Quyosh suv isitish poligeneratsiya tizimidagi issiqlik uzatilishi va havo oqimining sirkulyatsiya jarayonlari

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Dolzarbligi: Quyosh suv isitish tizimlari energiya ta’minotining barqaror va ekologik xavfsiz manbai sifatida jadal rivojlanib borayotgan sharoitda, ularning issiqlik samaradorligini oshirish va energiya yetkazib berishning uzluksizligini ta’minlash masalalari ayniqsa muhim ahamiyat kasb etmoqda. Bunda issiqlik uzatish jarayonlari, xususan konvektiv almashinuvning Nyusselt soniga bog‘liqligi, tizimning asosiy ishlash ko‘rsatkichlarini belgilab beruvchi hal qiluvchi omil hisoblanadi. Tadqiqotning dolzarbligi shundaki, mavjud adabiyotlarda quyosh suv isitkichlari bo‘yicha ko‘plab ishlar mavjud bo‘lsa-da, issiqlik almashinuvining aniq fizik mexanizmlari, oqim rejimining harorat taqsimotiga ta’siri va kollektor chiqishidagi issiqlik quvvati bilan o‘zaro bog‘liqligi yetarlicha chuqur ochib berilmagan. Ayniqsa, massa sarfi, absorber geometriyasi, ishchi suyuqlikning termofizik xossalari va quyosh nurlarining o‘zgaruvchan intensivligi kabi real ishlash sharoitlari uchun yanada aniq va ishonchli korrelyatsiyalar zarur. Shu jihatdan, ushbu tadqiqot issiqlik almashinuvi jarayonlarini tavsiflashning yangi metodik yondashuvlarini taklif etishi, analitik va empirik modellarning aniqligini oshirishi hamda ilg‘or raqamli modellashtirish orqali quyosh suv isitkichlarining konstruktiv yechimlarini optimallashtirishga imkon berishi bilan dolzarb hisoblanadi. Olingan natijalar issiqlik barqarorligini ta’minlash, energiya yo‘qotishlarini kamaytirish va tizimning umumiy samaradorligini oshirishga qaratilgan innovatsion echimlarni ishlab chiqishda katta ahamiyatga ega.

Maqsad: Ushbu tadqiqotning asosiy maqsadi — quyosh suv isitish poligeneratsiya tizimlarida sodir bo‘ladigan issiqlik uzatish, tabiiy va majburiy sirkulyatsiya jarayonlarini chuqur tahlil qilish, ularning termogidravlik xususiyatlarini aniqlash hamda tizim samaradorligini oshirishga xizmat qiladigan yangi ilmiy yondashuvlarni ishlab chiqishdan iboratdir. Tadqiqotda, ayniqsa, quyosh kollektoridan suv saqlagich (tank)ka bo‘lgan tabiiy termosifon oqimining shakllanishi, suv qatlamlanishi (stratifikatsiya), bosim farqi hosil bo‘lishi va sirkulyatsiya intensivligining Nyusselt soni, Reynold soni hamda issiqlik tashuvchi muhit zichligiga bog‘liqligi aniqlanadi.

Usullari: Ushbu tadqiqotda quyosh suv isitish poligeneratsiya tizimidagi issiqlik uzatish va suyuqlik hamda havo oqimining tabiiy va majburiy sirkulyatsiya jarayonlari nazariy, hisoblash hamda raqamli modellashtirish usullari asosida o‘rganildi. Dastlab termosifon tizimidagi tabiiy sirkulyatsiya kollektor–tank konturida suvning qizishi, zichlikning kamayishi, sovuq suvning pastki qatlamga cho‘kishi va tank ichida vertikal qatlamlanish jarayonlari orqali tahlil qilindi.

Natijalar: Ushbu tadqiqotda quyosh suv isitish poligeneratsiya tizimidagi issiqlik uzatish va sirkulyatsiya jarayonlari nazariy tahlil, hisoblash modellari va raqamli simulyatsiyalar asosida o‘rganildi. Termosifon tizimida suvning qizishi natijasida zichlik kamayishi, sovuq suvning pastki qismga cho‘kishi va tank ichidagi qatlamlanish tabiiy sirkulyatsiya mexanizmini aniqlash uchun asos qilib olindi. Sirkulyatsiyani hosil qiluvchi bosim farqi balandlik farqi va suv zichliklarining o‘zgarishi bo‘yicha baholandi. Issiqlik almashinuvi Nyusselt, Reynold va Prandtl sonlariga asoslangan korrelyatsiyalar orqali hisoblandi. Turbulent oqim sharoitida absorber kanallaridagi issiqlik almashinuvini kuchaytirish uchun qo‘pol yuzalar va turbulizatorlar qo‘llandi. Termogidravlik samaradorlik bosim yo‘qotishlari va issiqlik o‘tish koeffitsientlari nisbatiga qarab baholandi. Eksperimental o‘lchashlar CFD (ANSYS Fluent) modellashtirish natijalari bilan solishtirildi.

Kalit so‘zlar: Quyosh suv isitkich, poligeneratsiya tizimi, termosifon sirkulyatsiyasi, konvektiv issiqlik almashinuvi, nyusselt soni, reynold soni, turbulent oqimni kuchaytirish, absorber plastinkasi qo‘polligi, termik qatlamlanish, suv saqlagich dinamika, issiqlik samaradorligi, bosim yo‘qotishi, CFD modellashtirish, issiqlik almashinish modeli, termogidravlik samaradorlik koeffitsienti.

For citation: Abdukarimov B.A. Heat transfer and air-flow circulation processes in a solar water-heating polygeneration system. Scientific and technical journal of Problems of Energy and Sources Saving, 2025, no. 4, pp. 383-390.

https://doi.org/10.5281/zenodo.18694565

Received: 04.04.2025
Revised: 18.04.2025
Accepted: 10.07.2025
Published: 27.12.2025

Процессы теплообмена и циркуляции воздушного потока в полигенерационной системе солнечного водонагревания

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Актуальность: В условиях интенсивного развития систем солнечного водонагревания как устойчивого и экологически безопасного источника энергоснабжения особо важное значение приобретают задачи повышения их тепловой эффективности и обеспечения непрерывности подачи тепла потребителям. При этом процессы теплообмена, в частности зависимость конвективного теплообмена от числа Нуссельта, являются ключевыми факторами, определяющими основные эксплуатационные показатели таких систем. Актуальность исследования состоит в том, что, несмотря на наличие значительного числа работ, посвящённых солнечным водонагревателям, фундаментальные физические механизмы теплообмена, влияние режимов течения на распределение температуры и взаимосвязь этих факторов с тепловой мощностью коллектора раскрыты недостаточно полно. Особенно необходимо разработать более точные и надёжные корреляции для реальных условий эксплуатации, таких как изменение массового расхода, геометрии абсорбера, термофизических свойств рабочего теплоносителя и колебаний солнечной радиации. В этом отношении исследование является актуальным, поскольку предлагает новые методические подходы к описанию процессов теплообмена, повышает точность аналитических и эмпирических моделей и позволяет оптимизировать конструктивные решения солнечных водонагревателей с использованием современных численных методов. Полученные результаты имеют важное практическое значение для обеспечения тепловой стабильности, снижения энергетических потерь и повышения общей эффективности солнечно-тепловых систем.

Цель: Основной целью данного исследования является глубокий анализ процессов теплообмена и естественной и принудительной циркуляции в полигенерационных системах солнечного водонагревания, определение их термогидравлических характеристик и разработка научно обоснованных подходов, направленных на повышение эффективности системы. Особое внимание уделяется изучению формирования естественного термосифонного потока от солнечного коллектора к накопительному баку, стратификации воды, возникновению разности давлений и зависимости интенсивности циркуляции от числа Нуссельта, числа Рейнольдса и изменения плотности теплоносителя.

Методы: В исследовании процессы теплообмена, а также естественной и принудительной циркуляции жидкого и воздушного потоков в полигенерационной системе солнечного водонагревания изучались на основе теоретического анализа, расчётных моделей и численного моделирования. На первом этапе была проанализирована естественная термосифонная циркуляция, возникающая в контуре «коллектор–бак» в результате нагрева воды, уменьшения её плотности, опускания охлаждённых слоёв вниз и вертикальной стратификации в накопительном баке. Разность давлений, вызывающая циркуляцию, определялась исходя из перепада высот между коллектором и баком и изменения плотности воды. Конвективный теплообмен рассчитывался с использованием корреляций на основе чисел Нуссельта, Рейнольдса и Прандтля. Для интенсификации теплообмена в условиях турбулентного течения в каналах абсорбера применялись шероховатые поверхности и турбулизаторы. Термогидравлическая эффективность оценивалась по соотношению между потерями давления и коэффициентом теплоотдачи. Экспериментальные измерения сопоставлялись с результатами CFD-моделирования в ANSYS Fluent для проверки корректности теоретических моделей.

Результаты: В ходе исследования процессы теплообмена и циркуляции в полигенерационной системе солнечного водонагревания были изучены на основе теоретического анализа, расчётных моделей и численного моделирования. Установлено, что естественная циркуляция возникает вследствие уменьшения плотности воды при нагреве, опускания холодных слоёв вниз и формирования стратификации в накопительном баке. Разность давлений, обеспечивающая циркуляцию, определялась перепадом высот и изменением плотности жидкости. Теплообмен количественно оценивался с помощью корреляций на основе чисел Нуссельта, Рейнольдса и Прандтля. Усиление теплообмена в условиях турбулентного течения достигалось применением шероховатостей и турбулизаторов в каналах абсорбера. Термогидравлическая эффективность оценивалась по критерию соотношения между потерями давления и коэффициентом теплоотдачи. Экспериментальные данные хорошо согласуются с результатами CFD-моделирования в ANSYS Fluent, что подтверждает достоверность предложенных моделей.

Ключевые слова: Солнечный водонагреватель; полигенерационная система; термосифонная циркуляция; конвективный теплообмен; число Нуссельта; число Рейнольдса; интенсификация турбулентного потока; шероховатость пластины абсорбера; тепловая стратификация; динамика накопительного бака; тепловая эффективность; потери давления; CFD-моделирование; модель теплообмена; термогидравлический коэффициент эффективности.

Heat transfer and air-flow circulation processes in a solar water-heating polygeneration system

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Relevance: In the context of the rapid development of solar water-heating systems as a stable and environmentally safe source of energy supply, increasing their thermal efficiency and ensuring uninterrupted heat delivery to end-users are becoming particularly important. Heat transfer processes—especially the dependence of convective heat exchange on the Nusselt number-represent key factors that determine the operational performance of such systems. Although numerous studies on solar water heaters exist, the fundamental physical mechanisms of heat transfer, the influence of flow regimes on temperature distribution, and the relationship between flow behavior and the thermal output at the collector outlet have not been sufficiently explored. In particular, more accurate and reliable correlations are needed for real operating conditions such as changes in mass flow rate, absorber geometry, thermo-physical properties of the working fluid, and fluctuations in solar irradiance. From this perspective, the present study is highly relevant as it proposes new methodological approaches for characterizing heat-exchange processes, improves the accuracy of analytical and empirical models, and enables optimization of structural solutions in solar water-heating systems through advanced numerical simulations. The obtained results are of significant practical value for ensuring thermal stability, reducing energy losses, and enhancing the overall efficiency of solar-thermal systems.

Aim: The primary aim of this study is to conduct an in-depth analysis of the heat-transfer processes and the natural and forced circulation phenomena occurring in solar water-heating polygeneration systems, to determine their thermo-hydraulic characteristics, and to develop new scientific approaches aimed at improving system performance. Special emphasis is placed on examining the formation of natural thermosiphon flow from the solar collector to the storage tank, temperature-driven water stratification, the development of pressure differences, and the dependence of circulation intensity on the Nusselt number, Reynolds number, and density variations of the working fluid.

Methods: The heat-transfer mechanisms and the natural and forced circulation of liquid and air flows in the solar water-heating polygeneration system were investigated through theoretical analysis, computational modelling, and numerical simulation. Initially, natural thermosiphon circulation was analyzed based on water heating in the collector, density reduction, downward movement of cooler water, and vertical stratification within the storage tank. The pressure difference driving circulation was determined as a function of the height difference between the collector and tank and the density variation of the fluid. Convective heat transfer was evaluated using correlations based on the Nusselt, Reynolds, and Prandtl numbers. Under turbulent flow conditions, heat-transfer enhancement in the absorber channels was achieved through the application of surface roughness elements and turbulence-promoting devices. Thermo-hydraulic performance was assessed through the ratio of pressure losses to the heat-transfer coefficient. Experimental measurements were compared with CFD simulations performed in ANSYS Fluent to validate the theoretical models.

Results: This study investigated heat-transfer and circulation processes in a solar water-heating polygeneration system using theoretical analysis, numerical modelling, and simulation tools. Natural circulation was shown to arise from the reduction of water density during heating, downward movement of colder water, and stratification within the storage tank. The pressure difference driving the circulation was evaluated from the height difference and density change of the working fluid. Heat-transfer processes were quantified using Nusselt-, Reynolds-, and Prandtl-number-based correlations. Under turbulent conditions, heat-transfer enhancement was achieved using surface roughness and turbulators inside the absorber channels. Thermo-hydraulic performance was evaluated through the balance between pressure drop and heat-transfer coefficient. Experimental observations showed good agreement with CFD (ANSYS Fluent) simulation results, confirming the accuracy of the proposed models.

Keywords: Solar water heater; polygeneration system; thermosiphon circulation; convective heat transfer; Nusselt number; Reynolds number; turbulent-flow enhancement; absorber-plate roughness; thermal stratification; storage-tank dynamics; thermal efficiency; pressure drop; CFD simulation; heat-exchange modelling; thermo-hydraulic performance factor.

1. Introduction

The solar air heater has a simple design and is considered cost-effective due to insufficient maintenance. However, at the same time, the heat transfer performance between the air flow and the absorber plate leads to the fact that the thermal efficiency is also low due to the low thermal conductivity of the air.

One of the most common ways to increase the heat transfer coefficient is to install artificial roughness on the absorber plate. An artificial coarse absorber plate adhesive can break the bottom layer and create a strong absorber near the heated absorber, which allows faster flowing air in the outer region to be mixed with low-speed air near the wall, which leads to high heat [1-6]. Experimentally analyzed the activity of the solar air heater provided with various obstacles [7]. With different geometric parameters, the effect of several arc-shaped ribs on the properties of heat transfer and friction is assessed [8].

Another way to improve the performance of a solar air heater is to change the absorber plate. The operation of three types of solar air collectors with flat plate, v-corrugated and wing absorber has been studied [9-11]. An experimental and theoretical analysis of a double cross-corrugated and double-sided V-corrugated solar air collector has been conducted. An experimental investigation of solar air heaters with corrugated plate, crack whole plate and corrugated packaging has been conducted [13]. In addition, a number of studies have been conducted, and they are mainly aimed at improving performance by artificial rough rip installed in the absorber plate or modified absorber structure [12].

Furthermore to increase the heat transfer performance of a solar air heater is to change the shape of the air duct or the bottom plate in the air duct of a solar air heater. Two-pass transverse slotted solar air heater collector performance has Wave-like shaped absorption plate and bottom plate has been analyzed [14]. Studied the thermal performance of solar air heaters with a semicircular and triangular transverse cross-sectional channel under external processing [15]. This model is relatively simple to build and easier to install than other methods. In addition, this method can be artificially combined with a solar air heater with a coarse absorber.

In this case consider the case when the system of collectors, water thank and connecting pipe conductors is filled with cold water. Solar radiation passes through a transparent coating (glass) and heats the Collector's light-absorbing panel and the water in its channels. In the process of heating, the density of water decreases, the heated liquid begins to flow to the high point of the collector, and then moves along the pipe to the water thank. In buck, the heated water moves to the upper point, while cooler water settles in the lower part of the buck, that is, depending on the temperature, the separation of water into layers occurs.

Cold water moves along the pipe from the bottom of the tank to the bottom of the Collector. Thus, in the presence of sufficient solar radiation, a constant circulation is established in the contour of the collector, the speed and intensity of which will depend on the current density of solar radiation.

As a result, the difference in pressures in the system (Δp, *Pa*) the body calls for natural circulation in the solar collector, i.e.

$$\Delta p = g \times H \times (\rho_1 - \rho_2) \quad (1)$$

there $g = 9{,}81$ m/s^2; $N = H_1 - H_2$ (m) – the difference between the upper limit and the lower cold water inlet of the solar collector at the inlet of the heated water in the water thak; ρ_1 and ρ_2-the lower part of the water battery cold water, respectively (T_1) and the density of heated water (T_2) in the water battery.

The difference in how much (T1) and (T2) is high and the value of N is large, the intensity of the natural circulation of water in the device is high.

The peculiarity of such a system is that in the case of a thermosiphon system, it is necessary that the lower point of the water accumulator is no higher than 3-4 m from the upper point of the collector, in the pump circulation, the water thank can be optionally located.

Such a condition is important not only to ensure normal water circulation in the presence of solar radiation during daylight hours, but also to prevent reverse water circulation in the device. These devices are considered very simple in terms of their wide use, exploitation, preparation all over the world, especially in hot climate countries.

In cold climates, it is advisable to use a two-contour scheme of solar water heating collectors, not one-contour. It serves as the main heat carrier heated in the Collector any non-freezing, chemically inactive, (for example, a mixture of water with ethylene or propylene, antifreeze, glycanthine (a mixture of water with glycerin), etc.) liquids.

The thermo hydraulic magnification factor is a measure that relates the rate of heat transfer within a system to the properties of airflow, which is replaced by friction parameters and pressure drop through the flow chamber [16].

2. Methods and materials

Another way to enhance the performance of a thermal collector under Turbulent flow conditions is to use stationary energy on the inner surface of the absorber plate. This stagnant energy is usually not transported by air due to sufficient time. There are two main techniques for exploiting this energy: the first involves breaking the adhesive sub layer that stores this energy and creating geometric roughness on the plate. The second technique involves obstructing and remixing the air to lift towards the absorber plate to extract energy from the laminar sub layer using tabulators. However, the second technique leads to a significant improvement in heat energy transfer and a decrease in pressure when the roughness is much greater than the thickness of the lower layer.

As determined by the studies, the flow periodicity rises with Reynolds number (Re), and the overall loss coefficient develops almost steadily when the flow resistance is high.

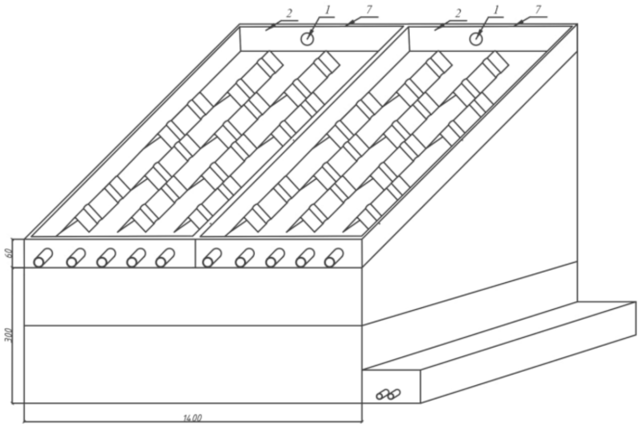

Fig.1. A polygeneration device for water desalination and hot water production based on a solar air heater

Dynamic state of triangular channel flat solar air heater: the principle of operation of this solar air heater is as follows. As a result of sunlight on the working surface of the collector, the absorber (3) heats up and absorbs air from the Collector's heated air outlet (1) pipe using a suction fan. The Collector includes an amount equal to the amount of heated air consumption through the air inlet pipes (5), air flow from the external environment along the working surface. This air flow increases itself in temperature under the influence of the convective heat exchange process. Convective heat exchange occurs on the working surface of the absorber (3) and along the inner and outer surfaces of the triangular-shaped (4) channels. The inner convex geometric shape (Figure 2), which is given to the air Channel of the triangular shape, fulfills the vases that form a heat.

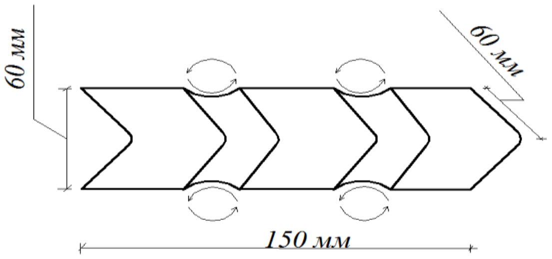

Fig.2. Scheme of the air duct air-acting duct

The thermal insulation (7) layer between the absorber and the body of the solar air heater prevents heat loss from the heated absorber and helps to transfer the available heat to the air.

Solar air heater heat conduction body made of low porous plastic (6) ensures that the heat in the working Chamber of the collector is not wasted

According to the flow planar, it can be divided into a boundary layer on the channel surface and an external flow. The boundary layer occupies a key role in the dynamic and heat exchange processes of the flow with the washable body. The loss of energy is determined by the elongation patterns in the action and the shedding produced by them.

According to the research work studied, the heat carrier in the receiving devices can be divided into three types of storage. Continuous, pre-discontinuous and discontinuous. The flow can be laminar and turbulent. The downstream method can be used to solve the boundary layer issue. We take the following deviations; methods for structurally solving boundary layer problems in a free-form profile given that the flow is stable and the air is incompressible, without two-dimensional heat exchange of the flow, are based on solving the momentum equation.

$$\frac{d\delta^{**}}{\partial x}+\frac{dV_0}{\partial x}\frac{\delta^{**}}{V_0}(2+H)=\frac{\tau_\omega}{\rho_0 V_0^2} \tag{2}$$

Where δ ** is the momentum loss thickness ; δ* is the compression thickness; v_0, ρ_0 is the velocity and density at the outer boundary of the boundary layer; N= δ*/ δ**; τω is the friction strain on the wall. In the case where the profile and velocity of the boundary layer are clear, the compression thickness is determined by expressions below.

$$\delta^{*}\int_0^{\delta}(1-\frac{\rho v}{(\rho_0 v_0)})dy \tag{3}$$

- pulse loss thickness.

$$\delta^{**}\int_0^{\delta}\frac{\rho v}{(\rho_0 v_0)}(1-\frac{v}{v_0})dy \tag{4}$$

Due to the fact that there are three uncertain parameters to the equation of pulses - δ**, δ* and τ ω, according to the method of solving the problem approximately, by a series of profiles and speeds depending on one parameter on the equation with one denomination. In place of such a parameter, the amount φ, called The Shape parameter, has been proposed, and as a result of this allows the development of structural methods of boundary layers according to theoretical grounds about the existence of internal scales of turbulence. [16] the method of contribution of the Turbulent boundary layer with a vanishing Meltdown is also of particular importance[17-18].

3. Results

The graphical results illustrate the two-phase (air–liquid) interaction processes that occur when a stream of hot air is introduced across the liquid volume. As the hot air flows downward, its elevated temperature induces an intensive evaporation process in the region near the liquid surface. During this process, the thermal energy carried by the air is transferred to the liquid molecules, causing a portion of the liquid to undergo a phase change and transition into vapor. In the boundary layer where this phase transformation occurs, a strong temperature gradient is formed, which enhances the local heat flux. The colored contours in the figure represent the distribution of air volume fraction: the upper region shows a high concentration of air, while the lower region is dominated by liquid. As the hot air penetrates into the liquid, convective up flow patterns are generated, promoting mixing, the formation of local vortices, and an increase in turbulence intensity. These vortex structures significantly increase the local rate of evaporation and lead to the formation of air bubbles within the liquid. As the bubbles rise, additional heat and mass transfer occur across the liquid–gas interface, further intensifying the overall energy exchange within the system.

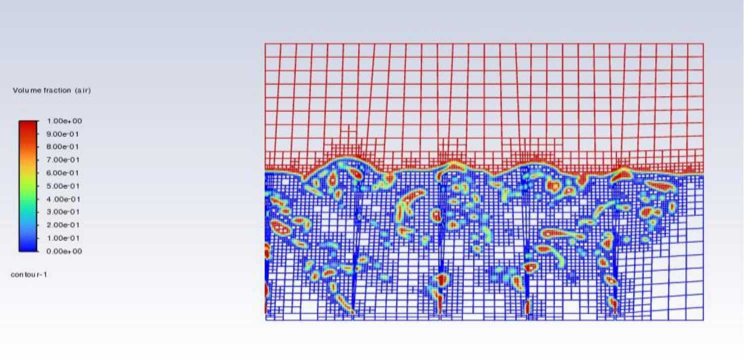

Fig.3. Isoclines of airflow motion in a channel with value Re=4183

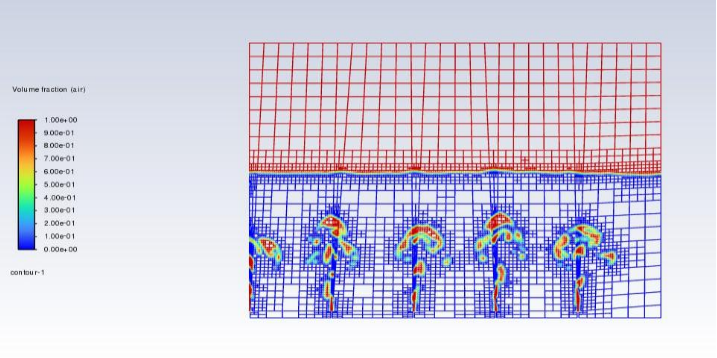

Fig.4. Isoclines of airflow motion in a channel with value Re=3552

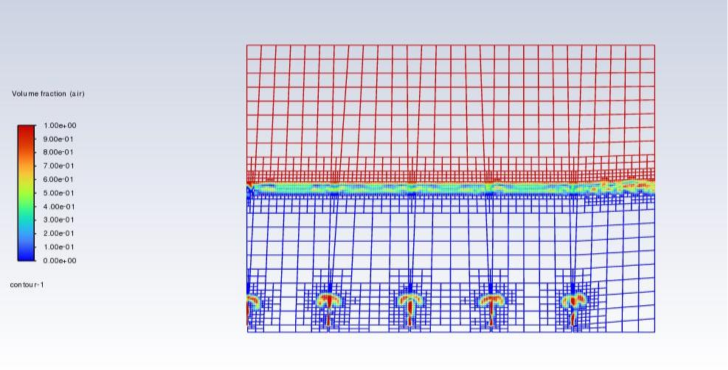

Fig.5. Isoclines of airflow motion in a channel with value Re=2764

In this method, the dimensions to the cohesion muxite decrease more rapidly compared to the dimensions in the entire boundary layer. As can be seen from the above (figures 3,4,5)in the sun air heater collector concave air channel, as the Reynolds number increases, heaps begin to form between the heaps in the air channel

4. Discussion

In this study, two-phase heat transfer processes occurring between the liquid phase and the gas phase in a solar polygeneration system operating on the basis of solar air-heating devices were thoroughly investigated using numerical modeling. The model accounted in detail for the penetration of hot air into the liquid surface and volume, the transfer of thermal energy from the air to the liquid molecules, the formation of an evaporation front, and the intensification of the interfacial temperature gradient. The investigation was conducted within the Reynolds number range of Re = 2000 to Re = 5000, which made it possible to observe the transition from laminar to turbulent flow, the emergence of vertical structures, and increased mixing intensity. Simulation results demonstrated that as the Reynolds number increases, convective heat transfer in the air–liquid contact zones intensifies significantly. At higher Re values, the appearance of upward-flowing vortices, enhanced turbulent momentum exchange, and active bubble diffusion introduce additional mechanisms of energy transfer that contribute to the rise in liquid evaporation rate. Consequently, the effective absorption of thermal energy delivered by the hot air stream increases, the temperature gradient near the phase interface becomes steeper, and the expansion rate of the evaporation front grows substantially.

This scientific approach provides a strong theoretical basis for the detailed analysis of two-phase heat-transfer mechanisms, the enhancement of evaporation processes, and the improvement of the overall thermal performance of solar polygeneration systems.

5. Conclusion

The conducted numerical and experimental investigations have demonstrated that the heat-transfer processes in a solar air-heating polygeneration system are strongly influenced by the interaction mechanisms between the gas and liquid phases, the intensity of convective mixing, and the evolution of turbulence structures within the flow domain. Analysis of two-phase interaction revealed that the introduction of hot air into the liquid volume significantly increases the evaporation rate due to enhanced convective heat flux, steep temperature gradients near the phase interface, and the formation of vortex-induced mixing zones. The transition from laminar to turbulent regime within the Reynolds number range of Re = 2000 and 5000 was found to play a decisive role in intensifying momentum exchange, bubble dispersion, and thermal energy absorption in the system. Experimental studies performed on the newly developed solar air collector with a triple-shaped bottom channel confirmed that channel geometry has a substantial effect on airflow stability, turbulence generation, and heat-transfer enhancement. The triple-channel configuration promotes improved mixing and higher local velocities, which contribute to more uniform temperature distribution and an overall increase in the collector’s thermal efficiency. These experimental findings validate the numerical observations and highlight the need for a refined mathematical model capable of accurately describing airflow behavior in complex channel geometries. Therefore, the research results justify the development of an advanced mathematical model of airflow within the collector’s air channels. Such a model should account for transitional and turbulent flow regimes, geometric-induced flow restructuring, temperature-dependent fluid properties, and multiphase evaporation effects. The creation of this model will enable more precise prediction of thermal performance, optimization of collector design, and enhancement of polygeneration system efficiency under varying operational conditions

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