Optimizing Efficiency of Solar Double-Pass Air Heater through Fluid Combination Approach

Abhishek Agarwal [1*]

[1]Department of Mechanical Engineering, College of Science & Technology, Royal University of Bhutan, 21101 Phuentsholing, Bhutan

Abstract. The solar air_heater (SAH) is one of the main devices that are used for harnessing solar energy for multipurpose functions. The double-pass solar air_heater (DPSAH) is an advanced model with ducts that transport the air to the two leaves of the loops. This technology is applied where space heating, thermal energy for drying processes, heat pumping applications, etc. are required. This investigation aims to determine the thermal characteristics of an air heater with a double-pass design that works by using CFD simulation. The study is to be carried out by (air flow rate and pressure distribution) measurement within the system. The process relies on the mixture containing both CO2 and O2 as the medium through which the process takes place. The CFD (Computational Fluid Dynamics) analysis results support that CO2 is an efficient working fluid resulting in better heat exchange. This is evident in the fact that supplementary thermal efficiency at the exhaust duct is 1.76% higher than that of air only. Additionally, the mixture of CO2 and air demonstrates increased efficiency with a 15.2% increase in efficiency relative to air alone. It is due to the different specific heat capacities of the gases that the mixture has a higher average specific heat. Therefore, the gas can store more energy, leading to higher thermal efficiency. The outcomes of this experiment demonstrate the possibility of gas combination for the enrichment of the DPSAH efficiency. This research enlightens on thermal energy systems and is an asset in improving the proficiency of solar air heating systems operation.

1 Introduction

The solar energy occurring from the emission of radiation from the sun's surface serves as the foremost bioenergetic source of our ecosystem. The photons that energy beings and consist of individual energy packages are the source that is used for energy carriers from space to Earth. Research over the last few years has proved that the Earth's surface generates astronomical solar energy precipitation, which is about 10,000 times more than global energy consumption. India has average solar radiation many sources irradiance intensity is approximately 2000 kWh/m² as compared with the global average of 2500 kWh/m². The use of the expressed opportunities can be direct like solar panel which collects energy through photovoltaic cells as well as indirect like concentrating solar power which concentrates sunrays by reflecting it and heats-up a thermal fluid that turns the wheel and generates power. The direct method involves taking advantage of biomass heat and light, and the indirect method employs litter, winds, waves, ocean temperature fluctuations, and the Gulf Stream current system. After all of the times, we had both humans and nature that took vitally essential temperature by solar energy to develop a portion of food. Harnessing clean energy from the sun occurs in multiple ways; running machines, pumping houses, treating sewage, refrigerating areas, and ultimately heating and cooling buildings, swimming pools, as well as water, are some of its applications. Additionally, solar energy is applied in cars, stoves, stills, furnaces, and distillation machines. This list is not limited to crop dryers and sewage dryers. Solar-powered purifier airs should not be underestimated, as they contribute to reducing greenhouse gas pollution by stabilizing the energy that the community uses for various applications without heating and cooling included. These systems have a life cycle that is longer, are required to maintain a little, and take a short payback period. On this basis, they can be easily integrated into the already existing conventional systems for drying. Heated air at these temperatures (50-80 c) is a standard application of these processes mainly experienced in culinary and food production sectors. Among these applications are the drying of coffee and tea beans, veggies and fruits, grains, mushrooms, spawn, and seasonings. Besides, throughout activities in which leather, textiles, wood, chemicals, rubber, paper, and medicines are produced, hot air plays a crucial role. The significance of solar-air heaters (SAH) goes beyond their versatility and technical features, as they can be employed in a variety of commercial and residential setups to dramatically expand the application of sustainable energy resources. The literature related to solar air_heater (SAH) underlines the continuous efforts aimed at improving the

* Corresponding author: agarwala.cst@rub.edu.bt

efficiency and effectiveness of these devices. The pursuit of this goal is a result of the growing energy crisis, which increases the need for sustainable energy solutions. Chauhan and Thakur [1] gave an excellently summarized, in-depth study of the SAH that used the technology of an impinging jet, demonstrating that its performance was notably better than that of present-day SAHs under certain conditions of Reynolds numbers. The authors, who have recently proven an even higher efficiency of 70%, justifiably identify this technology as a possible way for energy demand reduction. As to the subject of air mass flow rate and solar radiation impact on SAH temperature and solar air_heater (SAH) effectiveness; Aboghrara et al. [2] studied it by using a corrugated absorber plate design. The focus of their research allocated enhanced heat transmission in the process of jet impingement on the absorber plate through the air circulation rate testifying to the key point nature of this impingement in the perfection of heat transfer properties. The authors of Das et al. [3], introduced an ANN [artificial neural network] for a SAH (symmetrical annular heat sink) subjected to convectors within jet impingements to look at the thermal transmission characteristics. Their research showed how precise and complex ANN models were in calculating heat movement parameters, giving another possibility of achieving the same results, but with fewer tools and steps, rather than empirical or computational methods. According to Alomar et al. [4], an experimental study has been conducted to identify the viability of impinging jets in SAH application and a V-grooved plate's absorptivity. Their research, which involved applying the novel Models similarly, concluded that the first model (Model-1) produced an outlet temperature higher than Model-2. This suggests that performance can be greatly improved by using this innovative design modification. Numerical analysis by Yadav et al. [5] was performed for a sphere absorber with jet impingement, optimizing operational parameters demonstrated a successful increase in performances in thermo-hydraulic [6]. Their study rekindles the impact of the right jet angle and pitch that shall help to avert fuel wastage brought about by SAHs. Singh et al. [6] pointed out the double-pass impinging jet system with circular jet holes and the significance of using porous materials in the rolled plate in the study of the system efficiency. From their results on point, we can see that the porous media are impediments to the efficiency, however with that in mind, this is of major importance in the complex transfer of heat dynamics in SAHs. Mund et. al. [7] introduced in one of their experimental types of research to investigate the impinging jet supplemental air heater [IJSAH] using the wire mesh simulators of different dimensions, and the denouement proved to be the optimized ideal mesh of 3 inches by 3 inches offering superior theoretical performance in terms of the thermohydraulic features. This again proves the necessity to implement it appropriately by improving the design parameters to achieve the desired performance level to ensure harmony in SAH. According to a numerical study carried out by Moshery et al. [8], vibrating jet-impingement SAH absorbers scaled parameters with the optimum efficiency of 78 % by objectively adjusted operational parameters. The studies revealed that the latter two methods could lead to dramatic efficiencies after applying sophisticated numerical modeling and optimization methods. In another recent study by Kamal et al. [9], the performance of SAHs with 3E models is investigated via numerical calculations. The outputs of the research have shown that under the above-mentioned conditions, a very high thermal and exergy efficiency can be achieved. The authors of the paper have created an example of the effectiveness of common ANN models in increasing the SAH efficiency by a great amount. Hussein Salih [10] has performed a numerical study of double-pass solar air heaters with the help of FORTRAN 90. The experimental work was done for three different solar irradiances of 600, 750, and 900 W/m^2. Numerical analysis was performed with three collectors with different geometry through the k-epsilon turbulence model. The thermal efficiency was evaluated at different solar irradiations obtained and were found to be .528, 0.513, and 0.503. In addition, calculations showed excellent agreement with experimental results. Further increase of mass flow rate results in smaller temperature difference. However, the results of these so many studies [11–14] demonstrate the progress of SAHs in order to improve the efficiency and adaptability of SAHs through numerical modeling, innovative design modifications, and optimization techniques. The findings provide evidence that gives an impression of solar array housing as a solution that can be used sustainably with efficiency, which is open for further developments talk of solar energy utilization. Current developments in the SAH designs and optimization have contributed to the enhancement of the gadget's thermal performance and energy gain [15]. Zhimin Dong et al. [16] examined constantly grooved solar air heaters and observed that the cross flow in the grooves and the longitudinal vortices in the core flow region helps in air mixing. They established the angle of inclination and the shape factor to arrive at the best SAH designs, and found that they are most effective with Reynolds' numbers of < 13,000 and that heat transfer by convection is enhanced by 1. 8 to 2. 3 times. Raoua Fattoum et al. [17] improved the SAHs with parallel porous wire mesh that works greater temperature variations, and improved the energy performance compared to earlier designs. From this it can be deduced that structural changes are very effective in enhancing SAH performance. Hiwa Abdlla Maarof et al. [18] proposed a Tubular three pass SAH with PCMs, to indicate that incorporation of PCMs enhances heat storage capacity as well as overall effectiveness. Tauseef-ur Rehman et. al. [19] employed a Deep Neural Network (DNN) to forecast the heat output of a double pass SAH with aluminum tubes and energy storage material. Through their work, they show that using DNN, SAH design as well as operations can be made more efficient. To summarize the works, it can be concluded that the improvement in the designs, the use of the advanced materials and computational modelling can enhance the efficiency of solar air heaters.

The existing research on (DPSAH) predominantly covers the case of the use of a single fluid as a working medium. Nevertheless, there is a paucity of researches that concentrate on the thermodynamic features of double-parabolic SAH which utilize a combination of gases as working fluids for example, CO_2 and O_2. Following this research gap, research on a DPSAH with different fluid combinations is recommended to gain an understanding of the performance differences.
The hypothesis is that the use of a mixture of CO_2 and O_2 as a working medium in the SAH will lead to better thermodynamics than a heater utilizing a single fluid. Incorporating CO_2 and O_2 in the working medium could boost heat transfer features, thus increasing the efficiency and effectiveness of the SAH systems.
Accordingly, the research question is formulated as, "What are the thermal characteristics, velocity of air and pressure fields distributed, of a DPSAH working with a combination of carbon dioxide and oxygen considered through CFD analysis?"
This study aims to fill the gap in the existing studies where the thermal efficiency of SAH with dual-pass of fluid is not properly analyzed. By employing CFD analysis, the research aims to investigate the performance of the solar air_heater in terms of the airflow rate and the pressure distribution scheme. The purpose is to elevate the heater's efficiency and effectiveness. The relevance of this research is in the potential to improve operational accuracy as well as the performance of double-pass solar-air-heater. CO_2-O_2 mix will be the working medium that aims to enhance heat transfer and amplify the effectiveness of the solar air_heater as a result.
Such practice might have a practical meaning in the design and implementation of sun-drive air heating systems thereby leading to more sustainable and energy-efficient solutions. This research is a novel undertaking to explore a mixture of CO_2 and O_2 as the working fluids in a double-pass solar-air-heater. According to the study of this solar air heating system, guidance would be given in this field for the researchers, therefore the researchers would generate innovative improvements in the design.
In effect, the aim of the current research is to test the heat distribution characteristics of the DPSAH through CFD. Based on the CFD results, air flow rate, and pressure distribution are obtained. The analysis of the system is based on a mixture of gas used as the working medium (CO_2 and O_2). The relevance of this research is in the potential to improve operational accuracy as well as the performance of DPSAH.
The research intent is to use a mixture of CO_2 and O_2 as the working fluid of the solar-air-heater. This is done in order to increase the working temperature and, consequently, the heating efficiency. Such a finding would have great notable value for solar air heating systems project development and design, which would then produce more sustainable and energy-efficient solutions. This study is innovative with respect to the use of CO_2 and O_2 as the working matter in the DPSAH which has not been investigated before. Specifying the thermal characteristics of this operational mode, the study would add to the existing body of knowledge related to the area of solar air heating systems and this could be the first step toward new design changes. The current study will evaluate the thermal characteristics of double-pass solar air_heater (SAH) using CFD. From the CFD analysis, the air-flow rate, and pressure distribution is evaluated. The analysis is conducted using a combination of fluid as a working medium i.e. CO_2 and O_2.

2 Methodology

The mathematical model of BLDCM a sensorless can be modeled and implemented by the means of mathematical modeling (transfer functions) shown in equations shown below. This study analyzes a double-pass solar air heater using CO_2 and O_2 as the working media by the CFD simulation. Thus, the experiment's thermal features are evaluated. The process starts with the CAD design of the solar air_heater geometry which is obtained using Creo Parametric design software [20]. Thereon, the CAD model is turned into a Parasolid file format and then imported into ANSYS design_modeler to complete the analysis process. Ansys software named ANSYS Fluent is used to perform the CFD analysis.

2.1 CAD Design of DPSAH

The CFD simulation process begins with the CAD model construction of the solar air_heater, double pass geometry in nature. The model of the double-pass solar air heater is developed in the Creo parametric design software, which is used for 3D modeling. The Parasolid file form is out of the developed CAD model and the ANSYS design modeler imports it. The designed drawing of a double-pass solar air heater is shown as an import luminaire in Figure 1.

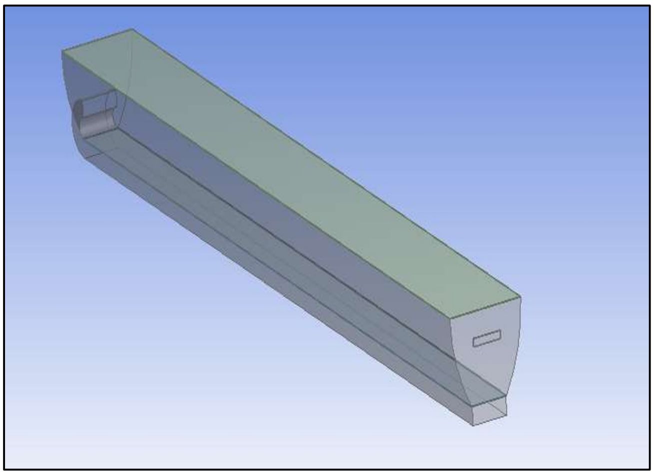

Fig. 1. CAD design of the DPSAH

2.2 Modeling and Discretization

Discretization of the CAD model of the DPSAH is carried out using the tetrahedral type elements [20] each with four nodes and each node has three degrees of freedom (DOF). The mesh size parameter is 1.1 mm along with normal rates of inflation and growth to accurately resemble the shape while making sure the computational efficiency is not compromised [20].

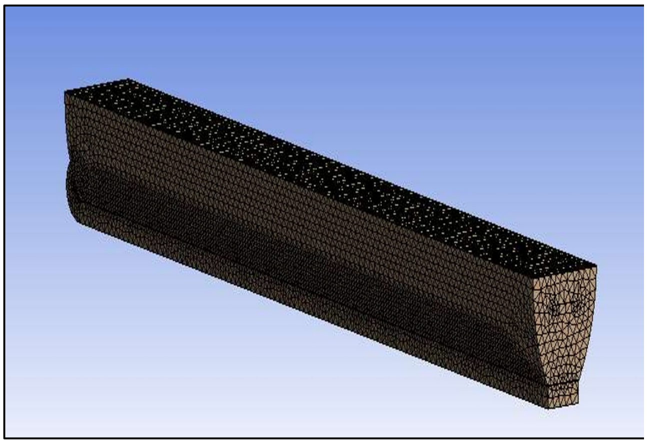

Fig. 2. A discretized model of the DPSAH

The number of elements generated is 192398 and the number of nodes generated is 41095. Domain definition and boundary conditions are shown in Figure 3.

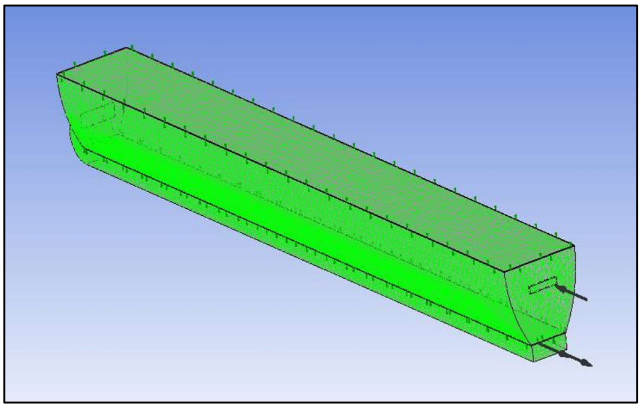

Fig. 3. Domain definition and boundary conditions

The computational domain is defined. The domain type is set to fluid type and reference pressure is set to 1atm. The turbulence model is defined as RNG k-epsilon [21]. The air inlet flow rate is defined as .01Kg/s as shown in figure 4.

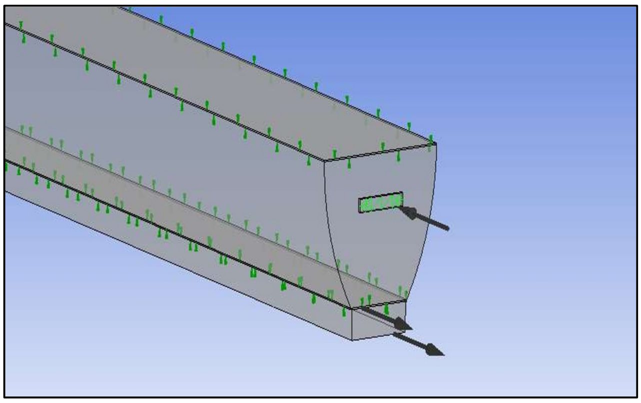

Fig. 4. Inlet air flow boundary condition

2.3 Simulation Scheme

Following the boundary conditions assertion, the solver specifications are specified. The settings of the solver (double precision and RMS residual target set to 0.00001) are used. As a result, the program checks the degree of convergence (so that the mass imbalance is close to zero). If this value does not exist within the convergence limits, the program must be stored and restarted, using the newly calculated pressure, velocity, and other scalar solutions as the starting guess. The iteration procedure is repeated until convergence is achieved.
The simulation is repeated iterating until the satisfaction of a very small mass imbalance. The thermal characteristics of the DPSAH with CO_2 and O_2 as the working fluids are studied. The study of the double-pass solar air_heater (DPSAH) undertakes the RNG k-epsilon turbulence model for its precision in replicating turbulent flows with adverse pressure gradients typical of solar air stoves. which is widely used for computing the influence of buoyancy and pressure gradients on turbulence making the simulation applicable to natural convection in solar air collectors. Moreover, as tetrahedral elements enable the formation of complex geometries with irregular shapes, this was the reason that tetrahedral mesh was used to mesh the geometry of a SAH that contains internal passages and fins. The meshes obtained using the tetrahedron technique are also computationally efficient and we need such a technique for large-scale simulations like this one. Generally, it was decided to apply the RNG k-epsilon turbulence model [22]with a tetrahedral element method for modeling the thermal behavior of the double-pass solar air_heater (DPSAH) in order to reach both accuracy and efficiency.

3 Results and discussion

The CFD simulation results provide valuable insights into the thermal characteristics of the double-pass solar air_heater (DPSAH) using different working mediums. Temperature distribution plots were generated for both air and a combination of CO_2 and O_2 as the working medium, revealing interesting patterns.

3.1 Temperature Distribution

For the case of air as the working medium (Figure 5), the temperature distribution shows an average temperature of 320.2K, with higher temperatures observed at the corners of the solar-air-heater. This indicates that heat is unevenly distributed within the system, which could impact its overall efficiency.

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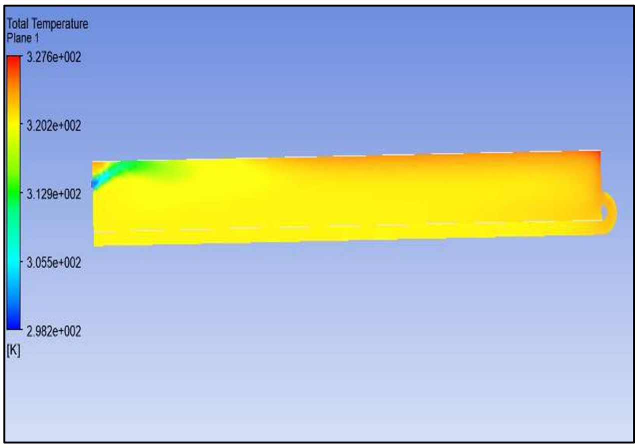

Fig. 5. Temperature distribution plot across DPSAH (air as a working medium)

3.2 Pressure Distribution

The pressure distribution plot in Figure 6 is obtained for a DPSAH with air as a working medium. The pressure magnitude is higher near the inlet with a magnitude of 99.9Pa. The pressure at the exit of the 1st pass is 74.9Pa.

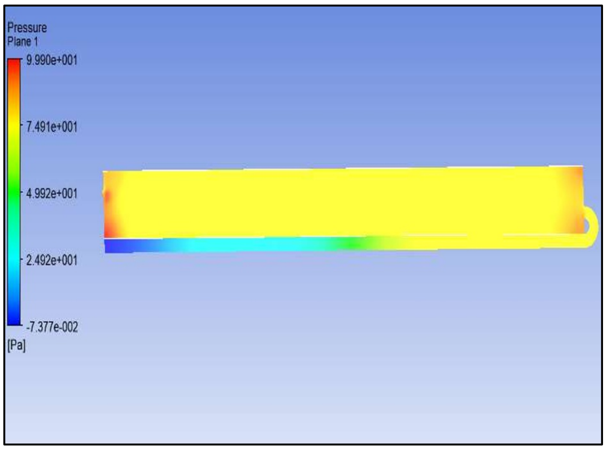

Fig. 6. Pressure distribution plot across DPSAH (air as a working medium)

3.3 Grid Independence Assessment

The grid independence examination is used as an input for the simulation studies. The values of the grid independence are depicted in Table 1 which is underneath.

Table 1. Grid Independence Evaluation

Elements	O/P Temperature (K)
192298	326.28
192318	326.93
192325	327.82
192381	327.92
192388	327.95
192398	327.94

From the study, a minor fluctuation was observed between 326.28K to 327.94K, despite the alterations in mesh density. The observation has shown that the results are fairly independent of mesh density and for the simulation, a grid with 192398 elements is selected. Through the CFD analysis of the DPSAH, the Grid Independence Test was performed to confirm that the accuracy of the results is not heavily affected by changes in the mesh density. By varying the number of mesh elements and checking the effect on the accuracy of the results, we will be able to set the appropriate mesh density that reduces the computational costs and increases the accuracy. This is a very important step, as it verifies the computational mesh and guarantees the validity of the simulation results.

3.4 Turbulence Kinetic Energy (TKE)

The turbulence is generated when the fluid air circulates inside the first chamber. The turbulence causes fluctuations in pressure and velocity profile. The TKE plot in Figure 7 shows the maximum magnitude at the center of 1st pass zone with a magnitude of $1.112m^2s^2$ which signifies higher turbulent fluctuations.

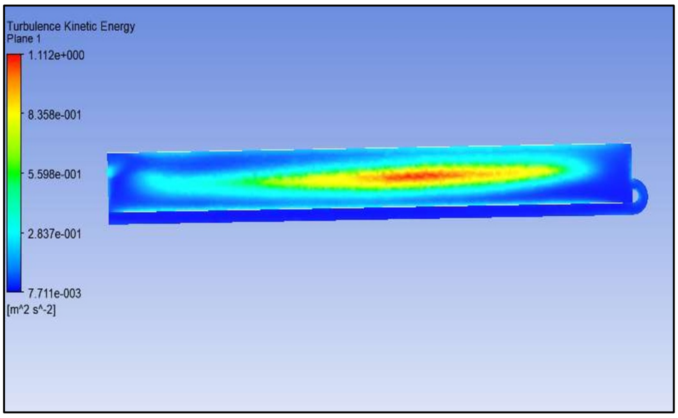

Fig. 7. TKE across DPSAH (air as a working medium)

The temperature distribution plot in Figure 8 is generated for a DPSAH with a combination of gases (air + CO_2) as the working medium.

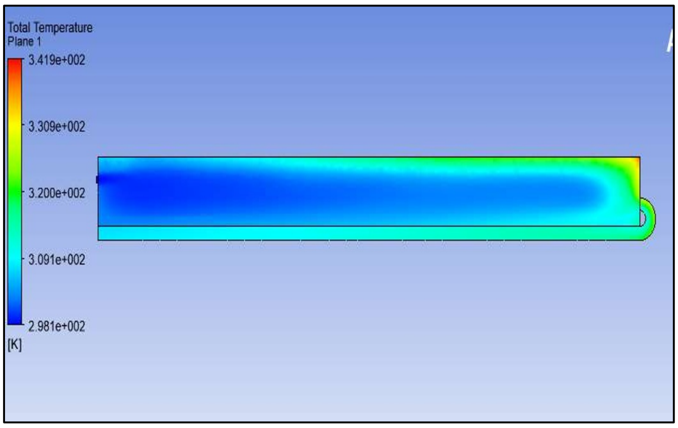

Fig. 8. Temperature distribution plot across DPSAH (air + CO2 as the working medium)

The distribution plot shows an average temperature of 330.9K at the top corner region of 1st cycle. The temperature distribution at the second pass is almost uniform with a magnitude of 309.1K. The pressure distribution plot is obtained for a DPSAH with (air + CO_2) as the working medium as shown in Figure 9.

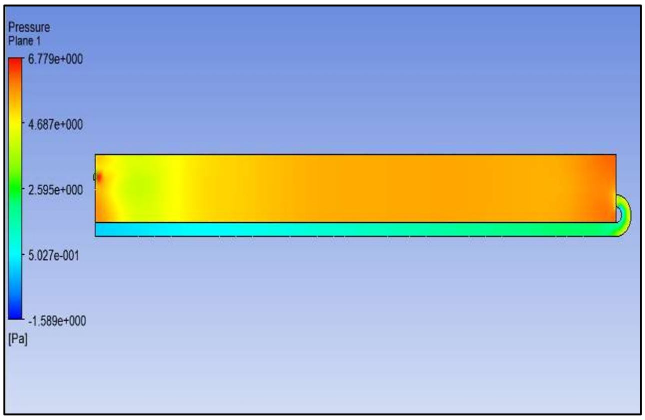

Fig. 9. Pressure distribution plot across DPSAH (air + CO2 as the working medium)

The pressure magnitude is higher near the inlet with a magnitude of 67.79Pa. The pressure at the exit of the 1^{st} pass is 46.8Pa. The second pass has an average pressure of 0.5Pa. The curvature tube at the end reduced the pressure of fluid significantly.

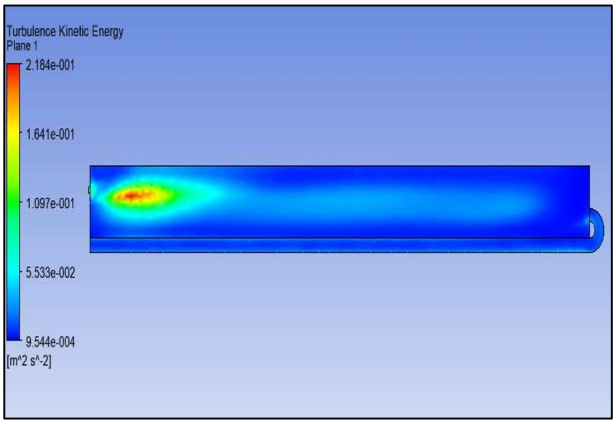

Fig. 10. TKE across DPSAH (air + CO2 as the working medium)

The turbulence is generated when the fluid (air + CO_2) circulates inside the first chamber. The turbulence causes fluctuations in pressure and velocity profile near the fluid inlet zone. The TKE plot in Figure 10 shows the maximum magnitude at the center of 1^{st} pass zone with the magnitude of .2184m^2s^2 which signifies higher turbulent fluctuations.

3.5 Efficiency Comparison

Equation (1) can be applied to calculate the thermal efficiency (η) of the collector as the ratio between the usefully received energy (Qu) by the collector's cavity and absorber to the net solar energy (Ac I) on its aperture [18].

$$\eta = \frac{Q_u}{A_c I} \quad (1)$$

Table 2. Comparison Chart

Fluid Type	Fluid Out Temp (K)	Cp (J/(kg-K)	Mass flow rate m (Kg/s)	η
Air	327.92	1004.4	0.01	0.781
CO2	335.51	851	0.01	0.841
CO2 (.2) +Air (0.8)	333.31	971.32	0.01	0.90

The efficiency obtained using air as the working medium is 0.781 which is in close agreement with the results in the literature [23] which is 0.773. The efficiency is determined for different fluid types i.e. air, CO_2, and a combination of fluids (CO_2 (.2) +Air (0.8)). The outlet fluid temperature is higher for CO_2 and (CO_2 (.2) +Air (0.8)) fluid combination. The thermal efficiency breakdown of the flue gas mixture demonstrates the highest efficiency of 0.90 for the mixture of carbon dioxide and air. Furthermore, the synergy between gases might improve the heat exchange mechanism that ultimately ensures a more efficient operation is achieved. In brief, the CFD prediction analysis conforms to our expectations and has the advantageous feature of generating valuable information regarding the thermal system behaviours of the solar double-flow air heater. The results emphasize the requirements of proper fluid choice and system optimization to have the best efficiency and productivity in solar air heating systems.

4 Conclusion

The CFD-based analysis conducted on the double-pass solar air_heater has great potential in the evaluation of its thermal properties. This superiority of CO_2 to the air-medium by a cooling down of 7.68 percent of efficiency has been demonstrated. The use of CO_2 as the working medium has demonstrated a higher thermal efficiency compared to air. In addition, CO_2 is not only miscible but also has greater efficiency than just air in creating a reaction between the two fluids. This leads to higher efficiency and the improvement of 15.2% over plain air. The greater heat capacity that is associated with this mixture is responsible for a more efficient exchange of energy, as the mixture contains unique specific heat capacities for both the gases used. The best property of the fluid is that it has a high Cp value which helps to absorb more energy and thus results in better thermal efficiency. The results of this study agree with the hypothesis that using a combination of fluids as a working medium in a DPSAH would provide better thermal properties. The thermal performance of such solar air_heater with three working fluids formulated by CO_2, combination gas, and control gas is resolved. Due to this experiment, it can be understood that employing CO_2 and combination gas rather than control gas could bring more benefits. The main limitation of this work is that it has investigated just the thermal characteristics of the double-pass solar air_heater without considering other factors like practical implementation or cost-effectiveness. Besides, the study has not taken the ideal conditions and the sensitive factors into account, which are probable in real-world circumstances and may impede the performance. Therefore, future work may be concerned with the development of the best layout for the DPSAH with the help of techniques for the enhancement of heat transfer by using artificial roughness or ribs. Moreover, more gases can be explored for their higher heat capacity and thermal stability to find efficient ways of using them in the hot air collector. Also, research would examine the possibility of constructing the solar air_heater in a way that it could be used in unison with traditional heating systems to achieve the best results. The forthcoming field of scientists should strive to enhance solar-air heaters' thermal efficacy while keeping prices competitive and funding implementation. These programs will be targeted at these factors and solar air_heater (SAH)s could thus evolve into more viable and sustainable heat supply sources in different activities.

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