BETTER EFFICIENCIES OF SOLAR AIR HEATERS ACHIEVED WITH DIFFERENT AIRFLOWS - A BRIEF REVIEW -

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Abstract: The use of solar air heater systems brings with it the convenience of having hot air at discretion for heating households with quite low prices compared to the use of conventional heating sources. The researchers desire to achieve the highest thermal efficiency of these systems has led to the emergence of different ways of improvement. The present work is focused on the available literature in the field of SAH systems made with different types of air flow. The paper also presents the different designs for the realization of airflow types used by researchers for high efficiency during the years 2017-2021.

Keywords: airflow, solar air heater, thermal efficiencies, heat transfer, fluid flow, convection, helical flow

1. INTRODUCTION

Due to the growing threat of environmental pollution and climate change around the world, renewable energy has attracted attention and is becoming an increasingly important concern for developing countries. The various types of renewable energies such as solar, wind, geothermal energy need advanced technologies, tidal, some renewable energies requiring expensive technologies. From the above listed, the only technology that is an exception is solar, which can be obtained in a reliable way, through a simple technology, easily existent in various parts of the world. Areas of solar energy use are: electricity generation through photovoltaic cells and thermal power plants; direct heating of water or air and providing passive ventilation in the dwellings. The easiest way to harness solar energy is to use solar heaters (SAHs) that heats a fluid (water or air) through a solar collector or a vacuum tube. The most commonly used are flat solar collectors that have multiple advantages: low cost, direct absorption of solar radiation, and they operate without the need of a solar orientation system [1].

The efficiency of a SAH system is affected by some parameters like the insulating materials, the number of glasses coverings, design of the absorbent plate and type of the system. A number of methods by which the heat transfer rates in the SAH can be increased are: the use of extensive surfaces, the use of artificial roughness on absorbent materials, etc. The use of multi-pass flow, porous media, selective coating on the absorbent plate are a series of methods that reduce losses from SAH to the environment. Increasing the thermal efficiency and heat transfer of a flat-plate solar collectors using obstacles as air turbulators and/or reflective surfaces are objectives of interest in the research environment [2].

By modifying the absorbent surface in solar air heaters, the interaction between air and plate changes, which causes the heat transfer rate to increase, making the SAH economically viable. The most important parameter when designing a solar air heater is the part where the absorbent plate is designed, part of which makes it thermally efficient and competitive with other systems on the market. Due to the low thermal efficiency and the deficiency

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of the heat storage capacity, it is an essential requirement to design absorbent plates that have 3D surfaces because such three-dimensional geometries can allow the maximum use of heat storage. A number of types of absorbents with flow arrangements have been studied and are being researched today with the aim of finding methods to improve thermal efficiency and flow characteristics in the air heaters [3]. The Figure 1 unveils a solar air heater model with its construction parts.

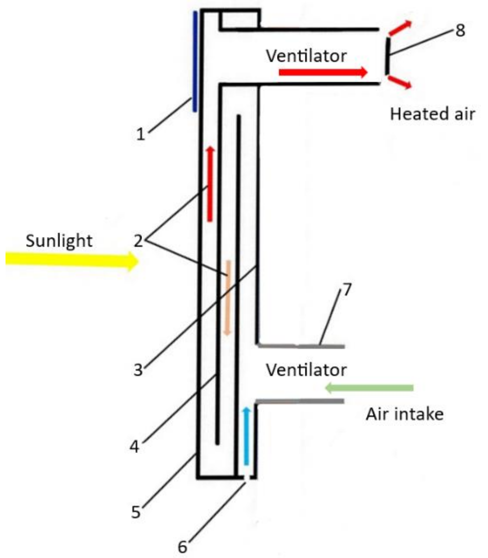


Fig. 1. Solar air heater panel: 1-PV panel to power fans; 2-airflow; 3-insulating material; 4-absorbent material; 5-transparent material; 6-outside air intake; 7-duct; 8-diffuser.

Because of their simplicity in design, very economical and with minimal maintenance SAHS have various applications and uses throughout the world like: heating residential dwellings (household use), industrial halls (industrial use), drying of vegetables and fruits, wood, having no problems related to frost and corrosion [4].

2. AIRFLOW TYPES USED IN SOLAR AIR HEATERS TO ENHANCE PERFORMANCES

The type of air flow is important in the realm of solar air heater systems because it can enhance the efficiency of heat transfer and augment the airflow characteristics of the equipment. After investigating the research in which the phrase "solar air heater" met at least once in the interval of 2017-2021 from the "Web of Science" database the form of airflow passages is classified. The classification of airflow passages presented in Figure 2 and detailed in Table 1 is exactly based on these publications and does not include the research period before 2017.

The article based on the study of rough jet and non-jet solar collectors was conducted to enhance the economic, energy and exergy optimization. Experimentally, by inserting a jet plate to the collector, an increase in exergy and energy efficiencies is achieved. This model of solar air heater has disadvantages such as increased costs and pollution. Results obtained: maximum energy efficiency of 59.4%; exergy efficiency equal to 1.58%; increased heating power; difference in temperatures – high outlet temperature compared to inlet temperature; decreased quantity of pollutants coming from CO_2, SO_2, NO. At the same time, it increases energy efficiency by 2.23%, exergy by 59% and costs by 150% [5].

Improved heat transfer for solar air heating systems has been experimentally analyzed using an inclined air jet [6]. The parameters used in the study were the mass flow rate, the relative diameter of the jet and the angle of attack with values in the ranges of 0.0128 to 0.0544 kg/s, 0.09-0.027, 15°-90°, respectively. The relative flow pitch and the relative distance of the jet ranged from 0.095-0.285 and 0.4-0.8. The maximum thermohydraulic performance was 2.38 for the relative distance of the jet of 0.6, the relative diameter of the jet of 0.18, the angle of attack of 60°, the relative flow pitch of 0.285 and the mass flow rate of 0.054 kg/s. The maximum exergy efficiency achieved for this type of system was 2.9.

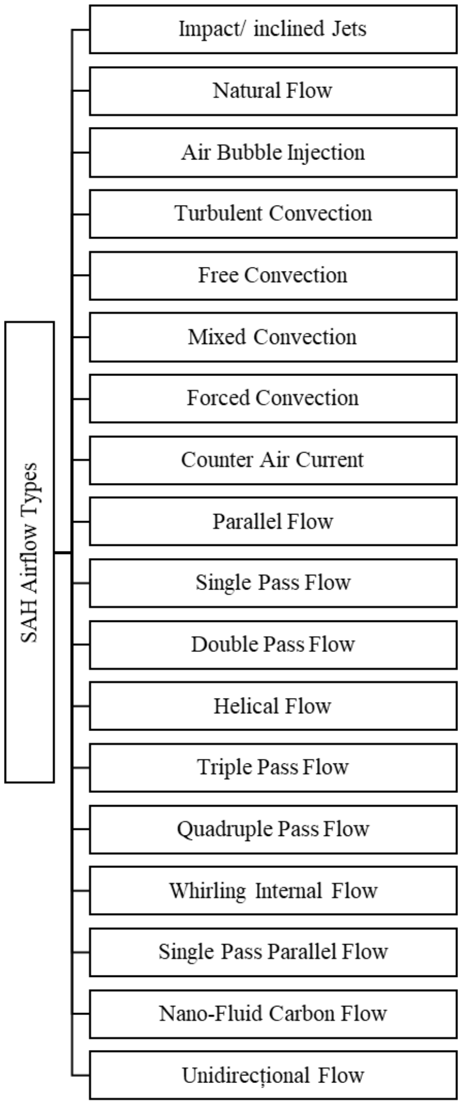


Fig. 2. Airflow types uses in solar air heaters.

The work considering natural flow was proposed and optimized a concept of integration of a double solar heating system that has high flow, with Trombe wall (thermal storage wall), integrated with SAH. Following optimization, an efficient design configuration is proposed after a total of seven independent configurations have been investigated. A significant increase in the flow rate of heated air mass by about 2.5 times can be observed if the Trombe wall is properly integrated, improving the hydraulic efficiency of the system. When increasing the mass flow, the exergy gain is substantial having a value of 142%, compared to a system that has a conventional design. Heating a space to a desired temperature with the new double SAH takes 70% less time, has a shorter payback life and can save tons of greenhouse gas emissions annually compared to conventional heating systems using fossil fuels. By using the SAH-Trombe double solar system the energy savings is significant, its integration into buildings can contribute to achieving the objectives of producing green energy from renewable sources with net-zero carbon emissions [7].

The effect of air bubbles injected into a solar air heating system was analyzed for the determination of thermal performance [8]. Air was injected through seven silicone tubes with thickness of 0.6 mm and an internal diameter of 8 mm with holes in diameter of 0.5 mm in the form of small bubbles at three air flow flows: 1; 1.5 and 2 L/min. Tap water was used as a working fluid and experiments were repeated three times for each airflow chosen for the study. The thermal efficiency of the system was about 16.5%, 69.2% and 68.8% for the injected air flow rates of 1; 1.5 and 2 L/min respectively.

Because of the negative effect of global warming and the high energy demand, a turbulent transient natural convection solar air heater is proposed to improve the system's thermal performance [9]. The solar flat air heater (SAH) is numerically investigated in terms of transient flow, airflow that is naturally ventilated and its thermal behavior. The Reynolds model of turbulence is used for the estimation of the heat flow and the Boussinesq approximation for the calculation of the buoyancy forces that is related to the density gradient. At an angle of inclination of 60° the maximum flow rate attains the peak, and the total increase in the incident radiation is 17%. It can also be noted that the effect of solar radiation and the width of the air duct increase the rate of the air flow by 100% and of the heat transfer by 35%. From the analyses carried out numerically using the finite element method, the efficiency of heat transfer is observed by a descending function of the angle of inclination, so that the maximum thermal efficiency is about 50%.

Free convection was used for the research of a solar air heating system with a solar radiation absorption surface with matrix of rectangular wings to determine the optimal arrangement of wings on the surface. The paper aims at the optimal arrangement in an air solar heater of three different configurations of fins, results with different sizes and distances between them while the flow of fluid and the heat transfer are directed through natural convection. The aim is to discover the optimal configuration of a matrix of fins to provide superior transfer of heat. Simulations are made for a heat flow that has values between 250-750 W/m^2. The height of the wings and the distance between the wings are varied to achieve the optimal configuration. The results show that the distance between the wings of 4.75 cm achieves a higher heat transfer with a saving of 33% of the material of the fins for the staggered configuration of the wings [10].

The numerical 3D study conducted for a solar air heating system with mixed convection investigated the consequence of channel height on airflow and heat transfer for upward fluid flow. Increasing the height of the canal creates a regime first chaotic then turbulent. Reducing the height of the channel can stabilize the flow. Nusselt shows large fluctuations and increases with the height of the channel [11].

The study involving forced convection was conducted for drying unripe and untreated bananas [12]. The mass flow, the thickness of the slices and the distance between the trays critically affect the drying behavior of the banana slices. Nevertheless, the choice of the size of the mesh of the tray must take into account the product to be dried. The combination: distance between slices of 0.15 m, fruit slice thickness of 0.002 m, mesh size of 0.01 m and mass flow of 0.03 kg/s resulted in average energy efficiency of 15.34% and exergy efficiency between 60.3 and 94.1%. These values are optimal for drying banana slices with the help of a solar air heating system.

The flow type in the counter-current was used in a SAH for heat transfer analysis and determination of fluid flow characteristics. The conduction of the system was with double passing provided with a combination of discrete staggered ribs in V. The study took into account the following parameters and their values: the Reynolds number "Re" with values in the range of 3000 – 21000, the relative distance of the inclined interval "I_g/L_v" valued within 0.4 to 0.8 and the angle of attack "α" with values within the interval 30°-75° while the rest of the roughness parameters had unchanging values. For this type of system, the thermohydraulic performance, the friction factor and the Nusselt number for the double-passing pipe with rough ribs were investigated. The outcomes of the study were compared with those of the double-pass channel without roughness, against which the counter-current ribbed system achieved a considerable improvement in the efficiency of the duct. Established on the experimental results, the optimal values of roughness and operating parameters were identified [13].

Parallel airflow was analyzed in a solar air heating system to determine the capabilities of systems with materials that retain and release temperature in double airflow mode [14]. Both thermal and numerical analysis is analyzed for a built-in PCM solar heater by parallel passage of air for flow combinations. To solve the differential equations of energy of each component in the collector, the Finite Volume Method is used. The maximum thermal performance of 64.1% was obtained for the total mass flow rate of 0.05 kg/s and the heat flow of 600 W/m^2. These values were considered optimal for the conducted study.

The design, manufacture, numerical analysis and environmental effects of a solar air heating system were analyzed under forced convection and a single-pass system [15]. The study included the analysis of four different models of solar systems. Also, the thermal performance and the exergy efficiency in single-pass and forced convection collectors with the help of a fluid mechanics program (CFD) were determined. The values obtained with this program had errors of less than 1%. Out of the four analyzed models resulted an environmental impact factor of 0.32, thermal efficiency equal to 91% and exergy efficiency of 4.7%. Although the Z-type model achieved an average efficiency of 78%, construction, temperature, mass flow and pressure distribution could be improved. The exergy efficiency for this type of model had values in interval 1.13-1.35%.

The double passage of the flow was integrated with the analysis of the solar air heating system with triangular wings on the absorption surface. The system's thermal efficiency was compared by examining two other systems with the same construction, without and with wings. The impact of the air mass flow present in the system on the thermal performance has been analyzed in various ambient conditions. The results showed that the temperature difference is constantly greater through the winged solar heating system, and the large variation between the input and output temperature indicates an efficient heat transfer. The daily thermal efficiency of the winged system was 61.42%, 59.41% and 56.57%; for the wingless system it was 57.08%, 53.28% and 51.04% considering the mass flow rate of 0.0121, 0.0101 and 0.0081 kg/s respectively. The use of a solar heating system with wings and double passage improved thermal efficiency by 4.3-6.1% compared to the solar system without fins. The efficiency of the winged system has always been higher than the efficiency of the system without fins indifferent of the mass flow rate present in the systems. The presence of wings in the upper air ducts, creates turbulence, the air thus has better contact with the absorption surface and penetrates into all regions raising the heat transfer [16].

The helical flow has been studied together with the solar dual-passing air heating system for the exploration of thermal efficiency and heat transfer [17]. This work continues the previous research of a solar air heater with double passage with HTF, where energy efficiency and heat transfer performance have been studied both experimentally and numerically in a channel with a triangular cross-section. This type of system reduces the quantity of inactive vortices generated at the edge of the passage of the air flow, which decreases the pressure drop. The results showed that optimized geometry led to an increase in thermo-hydraulic performance compared to the reference geometry for all Reynolds numbers, which shows an increase of 16.5%. The energy efficiency of optimized geometry improves by a maximum of 14.52% for all Reynolds numbers (Re=5000). The maximum energy efficiency of about 94% is achieved by the system for the Reynolds number equal to 50000 and the thermohydraulic yield factor had a maximum value of 2.65.

The solar triple-passing air heating system has been studied in combination with a mesh of tubes placed below the absorption surface of the system [18]. For the purpose of comparison, two solar systems with triple passage and with tubes below the absorption surface were analyzed: one with one bottle and one with two bottles as a material that covers the absorption surface and allows the sunlight to pass. Experiments with this type of systems were carried out in winter and compared in the same weather conditions. For all air mass flows, the results indicated that the solar system with triple passage with tubes below the absorption surface and with double layer of glass achieves greater efficiency compared to the single-glass system. The maximum efficiency was equal to 80.2% and 73.4%, respectively. The improvement in efficiency confirms that the addition of a network of tubes below the absorption surface and a double layer of glass have an important influence on the efficiency and capacity of heat transfer.

The solar quadruple air heating system was analyzed in combination with a greenhouse-based drying system. Performance tests were performed at mass flows of 0.008 and 0.010 kg/s. The average thermal efficiency achieved for the solar air heating system with quadruple passage is in the range of 71.63-80.66%. The largest instantaneous temperature difference in the quadruple system was 28.10 °C for the air mass flow rate equal to 0.008 kg/s. Experimental results have indicated that the integration of a quadruple-passing solar air heating system with a greenhouse-based drying system can considerably reduce drying time [19].

Studies on the solar air heating system with whirling internal flow were conducted numerically and experimentally [20]. Two types of swirling streams were analyzed: active and passive. Regardless of the presence of an active eddy flow or passive, the thermal performance of the system is improved compared to a system without eddy flow. The maximum increase rate of thermal efficiency of the active eddy flow model was 23.83% and of the passive eddy flow model was 16.03% under the same optimal study conditions. It follows that the performance improvement of the active swirling flow system is greater compared to that of the passive swirling flow system.

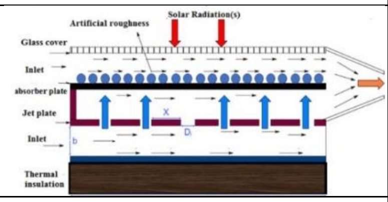
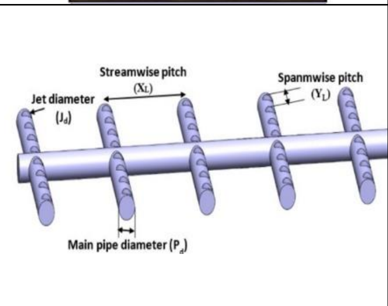
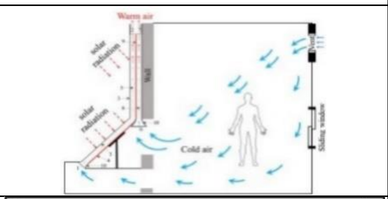
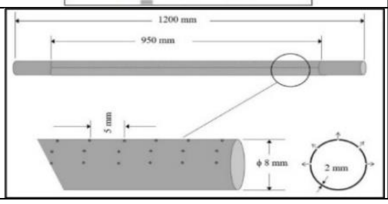
The parallel flow was analyzed integrated into a solar heating system with single-pass air and longitudinal circular wings on the absorption surface. The thermal study of the SAH was realized for five mass flow rates: 30, 45, 60, 75 and 90 kg/s present inside the 100 mm thick pipe. The experimental results accomplished by increasing the mass flow rate from 30 to 90 kg/s indicates augmentation in efficiency from 44.13 % to 56.98 % and from 24.98% to 36.62% respectively, considering the first and second law of thermodynamic. The outcomes conclude that the duration of the air flow within the duct plays an important role in the performances of the solar air heating system.

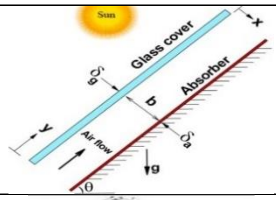
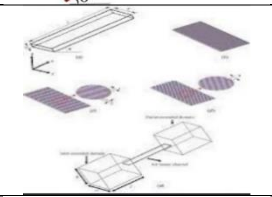
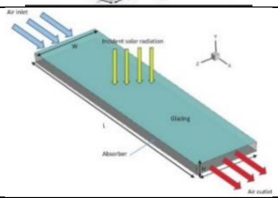
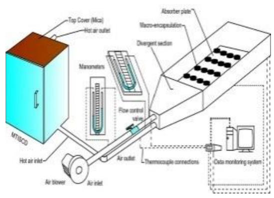
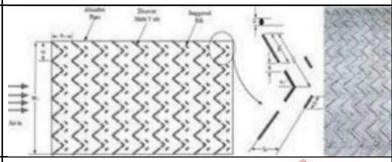
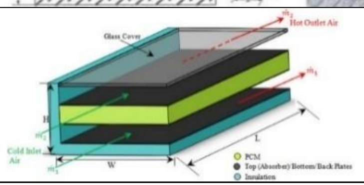
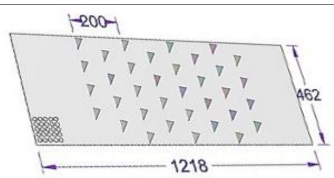
It is desired a lower flow rate to obtain the maximum exhaust air temperature and large differences amongst the inlet and output temperature [21].

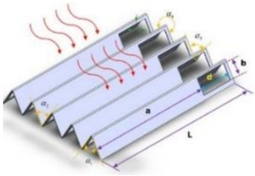
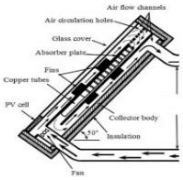
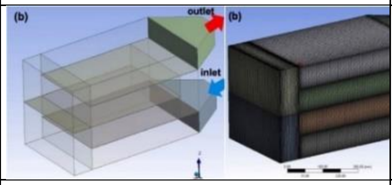
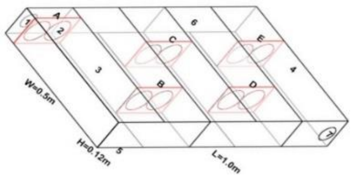
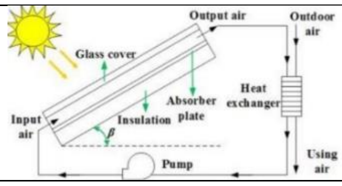
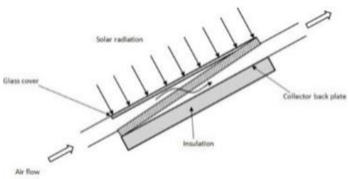
The effect of corrugated absorbent plates, the use of aerosol/black carbon nanofluids and turbulent flow in solar collectors was numerically investigated in a heat transfer study [22]. The use of CBNPs (carbon-black nanoparticles) with different volume fractions in a range from 0 to 0.1 in turbulent regime was also analyzed. By finite volume and SIMPE algorithm (Semi-Implicit Method for Pressure Linked Equations), the equation of continuity, momentum and 3D energy were solved. The corrugated absorbent plate was observed in a turbulent flow regime of and Reynolds number that ranged from 2,500 to 4,000. Choosing the right geometry was made on the basis of the criteria for evaluating the performance and the increase in air temperature from the entrance to the collector to the outlet of these. The research has a number of conclusions: for the sinusoidal wavy model, the largest PEC with the optimized Reynolds number of 2,500 is obtained; the rectangular wavy pattern has the greatest increase in temperature from the entrance to the output; at a volume fraction of 0.1 and Reynolds number of 4000, the best thermal performance conditions were achieved. The use of nanofluids throughout the Reynolds range with rectangular corrugated plate leads to a reduction in the output temperature of the SAH.

The unidirectional flow was used in the analysis of the thermal capacity of a solar heating system with porous bed air with the help of neural networks. The neural model was structured based on the datasets obtained from the experiments and the thermal efficiency values of SAHs. The maximum thermal efficiency obtained from the analyzes performed was 93.53%. Predictions obtained by the neural network method were also found close to experimental values for the specific systems compared [23].

Table 1. Solar Air Heaters with different airflows.

No.	SAH Type/ Reference	Representation of the system	Operating Parameters	Optimized Parameters	Key Results
1.	SAH with impact jets [5]		T_p=59.85-94°C; CO_2; SO_2; NO.	CO_2, SO_2 and NO emissions are reduced by about 122.6%, 122.66% and 123.19%.	Thermal Efficiency: 59%; Exergy Efficiency: 2.23%.
2.	SAH with inclined impact jets [6]		m = 0.0128; 0,0544 kg/s; α_J = 15-90°; J_d/P_d = 0.09-0.272 mm; X_L/L_{AP} = 0.095-0.285 mm; d_{AP}/H_D = 0.4-0.8 mm.	m = 0,054 kg/s; X_L/L_{AP} = 0.285 mm; α_J = 60°; D_p = 0.18 mm; d_{AP}/H_D = 0.6 mm; Y_L/W_{AP} = 0.071 mm.	Thermohydraulic Performance Factor: 2.38; Exergy Efficiency: 2.9%.
3.	Sah with high flow naturally driven [7]		h/R = 0.1-0.6; R = 50; 60; 70; 80; 90; 100 mm; I_R = 500-1100 W/m^2.	h/R = 0.3; R = 100 mm; θ = 60°; T = 194.5°C.	Thermohydraulic Efficiency: 72%.
4.	SAH with air bubble injections [8]		T = - 40°C; +580°C; Q_a = 1; 1,5; 2 L/min.	P = 8; h = 0.6 mm; D = 0.5 mm; I_R = 2.000 W/m^2; Q_a = 1.5 L/min.	Thermal Efficiency: 69.2%.

5.	SAH with turbulent transitional natural convection [9]		θ = 30-90°; I_R = 800-1200 W/m^2;	θ = 30°; Q_a grew 100%; q grew 35%.	Thermal Efficiency: 50%.
6.	Free convection SAH [10]		q = 250-750 W/m^2; S = 0.054; 0.047 m; θ = 15°; 30°; 45°.	S = 0.047 m.	Up to 33% of fin material is saved with 15 × 10 fins arrangement.
7.	Mixed convection SAH [11]		q = 200-1000 W/m^2; A = 10-40; Re = 50-1000;	Pr_{air} = 0.7; Re = 50; 100.	Thermohydraulic Performance Factor: 3.34; Maximum Friction Factor: 2.71%.
8.	Forced convection SAH [12]		m = 0.015-0.030 kg/s; h = 0.002-0.004 m; PS = 0.01-0.015 m; SP = 0.1-0.15 m; T = 23.3-60.5°C; I_R = 25-830 W/m^2.	PS = 0.01 m; SP = 0.15 m; m = 0.03 kg/s; G = 6 kg; θ = 10.18°; h = 0.002 m.	Exergy Efficiency: 60.3-94.1%; Average Energy Efficiency: 15.34%.
9.	SAH with counter air current [13]		Re = 3000-21000; I_g/L_v = 0.4-0.8; α = 30-75°.	-	Considerable improvement in pipeline performance.
10.	Parallel flow SAH [14]		q = 600-1000 W/m^2; m = 0.1-0.05 kg/s.	m = 0.03; 0.05 kg/s; q = 600 W/m^2.	Thermal Efficiency: 64.1%.
11.	Single-pass flow SAH [15]		v = 0.05-0.45 m/s.	Re = 3446; m = 0.0385 kg/s.	Environmental Impact Factor: 0.32; Exergy Efficiency: 4.7%; Thermal Efficiency: 91%.
12.	Double-pass flow SAH [16]		m = 0.0081; 0.0101; 0.0121 kg/s.	m = 0.0121 kg/s.	Thermal Efficiency: 67.52%.

13.	Helical flow SAH [17]		Re = 5000; 50000; 100000.	Re = 5000; m = 0.061 kg/s; I_R = 863 W/m².	Energy Efficiency: 94%; Thermohydraulic Performance Factor: 2.65.
14.	Triple-pass flow SAH [18]		m = 0.0075; 0.0188; 0.0282; 0.037 kg/s; I_R = 590; 636; 733 W/m²; θ = 39°; 49°; 56°; d = 100; 160 mm.	t_p = 2 mm; θ = 50°; m = 0.0075 kg/s; P_{PV} = 18 W.	Maximum Thermal Efficiency: 80.2%.
15.	Quadruple-pass flow SAH [19]		m = 0.008; 0.010 kg/s;	T = 28.10°C; m = 0.008 kg/s.	Maximum Thermal Efficiency: 80.66%.
16.	SAH with whirling internal flow [20]		v = 1.5; 2.0; 3.5; 5.0 m/s;	q = 650 W/m²; T = 14.85°C;	Rate of increase in thermal efficiency (TEGR): 23,83%.
17.	Single-pass parallel flow SAH [21]	-	M = 30; 45; 60; 75; 90 kg/hm²; h_d = 100 mm.	M = 90 kg/hm².	Maximum Thermal Efficiency: 56.98%.
18.	SAH with nano-fluid carbon flow [22]		Re = 2500-4000.	α_w = 3 mm; λ_w = 1 mm; Re = 2500.	Thermal Performance Factor: 1.9%.
19.	Unidirectional flow SAH [23]		m = 0.0100; 0.0225 kg/s.	The ANN architecture type TRAINLM is indicating certain prediction of thermal performance.	Maximum Thermal Efficiency: 93.53%.

4. CONCLUSIONS

Solar air heaters are an important main component of systems for using energy aborted from the sun. They are able to capture this energy and convert it at the level of the absorbent surface into thermal energy which in turn can be converted into hot air, which flows through the SAH system. In applications where heat is needed to be generated for crop drying, building heating, textile industry, water desalination, marine products industry, solar air heaters are used. Due to the advantages such as: simple design, low production and operating costs (they have a small number of parts in their composition) SAH works without producing problems and without noise being very environmentally friendly. The major disadvantage is that they have a low thermal performance due to the heat loss that is observed at the level of the upper cover (glass). This disadvantage has led to a series of studies and experiments worldwide to be done with the aim of increasing the thermal performance at the level of the absorbent (absorbent plate) by modifying it through different configurations and new materials [24].

By introducing a jet plate to the solar air collector, an increase in energy efficiency of 59.4% and of exergy by 59% is achieved. It also has disadvantages such as increased costs and pollution [5]. The inclined air jet impact on a solar heat collector absorbing plate, on improving heat transfer, revealed that the angle inclination of the air jet is beneficial. Following the research an exergy efficiency of 2.9 and thermohydraulic performance of 2.38 are achieved [6].

Numerical investigation in terms of transient flow, airflow that is naturally ventilated, and its thermal behavior shows that the impact of the air duct width and the solar radiation increases the rate of heat transfer by 35% [9]. The optimal arrangement in an air solar heater of configurations with different sizes and fin materials shows that their use leads to a high heat transfer, the best configuration being the one with staggered fins that leads to a saving of 33% of the fin material [10].

Following the research of the articles in this work, the results showed a thermal efficiency that falls within the values of 50%-93.53%; exergy efficiency 2.23-2.9; thermohydraulic performance with a factor between 1.9-3.34 and energy efficiency of maximum 94%.

NOMENCLATURE

T_p - plate temperature [°C];
m - mass flow [kg/s];
J_d/P_d - relative jet diameter [mm];
d_{AP}/H_D - relative jet spacing [mm];
Dd - relative distance of the jet [mm];
X_L/L_{AP} - wise pitch relative stream [mm];
Y_L/W_{AP} - wise pitch relative span [mm];
α, α_J - angle of attack [°];
I_R - solar intensity [W/m2];
h/R - design factor bell-mouth;
R - bell-mouth curvature radii [mm];
D - diameter [mm];
P - pressure
Q_a - flow air [kg/s];
q - heat flux [W/m2];
θ - inclination angle [°];
S - spacing between fins [m];
Pr_{air} - air flow;
A - aspect ratio;
Re - Reynolds number;
h - flake thickness [m];
PS - tray mesh size [m];
SP - tray spacing [m];
G - weight [kg];
I_g/L_v - relative inclined gap distance;
v - air velocity [m/s];
t_p - plate thickness [mm];
d - air duct diameter [mm];
P_{PV} - power of PV cell [W];
h_d - duct thickness [mm];
M - mass flow rate [kg/hm^2];
α_w - Wavy amplitude [mm];
λ_w - wavelength [mm].

REFERENCES

[1] Omid, N.K., Hamid, K.M., Seyed, M.A., Asgar, A., Mohsen, S.P., Hydrothermal performance of humid air flow in a rectangular solar air heater equipped with V-shaped ribs, Energy Science and Engineering, vol. 10, no. 1, 2022, p. 2276-2289.
[2] Hiren, U.T., Kalpesh, V.M., Experimental assessment of double-pass solar air heater by incorporating perforated baffles and solar water heating system, Renewable Energy, vol. 183, 2022, p. 385-405.
[3] Abuşka, M., Kayapunar, A., Experimental and numerical investigation of thermal performance in solar air heater with conical surface, Heat Mass Transfer, vol. 57, 2021, p. 1791-1806.
[4] Karmveer, Gupta, N.K., Alam, T., Cozzolino, R., Bella, G., A Descriptive review to access the most suitable rib's configuration of roughness for the maximum performance of solar air heater, Energies, vol. 15, no. 8, 2022, art. no. 2800.
[5] Farahani, S.D., Shadi, M., Optimization-decision making of roughened solar air heaters with impingement jets based on 3e analysis, International Communications in Heat and Mass Transfer, vol. 129, no. 6, 2021, art. no. 105742.
[6] Maithani, R., Sharma, S., Kumar, A., Thermo-hydraulic and exergy analysis of inclined impinging jets on absorber plate of solar air heater, Renewable Energy, vol. 179, 2021, p. 84-95.

[7] Singh, A.P., Kumar, A., Akshayveer, A., Singh, O.P., Effect of integrating high flow naturally driven dual solar air heaters with trombe wall, Energy Conversion and Management, vol. 249, 2021, art. no. 114861.
[8] Khwayyir, H.S., Baqir, A.S., Mohammed, H.Q., Effect of air bubble injection on the thermal performance of a flat plate solar collector, Thermal Science and Engineering Progress, vol. 17, no. 1, 2020, art. no. 100476.
[9] Nia, M.F., Nassab, S.A., Gandjalikhan, S, Ghodrat, M., Behnia, M., Numerical simulation of the transient turbulent natural convection in an inclined rectangular shaped solar air heater, Thermal Science and Engineering Progress, vol. 26, no. 36, 2021, art. no. 101109.
[10] Kumar, D., Premachandran, B., Optimum arrangement of fins in a free convection-based solar air heater, asme, Journal of Solar Energy Engineering, vol. 142, no. 2, 2020, p. 1-39.
[11] Boulemtafes-Boukadoum, A., Abid, C., Benzaoui, A., 3D numerical study of the effect of aspect ratio on mixed convection air flow in upward solar air heater, International Journal of Heat and Fluid Flow, vol. 84, 2020, art. no. 108570.
[12] Arun, K.R., Kunal, G., Srinivas, M., Kumar, S., Sujith, C.S., Mohanraj, M., Jayaraj, S., Drying of untreated musa nendra and momordica charantia in a forced convection solar cabinet dryer with thermal storage, Energy, vol. 192, 2020, art. no. 116697.
[13] Ravi, K.R., Kumar, M., Kumar, M., Saini, R.P., Experimental investigation on heat transfer and fluid flow characteristics for roughened counter flow solar air collector, International Journal of Green Energy, vol. 19, no. 8, 2021, p. 865-878.
[14] Verma, G., Singh, S., Computational multiphase iterative solution procedure for thermal performance investigation of phase change material embedded parallel flow solar air heater, Journal of Energy Storage, vol. 39, 2021, art. no. 102642.
[15] Alic, E., Das, M., Akpinar, E.K., Design, Manufacturing, Numerical analysis and environmental effects of single-pass forced convection solar air collector, Journal of Cleaner Production, vol. 311, 2021, art. no. 127518.
[16] Machi, M.H., Al-Neama, M.A., Buzás, J., Energy-based performance analysis of a double pass solar air collector integrated to triangular shaped fins, International Journal of Energy and Environmental Engineering, vol. 13, 2022, p. 219-229.
[17] Mesgarpour, M., Heydari, A., Wongwises, S., Geometry optimization of double pass solar air heater with helical flow path, Solar Energy, vol. 213, 2021, p. 67-80.
[18] Yassien, H.N.S., Alomar, O.R., Salih, Mothana, M.M., Performance analysis of triple-pass solar air heater system: effects of adding a net of tubes below absorber surface, Solar Energy, vol. 207, 2020, p. 813-824.
[19] Tuncer, A.D., Sözen, A., Khanlari, A., Amini, A., Şirin, C., Thermal performance analysis of a quadruple-pass solar air collector assisted pilot-scale greenhouse dryer, Solar Energy, vol. 203, 2020, p. 304-316.
[20] Hu, J., Guo, M., Guo, J., Zhang, G., Zhang, Y., Numerical and experimental investigation of solar air collector with internal swirling flow, Renewable Energy, vol. 162, 2020, p. 2259-2271.
[21] Raam, D.G., Sreekumar, A., Experimental studies on energy and exergy analysis of a single-pass parallel flow solar air heater, Journal of Solar Energy Engineering, vol.142, no. 1, 2020, art. no. 011003.
[22] Sadripour, S., 3d numerical analysis of atmospheric-aerosol/carbon-black nanofluid flow within a solar air heater located in Shiraz, Iran, International Journal of Numerical Methods for Heat and Fluid Flow, vol. 29, no. 4, 2018, p. 1378-1402.
[23] Ghritlahre, H.K., Prasad, R.K., Prediction of thermal performance of unidirectional flow porous bed solar air heater with optimal training function using artificial neural network, Energy Procedia, vol. 109, 2017, p. 369-376.
[24] Abdullah, A.S., El-Samadony, Y.A.F., Omara, Z.M., Performance evaluation of plastic solar air heater with different cross-sectional configuration, Applied Thermal Engineering, vol. 121, 2017, p. 218-223.