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Thermal Performance of a Counter-Flow Double-Pass Solar Air Heater With The Steady and Pulsating Flow

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HIGHLIGHTS

- The tubular solar absorber is placed perpendicularly to the direction of airflow.
- Pulsating flow increases the thermal performance by up to 15.2%
- Thermal performance is directly proportional to the pulsating frequency.

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ABSTRACT

The present work studied the influence of pulsating flow as an active method on the thermal performance of a double-pass solar air heater with a tubular solar absorber. A ball valve has been used as a pulse generator mounted at the downstream flow of the solar air heater. The experiments were under indoor conditions with a constant heat flux of 1000 W/m^2, and different air mass flow rates ranged from 0.01 to 0.03 kg/s. Moreover, the study covered three pulsation frequencies varied from 1 to 3 Hz. Based on the experimental outcomes, it can be observed that the heat transfer rate is enhanced by applying the pulsating flow, where it was found that the outlet temperature in the case of applying the pulsating flow rises by about 25.6 - 27% as compared with the steady flow case. Moreover, pulsating flow offers a higher effective thermal performance by about 15.2% at the maximum air mass flow rate compared with the steady flow. In addition, the findings pointed out that varying the pulsation frequency from 1 to 3 Hz produces an enhancement in heat transfer rate and in solar heater effective efficiency, where it was found that when changing the frequency from 1 to 3, the increment of effective efficiency ranged from 3.8 to 6.9% depending on the air mass flow value.

1. Introduction

Solar energy is an unlimited source of clean energy [1], and it contributes to reducing pollution levels, as harvesting and converting solar energy into other energy types do not result in any kind of pollutants [2]. Solar energy can be converted directly into electric energy by using photovoltaic systems [3] or into thermal energy by using different systems such as solar collectors [4], solar towers [5], etc. Solar air heaters are considered the simplest among all solar systems because of their low cost, ease of construction, and low maintenance [6]. Solar air heaters are commonly used in different applications, for instance, heating buildings in cold zones, pre-heating the air in industrial applications, egg incubation, drying crops, fruits, medical herbs, etc. [7].However, solar air heaters suffer from some drawbacks that affect their thermal performance, namely, energy loss, low convective heat transfer coefficient between the working fluid and the solar radiation absorbing surface, and inability to meet the load requirements sometimes due to the intermittent nature of the solar radiation source [8].

Many researchers adopted different techniques to cope with the cons of solar air heaters. For example, some researchers focused on solving the intermittency problem either by integrating the solar air heaters with different designs of thermal energy storage systems [9 and 10] or by using hybrid techniques involving utilizing fins with PCM [11 and 12] or nanotechnology with PCM [13 and 14].

Other researchers focused on reducing energy losses by mixing nanoparticles with black paint to improve the absorptivity of solar radiation [15] or by using different insulation materials [16].

On the other hand, many researchers focused on improving the convective heat transfer coefficient by adopting two different techniques namely: passive and active techniques.

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Passive techniques involve creating roughness [17], inserting turbulators like winglets [18], dimples [19], fins [20], etc., or replacing conventional absorber plates with new types such as corrugated absorbers [21] triangular absorbers [22], etc.

Active techniques involve modulating the flow rate of the working fluid. For example, pulsating flow can be considered an active technique to enhance the convective heat transfer coefficient. The flow in this method is characterized by fluctuations in both the pressure and the mass flow rate. It remarkably influences the heat transfer process since the pulsation weakens the thermal resistance by altering the boundary layer thickness [23]. Pulsating flows can be generated either by reciprocating pumps [24] or by steady flow pumps with the help of pulsating generating instruments such as ball valves [25], butterfly valves [26], etc.

Utilizing pulsating flow in solar collectors was investigated by some investigators [27]. However, to the authors' knowledge, no attempt has been made to apply the pulsating flow in solar air heaters. Thus, the present work aims to investigate the thermal performance of a new design of a counter-flow double-pass solar air heater under both steady and pulsating flow conditions.

2. Experimental Setup

The experimental setup shown schematically in Figure 1 involves three main parts: a test section, pulsating airflow system, and a supply airflow system.

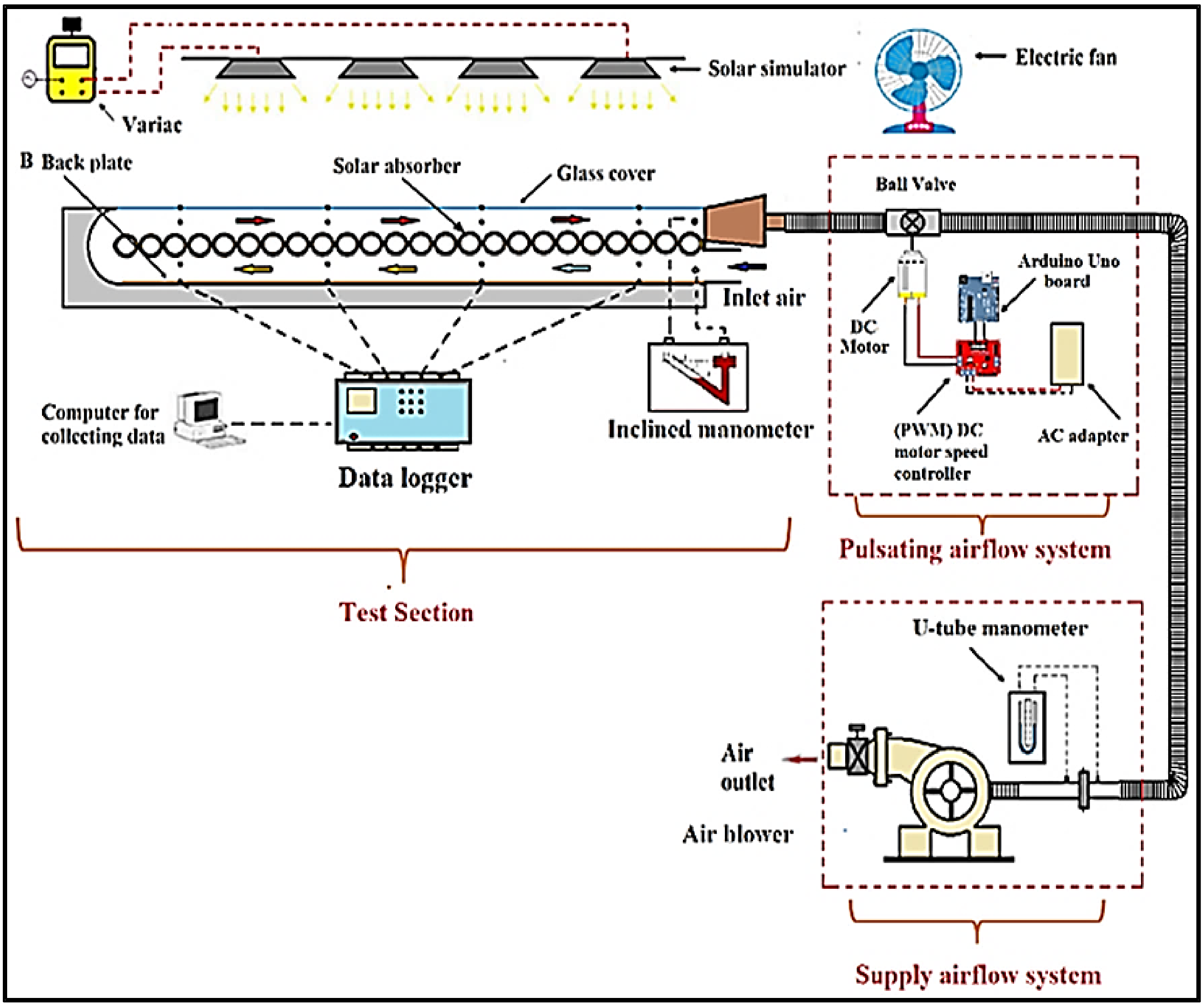

Figure 1: Schematic diagram of the experimental setup

The test section consists of a counter-flow double-pass solar air heater and an artificial solar simulator. The main components of the solar air heater are a wooden frame manufactured from a plywood sheet of 18 mm thickness, a glass cover of 4 mm thickness, upper and lower channels, a solar absorber, and a galvanized plate of 1 mm thickness. As shown in Figure 2, the solar absorber consists of 42 tubular capsules placed perpendicularly to the airflow direction. In addition, the upper face of the solar absorber was painted with black mat paint (Rust-oleum with absorptivity of 92%) to increase its absorptivity to solar radiation.

All dimensions, specifications, and materials used in the solar air heater are mentioned in Table 1. An artificial solar simulator comprising halogen bulbs and variac transformation has provided an artificial solar heat flux of 1000 W/m^2.

Pulsating airflow system, as shown in Figure 3, consists of a wooden frame, a ball valve with the potential to rotate 360 degrees for generating pulsating flow, a DC motor to rotate the ball valve, an AC adaptor, an Arduino-Uno board with the aid of (PWM) DC motor speed controller to control the rotation speed of the DC motor to achieve the required pulsating frequency.

Table 1: Dimensions, specifications, and materials of the solar air heater

Configurations	Details
Total length	1260 mm
Total width	340 mm
Total height	80.9 mm
Effective length	1200 mm
Effective width	300 mm
Height of upper & lower channels	32.15 mm
Material type of capsules	Copper
Effective capsule Length	300 mm
Outer Diameter	28.6 mm
Inner Diameter	26.7 mm
Thickness	0.9 mm
Number of capsules	42
Insulation thickness (Polyurethane foam)	50 mm

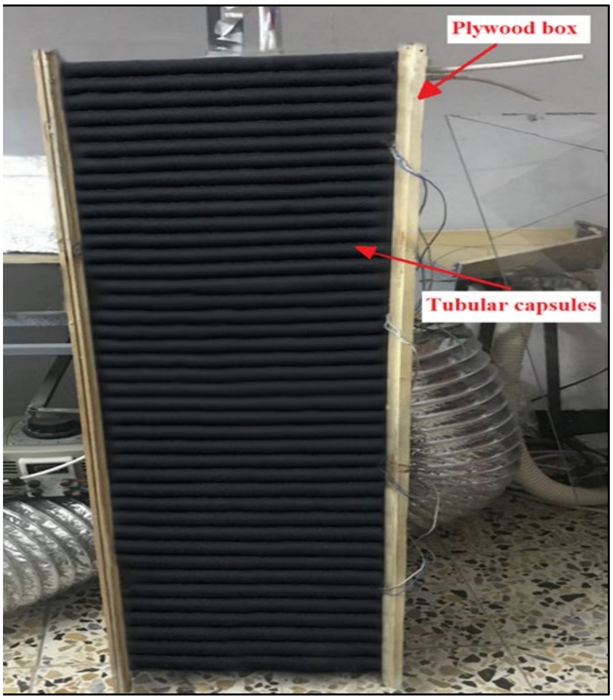

Figure 2: Solar absorber configuration

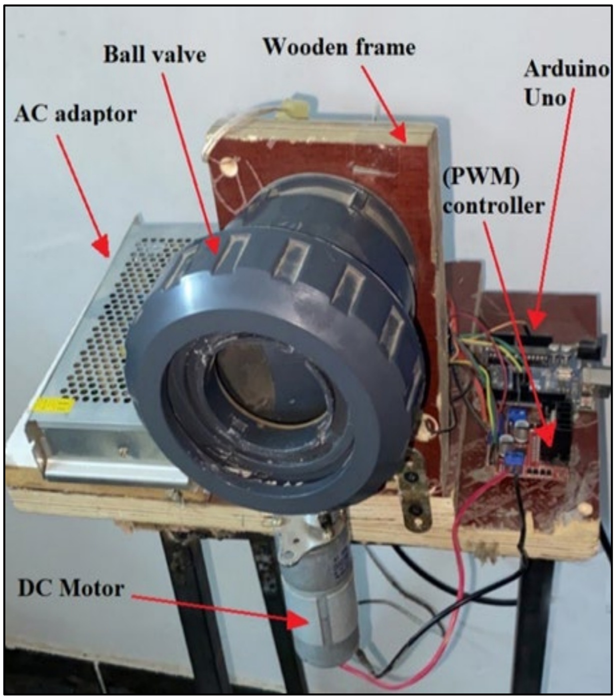

Figure 3: Pulsating airflow system

Pulsating flow was generated by rotating the ball valve, and for each revolution, the airflow was released and stopped twice. Thus the flow was assumed to be sinusoidal, as shown in Figure 4. The valve's rotation could be adjusted to rotate at specific rotation speeds to give different frequencies measured by the tachometer. Three frequency values of 1, 2, and 3 Hz were covered in all experiments. The air supply system involved an electric air blower with a manual valve that was placed on the pumping side of the blower to control the air mass flow rate value, a flexible hose, and an orifice meter with U-tube manometer to measure the air mass flow rate. The study covered five values of air mass flow rates ranging from 0.01 to 0.03 kg/s with an increment of 0.005 kg/s. To measure the temperature distributions, twenty-four thermocouples (type- K) have been placed in specified locations within the collector, as shown in Figure 5. Moreover, two thermocouples were installed at both the inlet and outlet of the solar heater to measure the air temperature rise. To measure the pressure difference through the solar air heater, an inclined manometer was connected to two holes located at the inlet and outlet of the solar air heater.

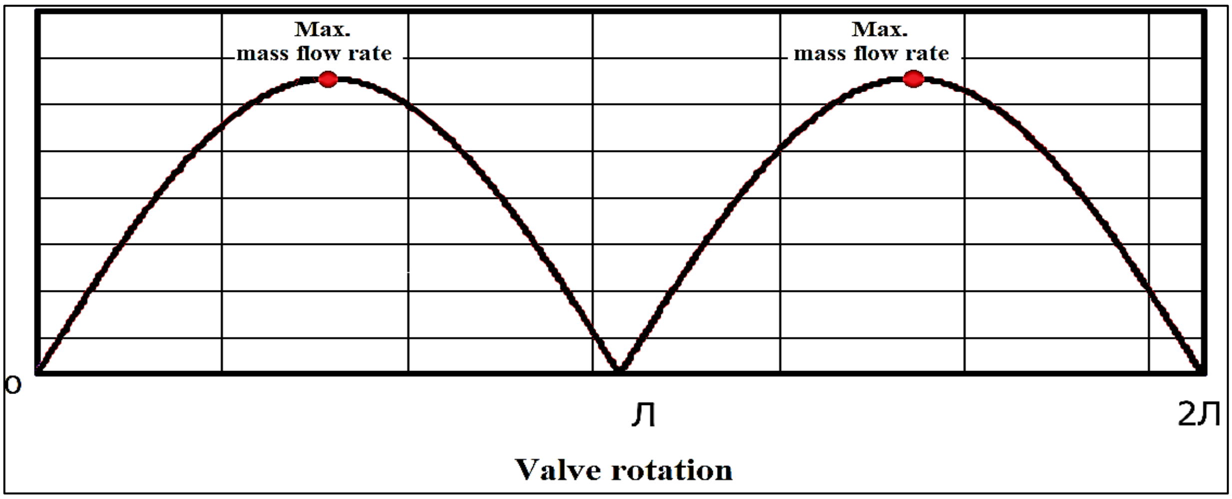

Figure 4: Pulsating airflow profile

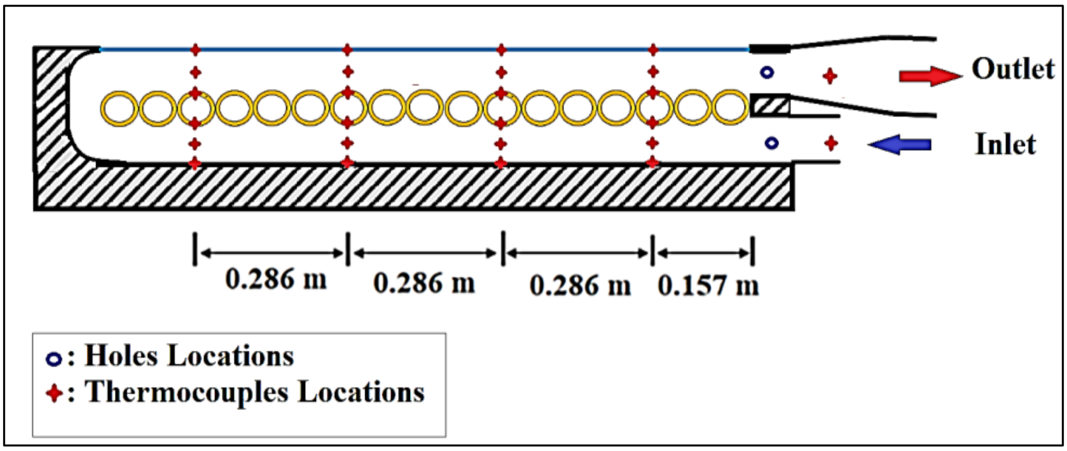

Figure 5: Locations of measuring points

3. Experimental Procedure and Data Analysis

3.1 Experimental Procedure

Firstly, and before each experiment, it must be ensured that all thermocouples reading is equal to 25°C, which is the room temperature. Then, the pulsating airflow system is switched on, and the rotation speed of the DC motor is adjusted to achieve the required frequency. After that, the electric air blower is switched on, and the manual valve adjusts the airflow to get the required air mass flow rate. Then, the artificial solar simulator is switched on and regulated at the desired heat flux. The system is left running until reaching a steady state after one hour, and during this time, all thermocouples' readings are measured every 5 minutes. Finally, when the steady state is achieved, the pressure drops across the solar air heater, and all temperature distributions are recorded. The above procedure is repeated for the steady flow case, except that the pulsating airflow system is switched off.

3.2 Data Analysis

The effective thermal performance of solar air heaters is assessed depending on the following formulas [28]:

$$\eta_{effective} = \frac{Q_{useful-P}}{Q_{in}} \tag{1}$$

Where: $\eta_{effective}$: Effective efficiency, Q_{useful}: Useful energy gain from solar air heater (W), Q_{in}: Received energy (W), P: Power required for pumping the airflow.

The power needed for the pulsating motor to pulsate the airflow is subtracted from the numerator of Eq. (1) to get the effective efficiency in the case of pulsating flow.

Useful and received energies can be represented by the following formulas [29]:

$$Q_{useful} = m^{\cdot}_{air} \,.\, Cp_{air}(T_{air,out} - T_{air,in}) \tag{2}$$

Where: $\dot{m}_{air}$: Air mass flow rate (kg/s), Cp_{air}: Specific energy of air (J/kg. °K), $T_{air,out}$: Outlet air temperature (°C), $T_{air,in}$: Inlet air temperature (°C).

$$Q_{in} = A_c \cdot I \tag{3}$$

Where: A_c: Collector area (m^2), I: Solar radiation (W/m^2).

For pulsating flow, the frequency and the mass flow rate can be calculated as follows [30]:

$$f = \frac{2N}{60} \tag{4}$$

Where: f: Pulsating frequency (Hz), N: Rotating speed of the ball valve (rpm).

$$\dot{m}_{pulsating}(t) = \dot{m}_{steady} . ABS(\sin(\pi f t)) \tag{5}$$

Where: $\dot{m}_{pulsating}$ (t): Pulsating air mass flow rate (kg/s), $\dot{m}_{Steady}$: Steady air mass flow rate (kg/s). t: Time (s).

3.3 Uncertainty Analysis

Any experimental work must include an uncertainty analysis to indicate the possible error values in measurement instruments. The uncertainty values were computed depending on the following formula [31].

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} W_1\right)^2 + \left(\frac{\partial R}{\partial x_2} W_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} W_n\right)^2\right]^{\frac{1}{2}} \tag{6}$$

Where: W_R: Total uncertainty, (W1, W2, … Wn): Uncertainty of independent variables, (x1, x2, …, xn): Independent variables.

Depending on the previous equation, the uncertainty of thermal efficiency can be written as follows:

$$W_{\eta th} = \left[\left(\frac{\partial \eta th}{\partial \dot{m}_a} W_{\dot{m}_a}\right)^2 + \left(\frac{\partial \eta th}{\partial I_{solar}} W_{I_{solar}}\right)^2 + \left(\frac{\partial \eta th}{\partial \Delta T} W_{\Delta T}\right)^2 + \left(\frac{\partial \eta th}{\partial \Delta p} W_{\Delta p}\right)^2\right]^{\frac{1}{2}} \tag{7}$$

The fractional uncertainty of measurements is in Table 2.

Based on Eq. (7), the uncertainty of the effective efficiency ranges between ± 0.07235 to ± 0.174697.

Table 2: Fractional uncertainty of experimental measurements

Parameter	Fractional uncertainty $\left(\frac{\partial R}{\partial x_n} W_n\right)$
Mass flow rate	± (0.001 to 0.0011)
Solar radiation	± (0.00105 to 0.0011)
Temperature difference	± (0.00313 to 0.028)
Pressure drop	± (1.42e-12 to 2.33e-9)

4. Results and Discussion

The experiments are carried out under constant indoor laboratory conditions at 1000 W/m^2, the inlet temperature of 25°C, and variable mass flow rate values. The findings of this work show the effect of changing the flow type on the thermal performance of solar air heaters. Furthermore, the comparison in terms of instantaneous outlet temperature, useful energy, and instantaneous effective efficiency has been presented in this part.

4.1 Validation of Experimental Outcomes

A validation between experimental outcomes and numerical work has been carried out, as shown in Figure 6. It can be observed that the deviation between the experimental and numerical results is within the acceptable agreement of 9.6%.

4.2 Outlet air Temperature

The assessment of outlet air temperature at variable mass flow rates for the steady and pulsating flow cases is shown in Figure 7. The experimental findings indicate that the outlet air temperatures in the case of pulsating flow are higher than those values achieved in the steady flow case, where the outlet air temperature in the case of steady flow was 48°C and 33.1°C at the minimum and maximum mass flow rate respectively, and these temperatures increase by about 25.6%, and 27% when applying the pulsating flow. This enhancement in outlet air temperature and heat transfer rate may be attributed to two reasons. The first one is increasing turbulence level due to pulsation, where the pulsation leads to increasing both the longitudinal and axial flows through the channel, improving both the longitudinal and radial mixing [32]. The second reason is introducing the forced circulations within the boundary layer due to pulsation. When the turbulent flow is pulsating, forced circulations create within the fluid due to the periodic pressure variations. These forced circulations promote eddies formation, leading to introducing the convection inside the boundary layer, thus improving heat transfer. While in the case of steady flow, the convection has no action on heat transfer in the inner boundary layer, which is at rest with the channel's wall [33]. In addition, it can be observed that the outlet air temperature increases as the pulsating frequency increases due to the increase in the intensity of the mixing process as increasing turbulence, enhancing the heat transfer rate [34].

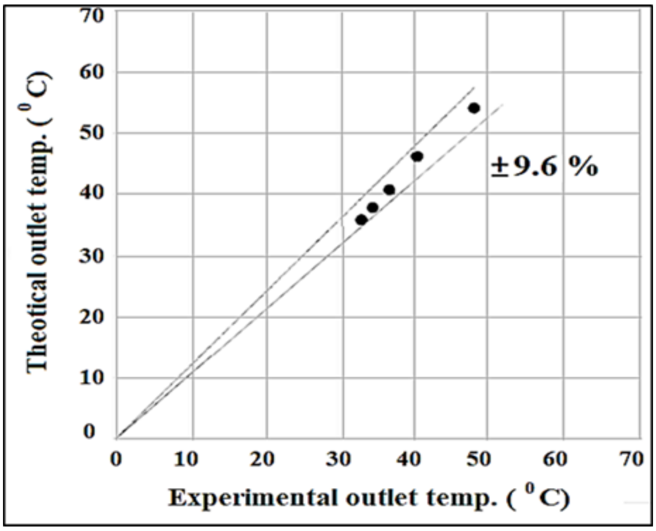

Figure 6: Validation of experimental outcomes

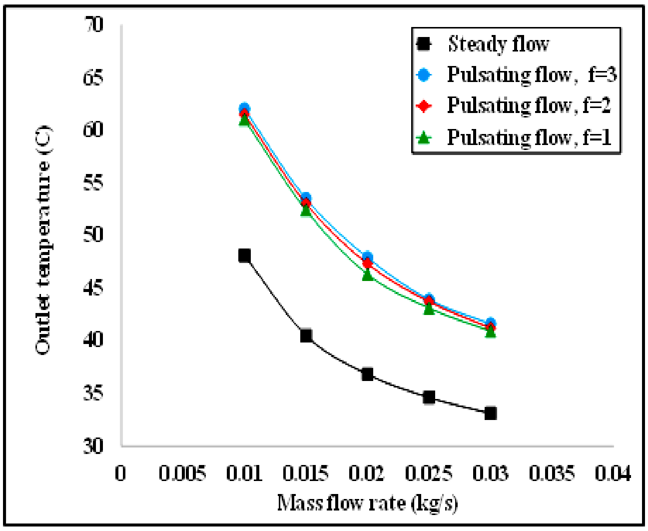

Figure 7: Outlet air temperature

4.3 Useful Energy

The thermal performance calculations of the solar air heaters mainly depend on the useful energy value extracted from the solar absorber plate by the airflow. Figure 8 shows the useful energy values for steady and pulsating flow cases at different mass flow rates. In general, it can be observed that useful energy production increases with rising mass flow rate value due to increasing the convective heat transfer coefficient [35]. In addition, Figure 8 shows that replacing the steady flow with pulsating offers a dramatic increment in producing useful energy. This increment may be attributed to the fact that the pulsating flow forces the thermal boundary-layer thickness to oscillate periodically, leading to making the ratio of the air residence time over the solar absorber's surface to the heat diffusion time high, allowing more heat to diffuse per unit volumetric flow. Hence, higher energy can be extracted by the airflow [36]. Furthermore, increasing the pulsating frequency leads to producing more useful energy. This behavior may be attributed to the fact that when the frequency value rises, the intensity of the turbulence increases, which leads to the enhancement of the flow mixing process, and thus more heat energy can be extracted. Conversely, when the pulsating frequency is reduced, the heat transfer deteriorates due to the periodic deceleration of the flow mixing process near the area adjacent to the wall [34]. The increment in the useful energy when replacing the steady flow with the pulsating flow is in the range of 1.4-12.7% at the pulsating frequency of 1 Hz, 8.6-20.3% at the pulsating frequency of 2 Hz, and 12.3-25.2% at the pulsating frequency of 3 Hz.

4.4 Effective Efficiency

Thermal and effective efficiencies are used to indicate future research improvement. The assessment of the effective thermal performance of the solar air heater under steady and pulsating flow cases at different mass flow rates is shown in Figure 9. The outcomes revealed that the effective efficiency increases remarkably when applying the pulsating flow. This behavior can be attributed to that pulsating flow causes appearing a large number of vortices on the wall surface that, in turn, destroy the boundary layer and improves the turbulence of the main flow throughout increasing both the fluid mixing and the effect of the heat exchange surface, hence, enhancing the heat transfer rate [37]. Furthermore, the effect of pulsating flow increases at the large values of the air mass flow rates (i.e., at high Reynolds number values). This result can be attributed to the fact that the heat transfer rate increases sharply with raising the pulsating flow speed [38]. It is found that the effective efficiency in the case of steady flow ranged between 64.8 to 68.1%, while in pulsating flow case, the effective efficiency ranged from 55.9 to 81.7%. Moreover, it can be observed that the effective efficiency in the case of pulsating flow is directly proportional to the pulsating frequency values, and this is because the heat transfer rate is a function of pulsating frequency (i.e., the thermal diffusion rate increases with increasing the pulsating frequency) [39]. It was found that when changing the frequency from 1 to 3, the increment of effective efficiency ranged from 3.8 to 6.9% depending on the air mass flow value.

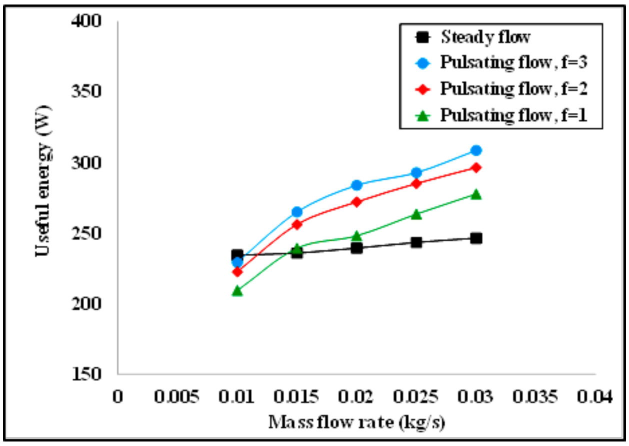

Figure 8: Useful energy

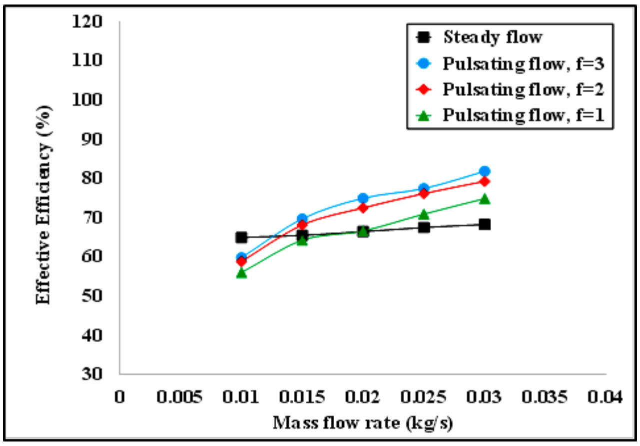

Figure 9: Instantaneous effective efficiency

5. Conclusion

The outcomes of the present work can be summarized in the following brief points:

1) A remarkable enhancement in heat transfer rate can be achieved when applying the pulsating flow.
2) Increasing the pulsating frequency enhances the heat transfer rate, where the maximum outlet air temperature can be obtained by applying pulsating flow at 3 Hz.
3) Pulsating flow offers higher useful power than the steady flow with an increment range of 1.4-12.7% at the pulsating frequency of 1 Hz, 8.6-20.3% at the pulsating frequency of 2 Hz, and 12.3-25% at the pulsating frequency of 3 Hz.
4) Compared with a steady flow, Pulsating flow offers a higher effective thermal performance by about 15.2% at the maximum air mass flow rate.
5) Depending upon the outcomes of this work, it can be demonstrated the feasibility of using the pulsating flow as an effective method for enhancing the thermal performance of solar air heaters.

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Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

[1] A. Kumar, P. Bhandari, K.S. Rawat, Numerical Simulation of Solar Air Heater using Paraffin Wax-Aluminum Compound as Phase Changing Material, Aptisi Transactions on Technopreneurship (ATT), 3 (2021) 164-170. https://doi.org/10.34306/att.v3i2.199

[2] S. Khanmohammadi, H.A. Chaghakaboodi, F. Musharavati, A new design of solar tower system amplified with a thermoelectric unit to produce distilled water and power, Appl. Therm. Eng, 197 (2021) 1-15. https://doi.org/10.1016/j.applthermaleng.2021.117406

[3] Z. Song, J. Liu, H. Yang, Air pollution and soiling implications for solar photovoltaic power generation: A comprehensive review, Appl.Energy, 298 (2021) 117247. https://doi.org/10.1016/j.apenergy.2021.117247

[4] J.M. Jalil, N.A. Abdulkadhim, Vacuum Effect on the Performance of Solar Air Collector with Micro-Channel Absorber Plate, Eng. Technol. J. 37 (8) (2019) 348-53. https://doi.org/10.30684/etj.37.8A.6

[5] J. Chen, G. Xiao, H. Xu, X. Zhou, J. Yang, M. Ni, K. Cen, Experiment and dynamic simulation of a solar tower collector system for power generation, Renew.Energy, 196 (2022) 946-958. https://doi.org/10.1016/j.renene.2022.07.045

[6] D. Zhang, J.P. Li, Y.J. Cho, l. Wang, J. Nan, Thermal performance investigation of modified flat plate solar collector with dual-function, Appl. Therm. Eng., 108 (2016) 1126–1135. https://doi.org/10.1016/j.applthermaleng.2016.07.200

[7] A. Mahmud, K. Sopian, M.A. Alghoul, M. Sohif, Using a paraffin wax-aluminum compound as a thermal storage material in a solar air heater, J. eng. Appl. Sci., 4 (2009) 74-77.

[8] S.M. Salih, J.M. Jalil, S.E. Najim, Double-Pass Solar air Heater (DP-SAH) utilizing Latent Thermal Energy Storage (LTES), Mater. Sci. Eng., 518 (2019) 1-14.

[9] A.K. Raj, M. Srinivas, S. Jayaraj, A cost-effective method to improve the performance of solar air heaters using discrete macro-encapsulated PCM capsules for drying applications, Appl. Therm. Eng., 146 (2019) 910-920. https://doi.org/10.1016/j.applthermaleng.2018.10.055

[10] A.H. Abed, Thermal storage efficiency enhancement for solar air heater using a combined SHSm and PCM cylindrical capsules system: experimental investigation, Eng. Technol. J., 34 (5) (2016) 999-1011.

[11] H.M. Ali, A.I. Bhatti, M. Ali, An experimental investigation of performance of a double pass solar air heater with thermal storage medium, Therm. Sci., 19 (5) (2015) 1699-1708. https://doi.org/10.2298/TSCI140824140A

[12] T. Josyula, S. Singh, P. Dhiman, Numerical investigation of a solar air heater comprising longitudinally finned absorber plate and thermal energy storage system, J. Renew. Sustain. Energy , 10 (2018) 1-22. https://doi.org/10.1063/1.5035136

[13] N.A. Habib, A.J. Ali, M.T. Chaichan, M. Kareem, Carbon nanotubes/paraffin wax nanocomposite for improving the performance of a solar air heating system, Therm. Sci. Eng. Prog., 23 (2021) 1-11. https://doi.org/10.1016/j.tsep.2021.100877

[14] Q. A. Jawad, A.M.J. Mahdy, A. H. Khuder, M.T. Chaichan, Improve the performance of a solar air heater by adding aluminum chip, paraffin wax, and nano-SiC, Case Stud. Therm. Eng., 19 (2020) 1-9. https://doi.org/10.1016/j.csite.2020.100622

[15] B. Madhu, A.E. Kabeel, R. Sathyamurthy, S.W. Sharshir, A.M. Manokar, P.R. Raghavendran, T. Chandrashekar, D. Mageshbabu, Investigation on heat transfer enhancement of conventional and staggered fin solar air heater coated with CNT-black paint—an experimental approach, Environ. Sci. Pollut. Res., 27 (2020) 32251-32269. https://doi.org/10.1007/s11356-019-07561-1

[16] P.G. Kumar, K. Balaji, D. Sakthivadivel, V.S. Vigneswaran, M. Meikandan, R. Velraj, Effect of using low-cost thermal insulation material in a solar air heating system with a shot blasted V-corrugated absorber plate, Therm. Sci. Eng. Prog 14 (2019) 1-10. https://doi.org/10.1016/j.tsep.2019.100403

[17] B. Das, J. D. Mondol, S. Debnath, A. Pugsley, M. Smyth, A. Zacharopoulos, Effect of the absorber surface roughness on the performance of a solar air collector: An experimental investigation, Renew. Energy, 152 (2020) 567-578. https://doi.org/10.1016/j.renene.2020.01.056

[18] P.G. Kumar, D. Sakthivadivel, K. Balaji, M. Salman, S.C. Kim, Performance enhancement of a double-pass solar air heater with a shot-blasted absorber plate and winglets, J. Mech. Sci. Technol. 35 (2021) 2743-2753. http://doi.org/10.1007/s12206-021-0544-x

[19] A. Bhushan, R. Kumar, A. Perwez, Experimental investigations of thermal performance for flat and dimpled plate solar air heater under turbulent flow conditions, Sol. Energy, 231 (2022) 664-83. https://doi.org/10.1016/j.solener.2021.11.060

[20] J.M. Jalil, R.F. Nothim, M.M. Hameed, Effect of Wavy Fins on Thermal Performance of Double Pass Solar Air Heater, Eng. Technol. J., 39 (2021)1362-1368. http://doi.org/10.30684/etj.v39i9.1775

[21] M.F. Mohammed, M.A. Eleiwi, K.T. Kamil, Experimental Investigation of Thermal Performance of Improvement a Solar Air Heater With Metallic Fiber, Energy Sources Part A, 43 (2021) 2319-2338. https://doi.org/10.1080/15567036.2020.1833110

[22] A.M. Rasham, B.A. Al-Bakri, Thermal performance of double-pass counter flow and double-parallel flow solar air heater with V-grooved absorber plate, Mater. Sci. Eng.,1076 (2021) 1-12. https://doi.10.1088/1757-899X/1076/1/012081

[23] M.A. Habib, A.M. Attya, A.I. Eid, A.Z. Aly, Convective heat transfer characteristics of laminar pulsating pipe airflow, Heat mass transf., 38 (2002) 221-232. https://doi.org/10.1007/s002310100206

[24] M.A. Habib, S.A.M. Said, A.A. Al-Farayedhi, S.A. Al-Dini, A. Asghar, S.A. Gbadebo, Heat transfer characteristics of pulsated turbulent pipe flow, Heat mass transf., 34 (1999) 413-421. https://doi.org/10.1007/s002310050277

[25] H.R. Kharvani, F.I. Doshmanziari, A.E. Zohir, D. Jalali-Vahid, An experimental investigation of heat transfer in a spiral-coil tube with pulsating turbulent water flow, Heat Mass Transf., 52 (2016) 1779-1789. https://doi.org/10.1007/s00231-015-1697-x

[26] N. Kurtulmuş, B. Sahin, Experimental investigation of pulsating flow structures and heat transfer characteristics in sinusoidal channels, Int. J. Mech. Sci. 167 (2020) 105268. https://doi.org/10.1016/j.ijmecsci.2019.105268

[27] P.C. Huang, C.C. Chen, H.Y. Hwang, Thermal enhancement in a flat-plate solar water collector by flow pulsation and metal-foam blocks, Int. J. Heat Mass Tran., 61 (2013) 696-720. https://doi.org/10.1016/j.ijheatmasstransfer.2013.02.037

[28] S.M. Salih, J.M. Jalil, S.E. Najim, Comparative study of novel solar air heater with and without latent energy storage, J. Energy Storage. 32 (2020) 1-14. https://doi.org/10.1016/j.est.2020.101751

[29] A. El-Sebaii, S. Aboul-Enein, M. Ramadan, S. Shalaby, B. Moharram, Investigation of thermal performance of double pass-flat and v-corrugated plate solar air heaters, Energy. 36 (2011) 1076-1086. https://doi.org/10.1016/j.energy.2010.11.042

[30] E.A. Elshafei, M.S. Mohamed, H. Mansour, M. Sakr, Experimental study of heat transfer in pulsating turbulent flow in a pipe, Int. J. Heat Fluid Flow. 29 (4) (2008) 1029-1038. http://dx.doi.org/10.1016/j.ijheatfluidflow.2008.03.018

[31] M.M.M. Salih, O.R. Alomar, H.N.S. Yassien, Impacts of adding porous media on performance of double-pass solar air heater under natural and forced air circulation processes, Int. J. Mech. Sci. 210 (2021) 1-14. https://doi.org/10.1016/j.ijmecsci.2021.106738

[32] M.A. Habib, A.M. Attya, S.A.M. Said, A.I. Eid, A.Z. Aly, Heat transfer characteristics and Nusselt number correlation of turbulent pulsating pipe air flows, Heat Mass Transf., 40 (2004) 307-318. https://doi.org/10.1007/s00231-003-0456-6

[33] O.E. Karamercan, L. Gainer, The effect of pulsation on heat transfer, Ind. Eng. Chem. Fundam., 18 (1979) 11–15. https://doi.org/10.1021/i160069a003

[34] W. Jarosinski, Experimental study of heat transfer from the heated rib-roughed wall to a steady or pulsating flow, SAE Technical Paper Series, (2001) 1-11. https://doi.org/10.4271/2001-01-1249

[35] H. Hassan, S. Abo-Elfadl, M.F. El-Dosoky, An experimental investigation of the performance of new design of solar air heater (tubular), Renew. Energy, 151 (2020) 1055-1066. https://doi.org/10.1016/j.renene.2019.11.112

[36] P.C. Huang, C.C. Chen, H.Y. Hwang, Thermal enhancement in a flat-plate solar water collector by flow pulsation and metal-foam blocks, Int. J. Heat Mass Transf., 61 (2013) 696-720. https://doi.org/10.1016/j.ijheatmasstransfer.2013.02.037

[37] Z. Cheng, Z. Wang, X. Sun, T. Fu, Multi-objective optimization of self-excited oscillation heat exchange tube based on multiple concepts, Appl. Therm. Eng. 197 (2021) 1-15. https://doi.org/10.1016/j.applthermaleng.2021.117414

[38] X. Wang, N. Zhang, Numerical analysis of heat transfer in pulsating turbulent flow in a pipe, Int. J. Heat Mass Transf., 48 (2005) 3957-3970. https://doi:10.1016/j.ijheatmasstransfer.2005.04.011

[39] S.W. Chang, T.H. Cheng, Thermal performance of channel flow with detached and attached pin-fins of hybrid shapes under inlet flow pulsation, Int. J. Heat Mass Transf., 164 (2021) 11-24. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120554