is a direct result of the diminishing temperature difference between the water and the wall, which reduces the driving force for heat transfer. Effective thermal exchange is dependent on a substantial temperature gradient, which is less pronounced as the water heats up along the tube (Dinzhos et. al. 2005).

The results indicate that an optimal flow velocity exists, at which the balance between heat transfer efficiency and uniform heating is achieved. For this system, the optimal velocity lies in the range of 3–4 m/s. Within this range, the water temperature rises effectively along the tube, approaching 345 K at the outlet, while energy losses due to flow resistance remain manageable. At excessively high velocities, such as 5 m/s, the additional heat transfer efficiency is counterbalanced by increased energy consumption for pumping the fluid. This results in a decrease in the overall energy efficiency of the system. Achieving an optimal balance is essential for ensuring both effective heat transfer and minimal energy losses (Iskenderov et. al. 2024).

Figure 2 provides insights into R_u as a function of flow velocity. A clear inverse correlation is observed, where R_u decreases with increasing velocity. At a low velocity of 0.5 m/s, R_u is approximately 0.0135, indicating significant non-uniformity in the temperature distribution along the tube. As the velocity increases to 3.5 m/s, R_u drops to 0.0095, signifying a substantial improvement in the uniformity of heat distribution. This trend confirms that higher flow velocities enhance the mixing of fluid layers, reducing temperature variations along the tube and promoting more homogeneous heating.

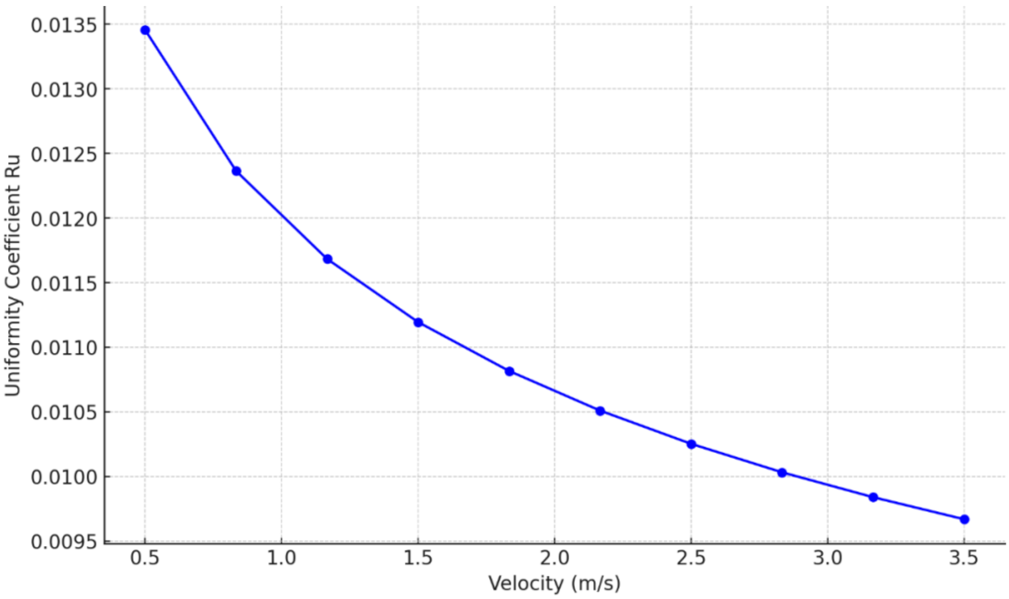

Fig. 2. Dependence of the uniform heating coefficient R_u on the water flow velocity (which is related to heat transfer intensity) in a tube with a ribbed surface
Source: created by the authors

Rys. 2. Zależność współczynnika równomiernego nagrzewania R_u od prędkości przepływu wody (która jest związana z intensywnością wymiany ciepła) w rurze z żebrowaną powierzchnią

The transition to turbulent flow plays a critical role in reducing temperature imbalances within the system. Enhanced turbulence leads to the creation of small eddies and increased fluid mixing, which distribute heat more evenly throughout the tube. This effect is reflected in the reduction of the uniform heating coefficient as the flow velocity rises. For example, at 3.5 m/s, the improved turbulence ensures that localized overheating zones are minimized, resulting in a more uniform thermal profile along the tube.

The graphical analysis suggests that optimizing the flow velocity is key to achieving the best performance in solar water heating systems. While higher velocities improve heat transfer and reduce temperature gradients, they also increase energy consumption for fluid circulation. For instance, pumping energy requirements are substantially higher at 5 m/s compared to 3 m/s, leading to diminishing returns in overall system efficiency. Therefore, it is crucial to identify a compromise between enhanced heat transfer and reduced energy costs. In this study, the optimal velocity range of 3–4 m/s ensures a balance between thermal performance and energy efficiency.

The results presented in Figures 1 and 2 provide a comprehensive understanding of the interplay between flow velocity, heat transfer efficiency, and temperature uniformity in solar water heating collectors. The findings emphasize the importance of turbulent flow and ribbed tube surfaces in enhancing heat transfer performance. Ribbed surfaces contribute to the generation of additional turbulent eddies, further improving uniform heating and enabling efficient heat transfer even at moderate velocities (Fialko et. al. 2020). By optimizing flow parameters, significant improvements in energy efficiency and system stability can be achieved. These results form a foundation for developing design recommendations and operational strategies to optimize the performance of solar water heating systems. The study's findings demonstrate the significant impact of flow velocity and tube geometry on heat transfer efficiency and uniformity in solar water heating collectors. Specifically, the findings suggest that commercial solar collectors should be equipped with internally ribbed tubes that are geometrically optimized – rib heights of approximately 0.5 mm and densities around 10 ribs per centimeter proved effective in enhancing turbulence and improving heat transfer at moderate flow rates. Furthermore, the hydraulic design should aim to maintain flow velocities within the optimal range of 3 to 4 m/s, where a balance is achieved between high heat transfer coefficients (up to 520 $W/m^2 \cdot K$) and acceptable pressure losses. This flow regime ensures both thermal efficiency and uniform temperature distribution, reducing thermal stress and stratification in the collector. In practical terms, pump sizing and flow regulation mechanisms should be integrated into commercial systems to maintain this optimal velocity range (Voloshina et. al. 2020). Additionally, thermal insulation should be tailored to maintain a wall temperature of approximately 360 K, as assumed in the simulations, to stabilize the temperature gradient that drives efficient heat exchange. These strategies collectively enhance energy efficiency, reduce operational costs, and extend the service life of solar thermal systems under varying climatic and usage conditions.

While the numerical results presented in this study provide insight into the influence of flow velocity and turbulence on heat transfer efficiency under controlled conditions, the real-world performance of solar water heating collectors is significantly affected by external environmental factors. Ambient temperature variations directly influence the initial temperature of the working fluid entering the collector. Lower ambient temperatures may increase the temperature gradient between the tube wall and the fluid, potentially enhancing heat transfer; however, they may also lead to greater heat losses to the surroundings, particularly if insulation is insufficient. Conversely, higher ambient temperatures reduce thermal losses but may limit the driving temperature difference required for optimal heat exchange (Ismanzhanov et. al. 2012). Sunlight intensity is another critical factor, as it determines the amount of thermal energy absorbed by the collector surface and transferred to the working fluid. Fluctuations in solar irradiance throughout the day or due to cloud cover result in unsteady thermal boundary conditions, which can impact the uniformity of heating along the tube and the stability of outlet temperatures.

Furthermore, wind speed plays a substantial role in convective heat loss from the outer surface of the collector (Skochko et. al. 2024). Higher wind speeds can increase these losses, effectively lowering the temperature of the tube wall and thereby reducing the available heat flux for transfer to the working fluid. Therefore, while the study assumes a constant wall temperature (e.g., 360 K) to isolate the influence of flow parameters, future models should incorporate dynamic boundary conditions that reflect environmental variability. Doing so would enhance the predictive accuracy of the simulations and improve the practical applicability of the design recommendations for solar collectors under diverse climatic conditions.

Increasing flow velocity leads to a transition from laminar to turbulent flow, which enhances fluid mixing, improves heat transfer coefficients, and results in a more uniform temperature distribution along the tube. For instance, at a velocity of 3 m/s, the water temperature reaches approximately 340 K at the outlet, while at 5 m/s, it approaches 350 K, closely matching the wall temperature. This highlights the efficiency of turbulent flow in facilitating effective heat exchange. Ribbed tube geometry further enhances heat transfer efficiency by generating additional turbulence, even at moderate flow velocities. This enhancement increases the effective heat transfer coefficient by 25–35% compared to smooth tubes, contributing to more uniform temperature profiles. The uniform heating coefficient decreases from 0.0135 at 0.5 m/s to 0.0095 at 3.5 m/s, confirming that turbulence induced by ribbed surfaces significantly reduces temperature variations along the tube. Optimal performance is achieved within a flow velocity range of 3–4 m/s, where heat transfer efficiency is maximized without incurring excessive energy losses due to pressure drops. At higher velocities, such as 5 m/s, the additional energy required for pumping outweighs the benefits of improved heat transfer. These findings highlight the critical balance between heat transfer performance and energy efficiency, providing a framework for optimizing the design and operation of solar water heating systems to achieve sustainable and efficient energy utilization.

3. Discussion

The optimization of heat transfer processes in solar water heating collectors has been extensively studied. Various approaches have been explored, including the use of ribbed tube surfaces, nanofluids, and modified heat exchanger designs. This discussion compares the findings of this study with those of previous researchers, identifying commonalities, differences, and contributions to the field.

The study by Rahman et al. (2021) investigated heat transfer and pressure loss characteristics in rectangular channels with rib-roughened surfaces. Their findings demonstrated that while ribbed surfaces enhance heat transfer, they also lead to increased pressure drop. This research supports this conclusion, as it is observed that although increasing flow velocity improves heat transfer, excessively high velocities result in significant energy losses due to pressure drop. Unlike Rahman et al., this study further explores how turbulence generation by ribbed surfaces contributes to heat transfer uniformity in solar collector tubes. Similarly, Li et al. (2023)

conducted an entropy generation analysis on a twisted corrugated spiral heat exchanger used in solar ponds. They found that heat transfer efficiency improves with geometric modifications but also leads to an increase in pressure losses. These findings are consistent with this, as it is also observed that ribbed surfaces enhance turbulence and heat transfer while requiring optimization to minimize energy losses. Temperature non-uniformity is a common issue in solar collectors, and several studies have sought to optimize this aspect. Halimi et al. (2023) investigated temperature non-uniformity in parabolic trough collectors using U-pipe exchangers and found that design optimization significantly enhances temperature distribution. This study supports this observation, demonstrating that moderate flow velocities contribute to more uniform temperature profiles. However, this work provides additional insights into how ribbed tube designs improve temperature uniformity through enhanced turbulence.

The experimental study by Hou et al. (2023) examined heat transfer performance in horizontal tubes with axially non-uniform heating. Their findings indicated that temperature gradients in such systems lead to inefficiencies, necessitating the development of improved thermal management strategies. This study complements these findings by demonstrating that flow velocity optimization and ribbed surfaces facilitate more uniform heating, thereby mitigating the effects of non-uniform temperature distribution. Several studies have explored the role of nanofluids in improving heat transfer. Avargani et al. (2023) investigated various nano heat transfer fluids in solar air heating systems and reported significant improvements in thermal efficiency. Similarly, Babar et al. (2024) highlighted the potential of nanofluids to enhance heat exchanger performance, emphasizing their improved thermal conductivity and heat absorption capacity. This research, however, takes an alternative approach by focusing on modifying flow conditions rather than fluid properties. While nanofluids improve heat transfer, their implementation presents challenges, such as stability issues and higher viscosity (Hussein et al. 2025). Instead, this study suggests that optimizing flow velocity and introducing ribbed tube structures can achieve similar enhancements without altering the working fluid.

Flow dynamics play a crucial role in heat transfer efficiency. Abdukarimov et al. (2024) investigated hydrodynamic processes in solar air heater collectors with triangular channels and found that modifying channel geometry optimizes flow characteristics, enhancing heat transfer. This study supports this finding, demonstrating that ribbed tube surfaces generate turbulence, which improves heat transfer efficiency even at moderate flow velocities. Mohammed et al. (2023) studied the performance of flat-plate solar water heating systems using various nanofluids. They reported that while nanofluids enhance heat transfer, they also increase viscosity, which can result in a higher pressure drop. This is consistent with the observation that increased flow velocity enhances heat transfer but can also introduce energy losses due to pressure drop (Kudabayev et al. 2022). The effect of geometrical modifications in heat exchangers has also been investigated in recent studies. Pandey and Prakash (2024) conducted an experimental investigation and simulation of a helical coil heat exchanger with a hematite thermal reservoir. They found that helical coil geometry enhances heat transfer but also raises concerns about pressure drop. This study aligns with these findings, demonstrating that surface modifications, such as ribbed tube designs, enhance turbulence and heat transfer while requiring optimization to minimize pressure losses.

Olabi et al. (2021) analyzed the impact of combining nanofluids with modified heat exchanger geometries, demonstrating that nanofluid-enhanced heat exchangers improve thermal efficiency. However, they also found that increased viscosity of nanofluids leads to higher pressure losses, necessitating optimization of flow parameters. This study presents an alternative approach, demonstrating that ribbed tube modifications can enhance heat transfer performance without the need for nanofluids, thereby making the system more energy-efficient.

Pahlavanian et al. (2024) investigated the enhancement of parabolic trough solar collectors through numerical optimization, twisted tapes, and nanofluids, finding that combining these elements significantly improves thermal efficiency. This research complements the existing knowledge by demonstrating that ribbed tubes can enhance heat transfer without requiring additional inserts, thereby offering a simpler alternative for optimization. Said et al. (2025) reviewed the application of nanofluids, turbulators, and novel working fluids in heat transfer systems, concluding that while these modifications significantly enhance performance, they also introduce higher pressure drops. These findings align with this, emphasizing the need for an optimal balance between improved heat transfer and minimized energy losses.

The effects of flow distribution on heat transfer efficiency were studied by Yang et al. (2023), who investigated two-phase flow in parallel flow heat exchangers. They found that improper flow distribution leads to localized overheating and reduced efficiency. These findings support this, as it is observed that maintaining an optimal flow velocity enhances temperature uniformity and prevents heat accumulation in specific areas.

Dhavale and Lele (2024) analyzed the thermal-hydraulic performance of heat exchangers with metal foam inserts, concluding that while metal foams enhance heat transfer, they also increase pressure losses. Similarly, this research found that while ribbed tube surfaces enhance heat transfer, they require optimization to prevent excessive pressure drops. Finally, Jaiswal et al. (2023) reviewed nanofluid-based solar water heaters, highlighting their potential to enhance heat transfer but also addressing stability concerns. This study provides an alternative solution by demonstrating that flow velocity optimization and tube surface modifications can improve heat transfer efficiency without the need for nanofluids.

The findings of this study contribute to the broader field of solar collector optimization by demonstrating that flow velocity and turbulence have a significant influence on heat transfer performance and temperature uniformity. While previous research has extensively explored nanofluids, surface modifications, and hybrid heat transfer enhancement techniques, this study uniquely emphasizes the role of ribbed tube surfaces in improving heat transfer efficiency without the need for advanced working fluids.

Conclusions

This study addressed the problem of optimizing heat transfer processes and achieving uniform heating of the heat transfer fluid in solar water heating collectors, considering key factors such as flow velocity and flow characteristics (laminar or turbulent). The numerical experiments conducted revealed that increasing the flow velocity, particularly when transitioning to turbulent flow, has a significantly positive effect on heat transfer efficiency, promoting a uniform temperature distribution in the heat transfer fluid. However, the study also confirmed the existence of an optimal flow velocity, which leads to increased pressure losses, ultimately reducing the overall energy efficiency of the system.

The results demonstrated that at a flow velocity of 3–4 m/s, the heat transfer coefficient reached its optimal value of 450–520 W/m^{2}K, ensuring efficient heat exchange without excessive energy losses. At lower velocities, such as 1 m/s, heat transfer remained limited, with a coefficient of 180 W/m^{2}K, leading to significant temperature gradients along the tube. Conversely, at excessively high velocities exceeding 5 m/s, pressure losses increased sharply, reducing the system's net energy efficiency despite improved heat transfer.

The temperature distribution results showed that at an optimal velocity of 3.5 m/s, the working fluid reached a uniform temperature of approximately 350 K, thereby minimizing temperature gradients along the tube. The uniform heating coefficient decreased from 0.0135 at 0.5 m/s to 0.0095 at 3.5 m/s, confirming that higher flow velocities contribute to more homogeneous temperature distribution.

Thus, increasing the flow velocity enhances turbulence, which in turn increases the heat transfer coefficient, making the heating process more efficient and uniform. Nevertheless, excessive flow velocities, which lead to significant pressure losses (resulting in an over 30% higher energy demand for pumping at 5 m/s compared to the optimal range), necessitate consideration of energy costs for pumping the fluid, which must be balanced to improve overall system performance. The introduction of ribbed structures on the internal surface of the pipes proved effective in enhancing turbulent mixing and, consequently, improving heat transfer even at moderate flow rates, which is particularly important for energy-efficient solutions. The use of ribbed surfaces increased the effective heat transfer coefficient by 25–35% compared to smooth tubes, confirming their significance in optimizing solar collector performance.

Prospects for further research lie in the development of more accurate methodologies that account for the influence of multiple external factors, such as solar radiation intensity and heat losses through insulation. Comprehensive consideration of all these parameters will enhance not only the performance but also the reliability of solar water heating systems, which is a key condition for their successful implementation in the field of renewable energy.

The Authors have no conflicts of interest to declare.

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Wpływ prędkości przepływu i turbulencji na procesy wymiany ciepła oraz jednolitość ogrzewania czynnika grzewczego w kolektorach słonecznych do podgrzewania wody

Streszczenie

Poprawa sprawności cieplnej i stabilności operacyjnej kolektorów słonecznych do podgrzewania wody wymaga optymalizacji wymiany ciepła i uzyskania równomiernego ogrzewania czynnika roboczego. W niniejszym artykule zbadano, w jaki sposób prędkość przepływu i turbulencja wpływają na procesy wymiany ciepła i rozkład temperatury w żebrowanych rurach kolektora słonecznego. Problem ten jest istotny dla maksymalizacji wykorzystania energii słonecznej i minimalizacji strat energii pomocniczej. W oparciu o przegląd ostatnich postępów w modelowaniu cieplno-płynowym, w artykule sformułowano cel zidentyfikowania optymalnych reżimów przepływu, które równoważą zwiększenie wymiany ciepła z efektywnością energetyczną. Symulacje numeryczne przeprowadzono przy użyciu metody różnic skończonych, zakładając ustalony przepływ turbulentny w żebrowanej rurze o średnicy 1,2 m i średnicy wewnętrznej 0,02 m, temperaturze ścianki 360 K i temperaturze wody wlotowej 300 K. Właściwości termofizyczne wody ustalono na 330 K. Wyniki wykazały, że optymalny zakres prędkości przepływu 3–4 m/s zapewniał skuteczną wymianę ciepła i minimalizował straty energii. Przy 3,5 m/s temperatura na wylocie osiągnęła 348 K, podczas gdy współczynnik przenikania ciepła osiągnął szczyt 520 $W/m^2 \cdot K$. Jednorodny współczynnik ogrzewania R_u zmniejszył się z 0,0135 przy 0,5 m/s do 0,0095 przy 3,5 m/s, co wskazuje na znaczną poprawę jednorodności temperatury. Żebrowane powierzchnie zwiększyły współczynnik przenikania ciepła o 25–35% w porównaniu z gładkimi rurami, nawet przy umiarkowanych prędkościach. Badanie pomyślnie zrealizowało swój cel i oferuje praktyczne zalecenia dotyczące optymalizacji konstrukcji i działania systemów solarnych w celu zapewnienia stabilnej i energooszczędnej wydajności.

Słowa kluczowe: dynamika płynu roboczego, równomierny rozkład temperatury, żebrowane powierzchnie, modelowanie numeryczne, straty ciśnienia w kolektorach słonecznych