Air space impact on the performance of a solar air heater

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Abstract

Hot air is required in many engineering applications such as heating spaces and drying food. Solar air heater is used to heat air in an environmentally-friendly way. The solar air heater consists of many components that are worthy to be studied to improve its performance. In the present study, the influence of air space height, between absorber and glass cover, on the air temperature and the mass flow rate at the exit of the solar air heater was experimentally and numerically investigated. Further, the temperature distribution along the heater absorber was numerically exhibited. The studied heights of air space were 3, 5, 7, and 9 cm. Experimentally, four identical solar air heaters, each had different air space, were designed and constructed. Numerically, COMSOL Multiphysics® software was adopted. The used implemented modules were Heat transfer in fluids and Laminar flow. In addition, surface-to-ambient radiation was used. The properties of air flowing through the air solar heater were based on that available in Material Browser. A comparison was performed between the experimental and numerical results, and an acceptable agreement was found with a deviation of 4.6% for the outlet air temperature and 6.8% for the air mass flow rate. The results showed that the highest air outlet temperature was gained with the narrowest space, particularly 88.95 °C at 3 cm. While the highest mass flow rate was gained with the widest space, i.e. 9.41 g/s at 9 cm.

Keywords: COMSOL Multiphysics® software, solar air heater, air space.

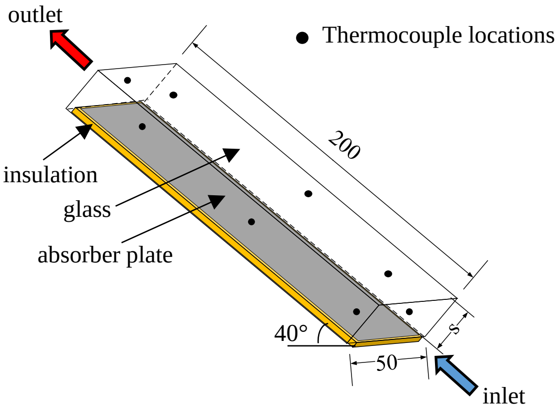
Introduction

Over the past decades, utilizing fossil fuel has shown its negative impact on the environment. The emissions produced by fossil fuel have caused global warming and climate changes. Replacing fossil fuels with environmentally-friendly energy sources has become a growing demand. Solar energy could be a great alternative to fossil fuel [1]. One of the most promising applications of solar energy is heating air [2,3]. For instance, hot air is required to heat spaces and dry food. Air can be heated in an environmentally-friendly way using a solar air heater. To enhance the performance of a solar air heater, various studies were conducted to modify its different components and parameters. In the present study, the height of air space between the absorber and the glass cover of a solar air heater was experimentally and numerically investigated. The numerical investigation was based on the Finite Element Method that is implemented in COMSOL Multiphysics® software.

Experimental Set-up

To investigate the impact of air space on the performance of a solar air heater experimentally, four identical solar air heaters were well designed and built, as shown in Figure 1. The four solar air heaters were 2 m length and 0.5 m width each. Each solar air heater had a different air space height (S), i.e. 3, 5, 7, and 9 cm. The solar air heaters were inclined by 40° with the horizon. Further, the experiments were carried out in Tikrit- Iraq (34°40' N 43°39' E) on April 18, 2019. The absorber of the solar air heater was a flat aluminum plate painted with a black coat. The glass cover was 4-mm thick. The temperature and velocity of the air entering and leaving the air solar heater were recorded. The temperature was measured using a calibrated K-type thermocouples and Applent AT4808 data logger. The air velocity was measured using BENETECH GM8 16C anemometer. Also, the solar radiation was measured using DAYSTAR DS-05 meter. For more details, the experimental set-up of the solar air heater was further described by Dheyab et al. [4].

(a)



(b)

Figure 1. Experimental setup (a) a photo, (b) a schematic diagram (dimensions in cm).

Governing Equations

The temperature of the air flowing through the air space rises up as it passes over the absorber plate. As a result, both the temperature and velocity distributions of the air change along the air space. The governing equations that describe this problem are the conservation of mass, momentum, and energy equations. The conservation of mass can be expressed as [5],

$$\rho\nabla . U = 0 \quad (1)$$

where ρ is the air density, and U is the air velocity.
The conservation of momentum equation could be written as [5],

$$\rho\frac{\partial U}{\partial t} + \rho(U.\nabla)U = \nabla.[-p + \mu\nabla U] \quad (2)$$

where t is the time, p is the pressure, and μ is the air dynamics viscosity.
While the energy equation can be expressed as [5],

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p U.\nabla T = \nabla.(k\nabla T) + Q \quad (3)$$

where T is the air temperature, C_p is the air specific heat, k is the air thermal conductivity, and Q is the heat flux.

Numerical Model

To solve the governing equations, Eqs. (1-3), COMSOL Multiphysics® was used. The Finite Element Method and all the aforementioned equations are implemented in this commercial code. To build the present model, a 3-D geometry was chosen. Since the problem was unsteady, a time-dependent study was selected. Two modules were implemented to represent the studied problem: Heat transfer in fluids and Laminar flow. Radiation impact was considered using surface-to-ambient radiation. The appropriate inlet, outlet, and surface conditions besides initial condition were used, as shown in Table 1, to match the experimental conditions. The studied geometry was a 3-D inclined rectangular (200×50 cm) with a tilt angle of 40°. Figure 2 depicts the studied model of the solar air heater.
The mesh of the built model consisted of tetrahedral, prism, triangular, and quadrilateral elements, as seen in Figure 3. The used elements sizes were fine and extra fine. At the boundaries, the mesh was extra fine, while for the remaining of geometry, the mesh was fine. The parameters of the created meshes are tabulated in Table 2. The total numbers of elements were 73654 for 3 cm, 120597 for 5 cm, 141997 for 7 cm, and 177717 for 9 cm models.

Table 1. Boundary and initial conditions.

Ambient	T= 31 °C, U= 4.6 m/s
Upper surface	$-n.(-k\nabla T) = h.(T_{ext} - T) + \varepsilon\sigma(T_{amb}^4 - T^4)$
Sides surfaces	$-n.(-k\nabla T) = 0$
Outlet	$-n.(-k\nabla T) = 0$, $[\mu(\nabla u + (\nabla u)^T)]n = 0$, $p=p_{atm}$
Initial	T= 31 °C, U=0 m/s, $p=p_{atm}$

Table 2. Mesh parameters.

Parameters / Element size	Fine	Extra fine
Maximum element size	0.043	0.019
Minimum element size	0.0081	0.0012
Maximum element growth rate	1.13	1.08
Resolution of curvature	0.5	0.3

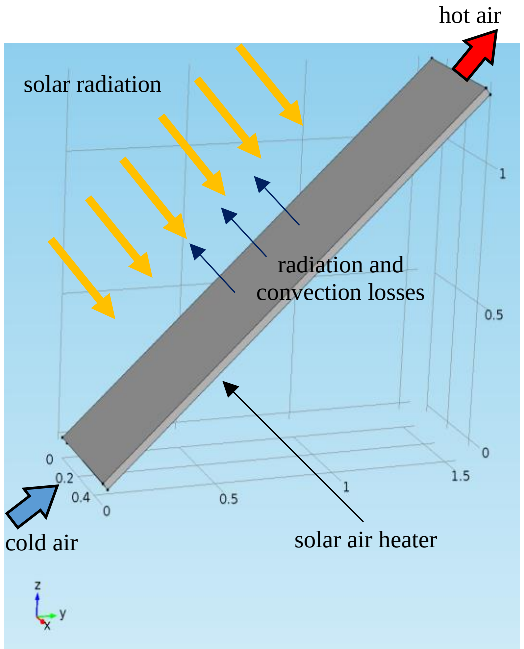


Figure 2. Schematic of the studied solar air heater (dimensions in cm).

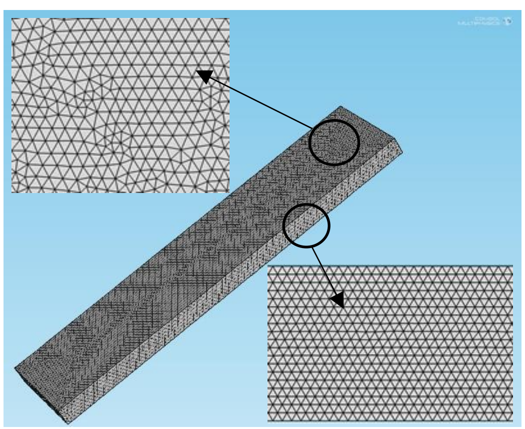


Figure 3. Mesh details of the 3-D numerical model developed and solved in COMSOL Multiphysics®.

Results and Discussion

A numerical simulation was performed using Finite Element Method that is implemented in COMSOL Multiphysics®. The calculated numerical results were compared with the experimental measurements of Dheyab et al. [4]. The compared results were at 13:00 for solar incident radiation of 1036 W/m^2 and an ambient temperature of 31 °C. The air temperature and the mass flow rate at the exit of the solar air heater were presented beside the solar air heater absorber temperature distribution.

The outlet air temperature was numerically calculated by COMSOL Multiphysics®. First, a comparison was performed between the present numerical results and the experimental results of [4], as shown in Figure 4. Less than 5% of divergence was noticed between the numerical and experimental results. For all studied air spaces, the numerical results were higher than those of the experimental ones. The reason behind that increment in numerical results was the heat losses associated with the experiments. Also, during test hours, ambient conditions were variable. On the contrary, in the numerical calculations, the ambient conditions were assumed constant. From Figure 4, it can be noticed that the outlet air temperature decreases as the air space height increases. The highest calculated outlet temperature was 88.95°C at 3 cm, while the lowest calculated one was 80.15 °C at 9 cm. In other words, the outlet air temperature decreased by 11% as the air space height was increased from 3 cm to 9 cm. In particular, although both air spaces of 3 and 9 cm were exposed to the same amount of solar radiation, the air temperature for the one of 9 cm was less than that of 3 cm. The main reason behind that is the higher air volume flowed through the air heater, by means of increasing the air space, caused this reduction in temperature.

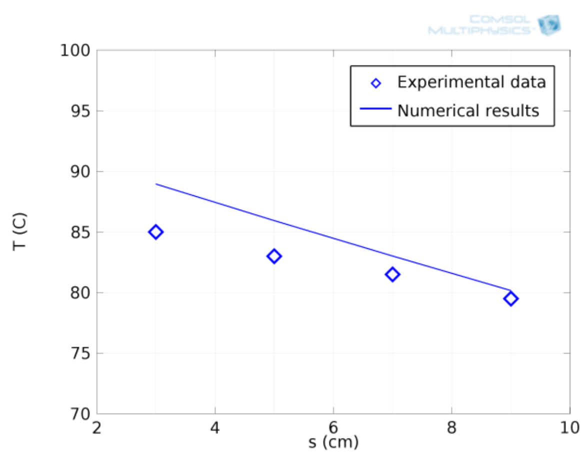


Figure 4. The air temperature at the exit of the solar air heater.

The mass flow rate of the hot air leaving the solar air heater versus the air space height is depicted in Figure 5. The numerical calculation results had the same trend of the experimental data, i.e. the mass flow rate increased as the air space increased. The highest deviation between the numerical and experimental results was 6.8%. The highest calculated mass flow rate was 9.41 g/s at 9 cm, while the lowest calculated mass flow rate was 7.65 g/s at 3 cm. Increasing the mass flow rate of the leaving air with the increase of air space was expected due to the increase in the amount of flowing air through the solar air heater. An 18.7% increase in the air mass flow rate was found. In addition, the air was accelerated due to heating it by the heater, as the air flowed through the heater, resulting in this increase in the air mass flow rate.

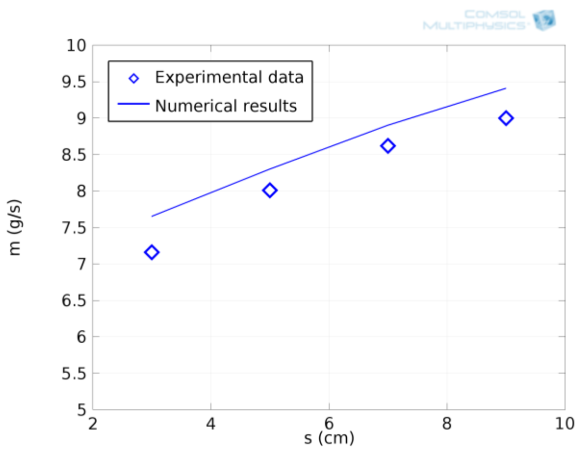


Figure 5. The air mass flow rate at the exit of the solar air heater.

Figure 6 displays the temperature distribution along the absorber of the solar air heater for the four studied air spaces, i.e. 3, 5, 7, and 9 cm. It can be noticed that the temperature of the solar air heater absorber at the exit of this absorber was higher than that at its entrance. At the entrance of the solar air heater, the air that entered the heater was cold. The temperature difference between the cold air and the hot absorber caused a high heat transfer rate from the absorber to the air. Therefore, the temperature of the absorber at the entrance of the heater was low. At the exit of the solar air heater, the air was already heated and its temperature was elevated. In this case, the temperature difference between the warm air and the hot absorber was lower compared to the case at the entrance, and subsequently, a lower heat transfer rate can be observed. Therefore, the temperature of the absorber at the exit was high. As a result, the absorber temperature was lower at the entrance of the solar air heater than that at its exit. In addition, the impact of increasing the air space can be noticed in terms of increasing the intensity of the absorber temperature. The wider the air space, the higher the solar air heater absorber temperature would be. In fact, the high mass flow rate of the air flowing through the heater gave the air less time to be heated by the absorber. In other words, cooling the absorber was less for the wide air space, causing lower outlet air temperature as aforementioned.

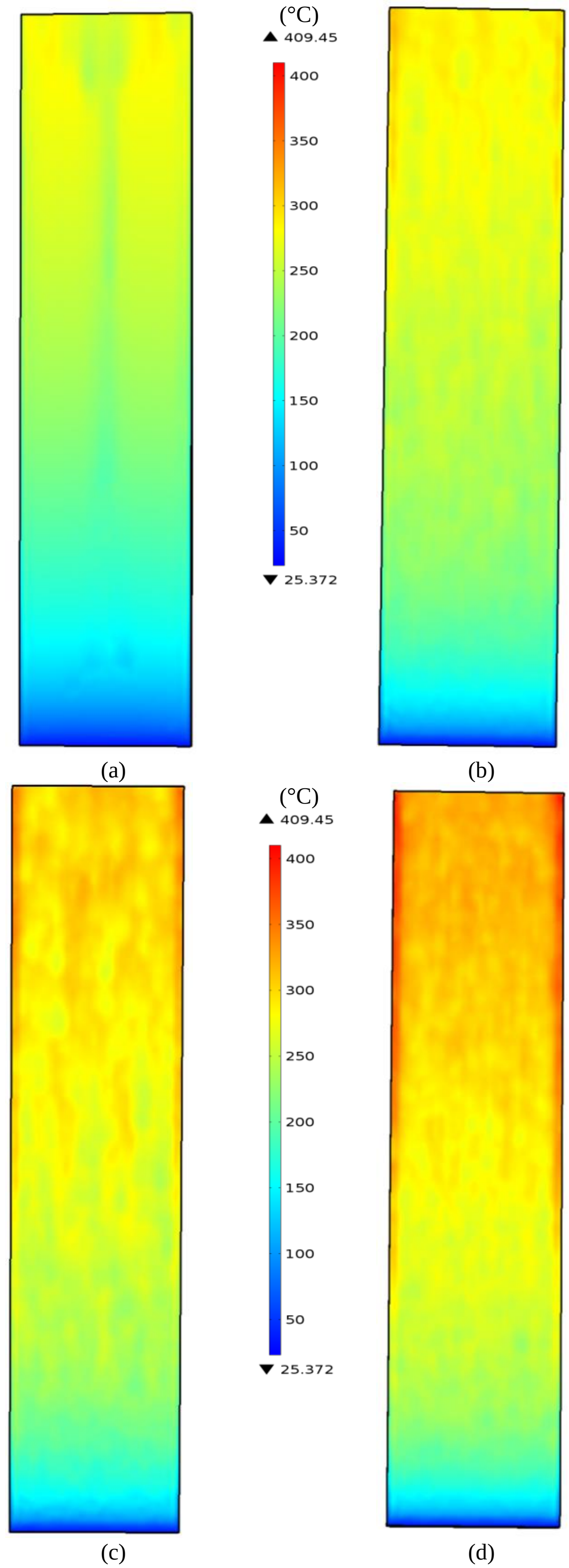


Figure 6. Temperature distribution along the solar air heater absorber for air space of (a) 3 cm, (b) 5 cm, (c) 7 cm, and (d) 9 cm.

Conclusions

The present work aimed to build a COMSOL Multiphysics® model to simulate the thermal behavior of air flowing through a solar air heater with different heights of air space, i.e. 3, 5, 7, and 9 cm. A 3-D model was built, and the Heat transfer in fluids and Laminar flow physics were adopted. The numerical results were compared with those of Dheyab et al. [4]. The results showed that as the air space height increases, the hot outlet air temperature decreases up to 11% in the range of air spaces studied here. This reduction in the outlet air temperature was caused by the higher air volume associated with wider air spaces. For the same reason, i.e. increasing the air space height, the mass flow rate of the exit hot air increased up to 18.7%. Moreover, the temperature of the solar air heater absorber was higher in the wide air spaces compared to that of the narrow ones. The high mass flow rate of the hot air associated with wide air spaces resulted in less time for the air to gain heat from the absorber and cool it down. Ultimately, further studies and optimizations are required to reveal the best outlet air temperature and mass flow rate and achieve the highest performance of the solar air heater.

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