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INVESTIGATION OF THERMOHYDRODYNAMIC PROCESSES IN THE SOLAR AIR HEATER ABSORBER OF A POLYGENERATION DEVICE INTENDED FOR FRESHWATER AND HOT WATER PRODUCTION

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Abstract

In this article presents the mathematical modeling and numerical analysis of heat and mass transfer processes in solar air heater collectors with complex absorbers, with particular attention to the role of embedded tube air channels and cavity depth geometry. Solar energy–based desalination and hot water production technologies are highlighted as sustainable and environmentally friendly solutions to the global freshwater shortage. The influence of geometric cavities on airflow structure was studied, demonstrating that indentation-induced vortices enhance turbulence near the wall, intensify temperature gradients, and significantly increase convective heat transfer. However, excessive cavity depth leads to additional turbulence and higher pressure losses, thereby reducing efficiency. Semi-empirical approaches derived from the hypotheses of Prandtl, Taylor, and Kolmogorov were applied to optimize boundary layer modeling, introducing the cavity coefficient (φ) as a governing parameter. Experimental and theoretical results confirm that properly optimized cavity geometries not only stabilize the airflow but also maximize thermohydraulic efficiency of solar collectors. Validation of the proposed mathematical model was carried out using COMSOL Multiphysics 6.0, with an average relative error of 4.6%, confirming the adequacy of the model. The findings provide a reliable foundation for the design and optimization of advanced solar air heater collectors integrated into polygeneration systems, contributing to sustainable water desalination, hot water supply, and improved energy efficiency under varying climatic conditions.

Keywords: solar air heater, polygeneration system, heat transfer, pressure, density of the flow, absorber, boundary condition, energy loses.

1. Introduction

Technologies for water desalination based on solar energy are currently considered an effective solution to the problem of drinking water scarcity faced by humanity today. According to reports by the World Health Organization (WHO) and the United Nations (UN), more than 2 billion people worldwide currently lack access to safe drinking water. This issue is associated with rapid population growth, urbanization, industrialization, and, in particular, global climate change, which leads to reduced rainfall, increased evaporation, and more frequent droughts, ultimately causing a sharp decline in freshwater resources [1].

In this context, solar energy–based water purification and desalination technologies stand out as environmentally friendly, renewable, and sustainable solutions. For instance, solar thermal systems (such as solar stills, multi-effect distillation (MED), and membrane distillation (MD) can be used to produce drinking water from saline water. These technologies are especially effective in hot climates and regions rich in solar resources [2]

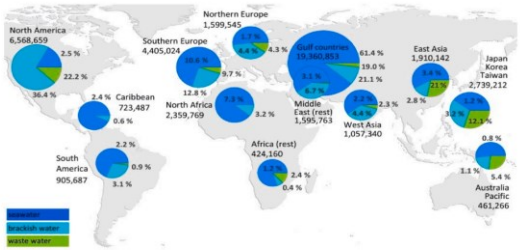


Figure 1. Global Potential Distribution of Water Desalination

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In addition, new types of solar desalination systems—such as interfacial evaporation methods or the use of photothermal materials enhanced with nanomaterials—are achieving even higher efficiencies. Research has shown that such systems can convert up to 86% of solar energy efficiently and generate up to 2 kg/m² of water vapor per hour [3].

In particular, integrating solar-powered desalination systems with cooling technologies can further enhance energy efficiency and overall system performance. This approach not only helps address the problem of water scarcity but also contributes to mitigating heat stress issues [2].

In many countries around the world, solar-based desalination is increasingly becoming a competitive solution for providing drinking water. Desalination of saline water is recognized as one of the most sustainable and promising alternative sources for water supply. It plays a significant role in the socio-economic development of many communities and industrial sectors. At present, more than 14,000 desalination plants are operating worldwide, producing several billion gallons of water per day. Of these, 57% are located in the Middle East and the Persian Gulf region, where they operate in conjunction with large conventional thermal and power plants. However, since these facilities are mainly powered by fossil fuels, their operating costs are steadily increasing, and the pollutants and greenhouse gases they emit are being recognized as increasingly harmful to the environment. Furthermore, such plants are often not economically viable even in coastal regions with abundant seawater, particularly in remote areas. In many regions, shortages of fossil fuels and inadequate or unstable electricity supply are also observed [4].

Nowadays, the use of solar air heaters is rapidly expanding in the processes of hot water production and desalination of saline water. These technologies, being environmentally friendly, renewable, and economically sustainable energy sources, reduce dependence on conventional energy resources and significantly decrease greenhouse gas emissions. In particular, the integration of solar air collectors into polygeneration systems makes it possible to simultaneously provide hot water supply, desalinate saline water, and even perform cooling functions. Research indicates that such systems demonstrate high energy efficiency and relatively low operating costs, making them especially suitable for application in regions rich in solar resources. Therefore, polygeneration technologies based on solar air heaters not only enhance water supply and energy efficiency but also serve as an important factor in ensuring sustainable development under the conditions of climate change [5]. The proposed solar water heating devices with concave air channels in the absorber can be effectively integrated not only into volumetric poly-generation systems but also into other types of heat and energy conversion technologies. Such integration, in particular, enables the multifunctional utilization of solar energy and allows achieving higher efficiency when used as a primary heat source. Moreover, double-basin solar stills can be connected to these systems, as they are based on a two-stage evaporation process. This configuration enhances energy conversion, increases the efficiency of the distillation process, and provides a greater amount of purified water compared to conventional single-basin devices.
It should be emphasized that **single-basin solar stills** represent the most common and historically established model of passive solar distillation systems. They consist of a simple basin that absorbs solar radiation and a transparent upper cover, utilizing solar energy to generate vapor and subsequently condense it to produce potable water. Due to their energy efficiency and ease of construction, this model is widely recognized as the fundamental and classic solar distillation system. Thus, integrating solar water heaters with concave air-channel absorbers into both double- and single-basin solar distillation systems contributes to intensifying heat transfer, accelerating the evaporation process, and improving overall energy efficiency. In this way, such systems offer an important solution for modernizing passive distillation units and advancing multifunctional (poly-generation) solar energy technologies.

2. Formulation of the problem

One of the most effective methods for improving the performance of solar air heater collectors with complex absorbers is the installation of embedded tube air channels into the working chamber of the collector. This type of embedded tube air channel provides high thermohydraulic efficiency and interacts with the airflow in the laminar or turbulent boundary layer without significantly affecting the main physical properties of the air stream, while effectively reducing viscosity on the tube surface. As a result, the heat transfer processes are intensified, and the overall heat transfer coefficient is increased.

In an advanced complex absorber, embedded tube channels help to optimize the hydrodynamic parameters of the flow, reduce energy losses, and organize efficient heat transfer, thereby maximizing the thermal efficiency of solar air heater collectors. At the same time, such designs are particularly important

for controlling turbulence and improving thermal conductivity [6].

The analysis of the structural organization of the airflow shows that, in general, the entire flow field volume can be divided into two main regions: the boundary layer located near the channel surface and the outer flow region beyond it. The boundary layer, characterized by its high viscosity properties, directly governs the dynamic and heat exchange processes with the channel surface. In this layer, velocity gradients of the flow increase significantly, which intensifies internal friction and heat transfer processes. The outer flow, by contrast, lies outside the direct influence zone of the boundary layer and is generally considered a potential flow region, where the influence of viscous forces can be regarded as negligible [7].

The dynamic and thermal interactions between these two regions represent one of the main factors defining the overall hydrodynamic and thermal characteristics of the flow. The potential flow region, through interlayer interactions, can significantly influence the boundary layer during energy transfer processes, thereby optimizing heat and mass transfer. The boundary layer itself plays the central role in the dynamic and thermal interaction processes between the flow and the surface it washes. Energy losses are primarily determined by flow separation phenomena and the formation of vortices caused by them. Therefore, to minimize energy losses, it is essential to create flow conditions that reduce the occurrence of flow separation to the lowest possible level [8-12].

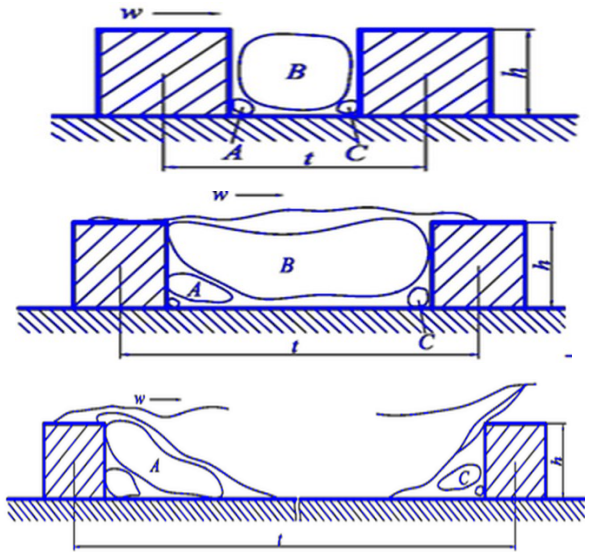


Figure 2. The effect of the temperature limit on the formation of air grooves.

In solar air heaters with complex absorbers, an increase in cavity depth directly influences the hydrodynamic behavior of the airflow and the heat transfer processes. This phenomenon represents an essential factor in determining the structural characteristics of the flow, including the development of the boundary layer, the level of turbulence, and the stability of the flow direction. Therefore, the proper selection and optimization of cavity depths are considered a key design parameter in enhancing the efficiency of solar air heaters.

An inaccurate or improper choice of cavity depth, on the other hand, may lead to the formation of undesirable vortices in the flow, which reduces the efficiency of heat transfer processes and causes energy losses. Hence, in the design of solar air heaters with complex absorbers, it is necessary to conduct in-depth theoretical and experimental analyses of hydrodynamics and heat transfer in order to optimize cavity depths.

Overall, accurate determination and optimization of cavity depths not only ensure the stability of airflow but also play a crucial role in increasing the thermohydraulic efficiency of solar collectors.

The efficiency of the solar air heater, which is developed for polygeneration systems proposed, is largely dependent on solar radiation. The following table shows the changes in climate, including solar radiation, in the Fergana region.

Average total solar radiation falling on Fergana region.

Table.1

Area	**Chanag of the solar radiation (W/m²)**			
	I	**IV**	**VII**	**X**
Kukon	295	388	815	483
Fergana	290	380	810	480
Shohimardon	288	515	800	378

A mathematical model of heat transfer and viscosity processes under continuous airflow conditions along the cavity surfaces of air channels in solar air heaters with complex absorbers is presented. In developing this mathematical model, the differential equations of the laminar boundary layer are expressed as follow

3. Methods

A mathematical model of heat transfer and viscosity processes under continuous airflow conditions along the cavity surfaces of air channels in solar air heaters with complex absorbers is presented. In developing this mathematical model, the differential equations of the laminar boundary layer are expressed

as follow. The plot is considered to consist of a curved line.

$$\frac{\partial}{\partial x}=\frac{\partial}{\partial \xi}\frac{\partial \xi}{\partial x}+\frac{\partial}{\partial \eta}\frac{\partial \eta}{\partial x}$$
$$\frac{\partial}{\partial y}=\frac{\partial}{\partial \xi}\frac{\partial \xi}{\partial y}+\frac{\partial}{\partial \eta}\frac{\partial \eta}{\partial y} \quad (1)$$

For this reason, to facilitate computation, using Mesis substitutions (x,r) the domain is reduced from a coordinate to a regular (ξ,η)quadrilateral

In this method, viscosity in the medium decreases more rapidly relative to the overall dimensions of the boundary layer. According to the law of conservation of momentum in hydrodynamic processes, when three unknown values are determined, approximate calculation methods are aimed at obtaining an equation with a single unknown. This is achieved by selecting velocity profiles that depend on one parameter. As such a parameter, the value φ, i.e., the cavity (indentation) coefficient, has been proposed. Based on the hypotheses of L. Prandtl, G. I. Taylor, and A. N. Kolmogorov regarding the fundamental characteristics of turbulence, semi-empirical methods for boundary layer calculations have been developed [6, 7, 8].

When considering the dependence of pressure and friction gradient on heat exchange processes, the mass conservation law equation is expressed as follows.

The differential equation for the state after the substitutions is as follows:

$$\begin{cases}
\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial \xi}+(U\eta'+F(x)V)\frac{\partial U}{\partial \eta}+\frac{\partial p}{\rho\partial \xi}+\eta'\frac{\partial p}{\rho\partial \eta}= \\
\quad =F(x)\frac{\partial}{\rho\partial \eta}\left(\rho(v+v_t)F(x)\frac{\partial U}{\partial \eta}\right)+(v+v_t)F(x)\frac{\partial U}{r\partial \eta}, \\
\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial \xi}+(U\eta'+F(x)V)\frac{\partial V}{\partial \eta}+F(x)\frac{\partial p}{\rho\partial \eta}= \\
=F(x)\frac{\partial}{\rho\partial \eta}\left(\rho(v+v_t)F(x)\frac{\partial V}{\partial \eta}\right)+(v+v_t)F(x)\frac{\partial V}{r\partial \eta}-(v+v_t)\frac{V}{r^2}, \\
\frac{\partial T}{\partial t}+U\frac{\partial T}{\partial \xi}+(U\eta'+F(x)V)\frac{\partial T}{\partial \eta}= \\
=F(x)\frac{\partial}{\rho\partial \eta}\left(\rho\left(\frac{v}{\mathrm{Pr}}+\frac{v_t}{\mathrm{Pr}_t}\right)F(x)\frac{\partial T}{\partial \eta}\right)+\left(\frac{v}{\mathrm{Pr}}+\frac{v_t}{\mathrm{Pr}_t}\right)F(x)\frac{\partial T}{r\partial \eta} \\
\frac{\partial \tilde{v}}{\partial t}+U\frac{\partial \tilde{v}}{\partial \xi}+(U\eta'+F(x)V)\frac{\partial \tilde{v}}{\partial \eta}=(P_v-D_v)+ \\
+\frac{F(x)}{\rho\sigma_v}\frac{\partial}{r\partial \eta}\left[r\rho(v+\tilde{v})F(x)\frac{\partial \tilde{v}}{\partial \eta}\right]+\frac{C_{b2}}{\rho\sigma_v}\left(F(x)^2\frac{\partial r\rho}{r\partial \eta}\frac{\partial r\tilde{v}}{r\partial \eta}\right),
\end{cases} \quad (2)$$

Where is the curvature function of the solid wall, $F(x)$-derivatives of the new coordinate, P_v-generation, D_v- dissipation.

The increase in heat dissipation is observed as a result of the addition of the heap between the boundaries of each heap to the main air stream. The heap is formed between the two limits of the heat sink, and the coefficient of heat transfer is characterized by the point of joining the main air stream.

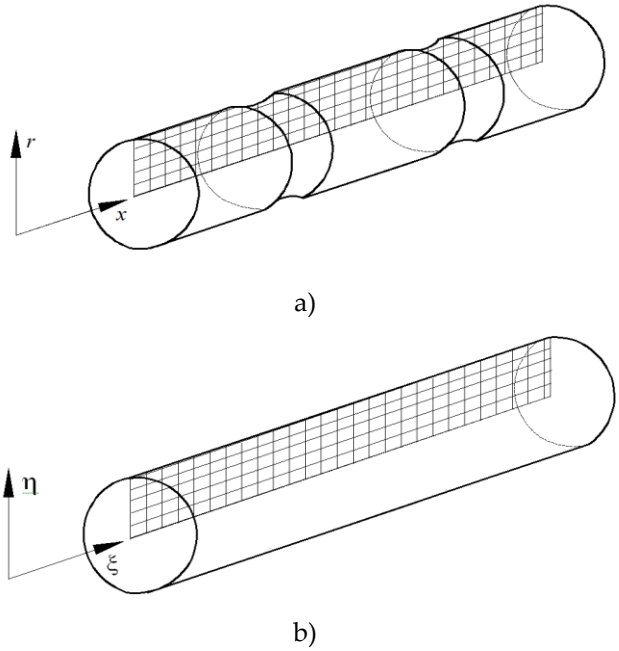


Figure 3. Scheme of transforming a curvilinear coordinate system into a regular rectangular coordinate system: curvilinear (a) and rectangular (b) Cartesian coordinate system.

Boundary condition on the wall, symmetry condition along the axis, and extrapolation condition at the outlet. These conditions are given as follows:

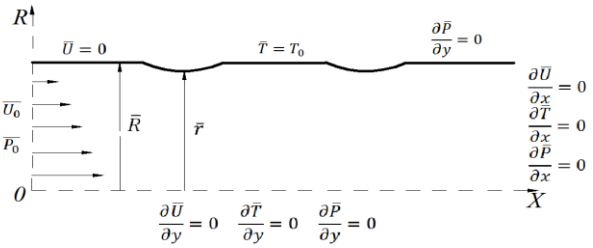


Figure 4. Initial and boundary conditions.

As a result of scientific research conducted to improve the efficiency of solar air collectors, it has been observed that the presence of geometric cavities in the air channels of the collector has a positive effect on the heat transfer process. In particular, compared to smooth-surfaced tubes, those with annular-shaped transverse indentations deform the airflow, generate localized vortex zones within the flow structure, and consequently enhance the effective performance of the heat transfer surface. Experimental studies have shown that such cavities drive the flow toward a quasi-

turbulent state, significantly increasing the temperature gradient near the wall, which in turn intensifies heat transfer through the tube wall.

The cavities formed on the tube surface induce suspended air vortices within the flow, which act as the primary mechanism for intensifying heat exchange. This effect is particularly pronounced at low Reynolds numbers, since the flow has not yet fully transitioned to a turbulent regime and the cavities exert a considerable influence on its structure. Experiments further revealed that both the height and positioning of the cavities are critical factors. When their geometric parameters are selected in proportion to the internal diameter of the tube—that is, corresponding to the transverse dimension of the flow zone—heat transfer reaches its maximum level. This condition enables the optimization of heat exchange with particles moving within the near-wall region of the flow. However, if cavity height is excessively increased, additional turbulence arises in the central region of the flow, which leads not to improved heat transfer but rather to increased pressure losses.

Based on experimental and theoretical analyses, it can be emphasized that cavities within air channels artificially promote turbulence, thereby significantly increasing the heat transfer coefficient. At the same time, not only geometric design but also the hydraulic properties of the flow play an important role in optimizing the heat exchange process. For instance, as the Reynolds number increases, turbulence intensity in the flow strengthens, but simultaneously the thermal resistance zone near the wall stabilizes, reducing the effectiveness of vortices in reaching the surface. This slows down the rate of increase in heat transfer intensity. Therefore, when flow parameters and the geometry of cavities on the inner tube surface are harmonized—that is, when optimal geometry is defined to match flow conditions—tubes can achieve maximum operational performance from an energy efficiency standpoint. The experimental results suggest that one of the most effective solutions to enhance heat transfer performance is the use of indented tubes, since they have been proven to provide significantly higher convective heat transfer rates compared to smooth tubes. This approach is particularly effective in solar air collectors operating under natural or forced convection conditions. The vortices formed within the airflow actively transport heat flux to the wall surface, thereby improving overall thermal efficiency. Taken together, theoretical modeling and experimental findings highlight the promising potential of indented tubes in thermal technologies and support their evaluation as a vital constructive element of heat transfer systems [14-16].

4. Results

In the indented air channel of the solar air heater collector (Fig. 5), it can be observed that as the Reynolds number increases, vortices begin to form between the indentations of the air tube. However, as shown in (Fig. 6), the increase in Reynolds number restricts the transport of heat toward the central axis of the tube, which negatively affects the overall performance efficiency of the device. Taking this into account, it is necessary to select an optimal flow velocity.

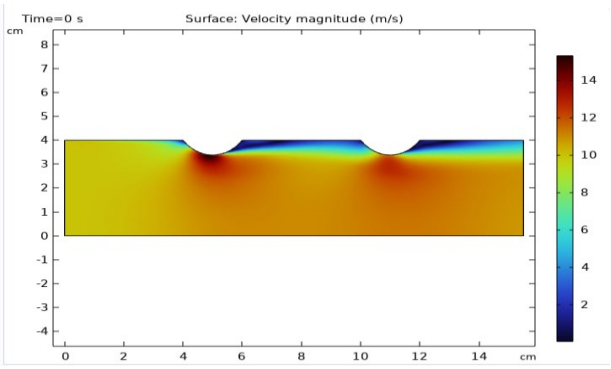
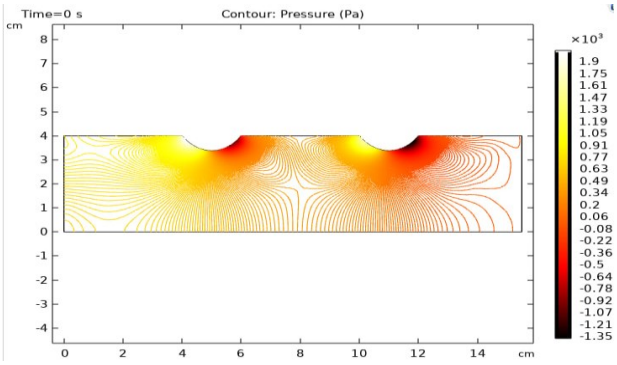
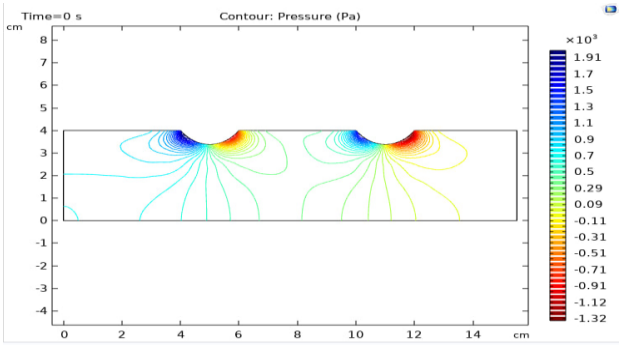


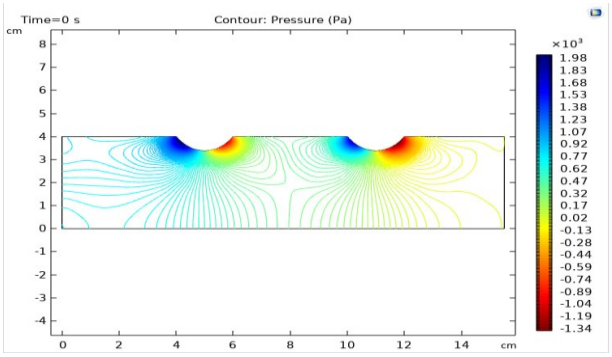
Figure 5. Variation of velocity vectors at concave boundaries



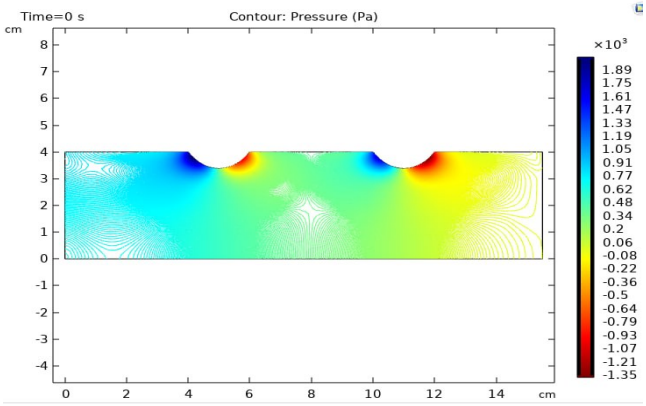
a)



b)



c)



d)

Figure 6. Variation of velocity vectors at concave boundaries

At the optimal depth of indentation in an air tube, the increase in hydraulic resistance and the increase in the heat transfer coefficient occur at the same rate. This makes it possible to reduce the size of heat exchangers, since with equal hydraulic resistance, heat transfer in indented air tubes is 25–40% higher compared to smooth tubes. Therefore, the optimal indentation depth is considered highly effective for intensifying heat transfer. The optimal indentation depth in the tube is defined within the range of $0.1 > 2h/D > 0.02$, while the optimal pitch is determined within the range of $25 > t/h > 10$.

4. Discussion

The results of the computational and theoretical analyses demonstrate that the proposed mathematical model adequately describes the thermo-hydrodynamic processes occurring in solar air heater collectors with complex absorbers. The model responses to changes in flow parameters, cavity depth, and geometric configurations were consistent with the physical nature of the studied processes, which indicates its reliability and suitability for engineering applications.

A key outcome of the study is the confirmation that the introduction of embedded cavities into air channels promotes controlled turbulence and enhances heat transfer efficiency. Experimental and numerical results show that, at optimal cavity dimensions ($0.1 > 2h/D > 0.02$ and $25 > t/h > 10$), heat transfer in indented tubes exceeds that of smooth tubes by 25–40%, while maintaining similar hydraulic resistance levels. This finding is in agreement with earlier studies that highlighted the importance of surface modifications and artificial turbulence generation in improving the performance of solar collectors (e.g., Prandtl's boundary layer theory and subsequent turbulence models by Taylor and Kolmogorov).

At the same time, the analysis revealed that excessive cavity depth can lead to undesirable vortex formation and increased pressure drop, thereby offsetting the benefits of enhanced heat transfer. These results confirm the necessity of optimizing cavity geometry in accordance with Reynolds number ranges and operating conditions. For instance, at low Reynolds numbers, cavity-induced vortices are especially effective in intensifying near-wall heat exchange, whereas at higher Reynolds numbers, the stabilization of the thermal resistance zone reduces the contribution of vortices to heat transfer enhancement.

The computational experiment carried out was aimed at testing the response of the proposed model to changes in individual parameters from a large range of data that have different dimensions and different intervals of changing values. The responses turned out to be explainable from the point of view of the nature of the object being studied, which serves in favor of the reliability of the proposed model. Accordingly, it can be used in the calculation and optimization of the heat exchanger and heating network with a single-strand structure. In this direction, it is promising to take into account the operation of the valve regulators connected to each heat exchanger.

5. Conclusions

This study has demonstrated that the integration of cavity geometries into solar air heater collectors with complex absorbers significantly enhances their thermohydraulic performance. The research confirmed that properly optimized cavities promote controlled turbulence, intensify temperature gradients near the wall, and improve the overall heat transfer coefficient. At the same time, the results showed that excessive cavity depth leads to additional turbulence and pressure losses, which can negatively affect efficiency. Thus, determining the optimal cavity depth and pitch is essential for maximizing the thermal performance of solar air collectors.

The proposed mathematical model, developed on the basis of boundary layer theory and validated using COMSOL Multiphysics 6.1 with an average relative error of 4.6%, has proven to be adequate for predicting the thermodynamic and hydrodynamic properties of compressible media in such systems. This confirms its applicability for the design, calculation, and optimization of solar air heater collectors and heat exchanger networks.

Furthermore, the findings emphasize that the use of indented tubes in solar air collectors provides 25–40% higher heat transfer efficiency compared to smooth tubes while maintaining similar hydraulic resistance levels. Such results not only advance the theoretical understanding of heat and mass transfer in indented channels but also provide practical design guidelines for the development of high-performance, energy-efficient solar thermal systems.

Overall, the research highlights that cavity optimization, combined with reliable numerical modeling, represents a promising approach for enhancing the efficiency of polygeneration systems designed for hot water production and desalination. These systems, being environmentally friendly, renewable, and sustainable, are particularly valuable in regions rich in solar resources and facing water scarcity, making them a key technology in addressing both energy and water challenges under the conditions of global climate change.

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