IJE TRANSACTIONS C: Aspects Vol. 33, No. 6, (June 2020) 1156-1166

International Journal of Engineering

Journal Homepage: www.ije.ir

Effects of Gas Radiation on Thermal Performances of Single and Double Flow Plane Solar Heaters

A. Dehghani Rayeni[a], S. A. Gandjalikhan Nassab*[a,b]

[a] *Mechanical Engineering Department, Islamic Azad University of Kerman, Kerman, Iran*
[b] *Mechanical Engineering Department, Shahid Bahonar University of Kerman, Kerman, Iran*

PAPER INFO

Paper history:
Received 02 February 2020
Received in revised form 23 February 2020
Accepted 19 March 2020

Keywords:
Solar Heater
Double Flow
Mixed Convection
Gas Radiation

ABSTRACT

In this paper, the thermal characteristics of single and double flow plane solar heaters with radiating working gas were analyzed and compared by numerical analysis for the first time. The laminar mixed convection gas flow in the heaters was numerically simulated by the CFD method using the finite volume technique. The set of governing equations included the conservation of mass, momentum and energy for the convective gas flows and the conduction equation for solid parts. Besides, the radiative transfer equation was solved by the discrete ordinate method for radiant intensity computation. From numerical results, the thermal efficiency of single flow heater found very sensitive to gas optical thickness, such that gas radiation always has positive influence on the performance of system. The efficiency increase about 50% was computed for optical thicknesses more than 2 in the test cases. However, for double flow gas heater with less sensitivity to gas radiation and reciprocating trend for thermal efficiency with optical thickness, 15% increase in thermal efficiency was seen at the optimum optical thickness. Comparison between the present numerical results and those reported in literature, showed good consistency.

doi: *10.5829/ije.2020.33.06c.14*

NOMENCLATURE

b	height of gas flow (m)
B	width of heater (m)
c_p	specific heat (kJ/kg K)
h	convection coefficient (W/m^2K)
I	radiation intensity (W m^{-2})
I_b	black body radiation intensity(W m^{-2})
k_g	glass thermal conductivity (Wm^{-1}K^{-1})
k_a	absorber thermal conductivity (Wm^{-1}K^{-1})
L	length of heater (m)
$\dot{m}$	mass flow rate (kg/s)
n	normal to the surface
q''	heat flux (W/m^2)
r	position vector (m)
s	direction
T_{in}	inlet temperature (K)
T	temperature (K)
u	x- velocity component (m/s)
v	y- velocity component (m/s)
$\bar{v}$	average velocity (m/s)
x	horizontal coordinate (m)
y	vertical coordinate (m)

Greek Symbols

α_g	absorbtivity of glass
$\beta = \sigma_a + \sigma_s$	extinction coefficient (1/m)
δ	thickness (m)
ε	emissivity
ω	albedo coefficient, $\sigma_s/(\sigma_s+\sigma_a)$
η	efficiency
σ_s	scattering coefficient (m^{-1})
σ	5.67×10^{-8} (W m^{-2}K^{-4})
σ_a	absorption coefficient (m^{-1})
$\tau_0 = \beta.b$	optical thickness
τ	transmissivity

Subscript

a	absorber
conv	convection
g	glass
insul	insulation
in	inlet
p	bottom plate

* Corresponding Author Email: *ganj110@uk.ac.ir* (S. A. Gandjalikhan Nassab)

Please cite this article as: A. Dehghani Rayeni , S. A. Gandjalikhan Nassab, Effects of Gas Radiation on Thermal Performances of Single and Double Flow Plane Solar Heaters, International Journal of Engineering (IJE), IJE TRANSACTIONS C: Aspects Vol. 33, No. 6, (June 2020) 1156-1166

1. INTRODUCTION

Renewable energy technologies are receiving increased attention to fulfill the world energy requirements, given the growing awareness about the change of climate. One of the methods in energy saving is conversion of solar irradiation into gas enthalpy by plane solar air heaters (SAHs). The outlet high temperature airflow can be used in many engineering applications [1, 2]. The flat plate solar air heater studied in this work is generally designed for low and moderate temperatures. Due to the low rate of heat transfer capability between the absorber plate and air flowing in the duct, thermal efficiency of these heat exchangers is generally low. In order to make this heat exchanger more effective, the thermal performance needs to be improved by enhancing the heat transfer rate. Efforts have been made by many investigators to combine a number of the most important factors to describe the thermal performance of solar collectors in a computationally efficient manner. The suggestion of present work is employing radiating working gas in solar gas heaters and receiving more thermal energy by combined radiation-convection heat transfer in the gas flow.

Many efforts have been put forward during the past two decades via experimental and theoretical methods for modification and optimum design of conventional solar air heaters by increasing convection coefficient and surface area [3, 4]. One of the promising methods is using double flow solar air heaters, in which the surface area between the gas flow and absorber plate is doubled by passing two airflows from above and below the absorber plate. They are called double flow single pass solar air heater in literature. The schematics of both the single and double flow heaters analyzed in the present work are presented in Figure 1.

In addition to studying multiple flow heaters, many investigators have given their attention on different factors such as using corrugated or finned absorber, heaters with phase change material, attaching baffles, artificial roughness, etc. [5-7]. Saha and Sharma [8] planned to investigate the effect of corrugated absorber plate on the performance of double-flow SAH based on the energy and exergy efficiencies. Chand et al. [9] studied the thermal behavior of louvered finned solar air collectors, numerically. Their work involves evaluating various parameters such as temperature rise, thermal efficiency, and effective efficiency compared with the simple plane solar air heater. Ozgen et. al [10] presented an analysis of the efficiency evaluation on a new type of double flow SAH. According to the results of the experiments, double-flow type of SAHs with aluminum cans have been introduced for increasing the heat-transfer area, leading to higher thermal efficiency. In addition, it was reported that double flow heaters have higher efficiency than single flow heaters operating under the same air mass flow rate. The effect of multiple C shape roughness on the absorber plate of double flow solar air heater was examined experimentally by Mohitkumar et. al [11]. Tyagia et al. [12] carried out a review of solar air heating system with and without the thermal energy storage technique. In a recent study by Kabeel et al. [13], a detailed review about a wide variety of design configurations and improving methods in SAHs was presented.

In all of the previous studies, the radiation effect of air was neglected, due to the low or moderate air temperature in these heat exchangers and low radiant absorption coefficient of air. It is expected that under high temperature condition or using radiating working gas such as the mixture of air with carbon dioxide and water vapor, which are two gases with high absorption coefficient, the gas radiation will play a central role in thermal behavior of gas heaters. In addition, by using radiating gas rather than air, some of the incoming solar irradiation directly absorbs by the convection flow, that enhances the energy transfer from solar irradiation into the gas flow.

Numerable research works has been carried out in reported in literature [14-15] on the effect of gas radiation in combined radiation and convection radiating gas flow. However, the thermal behavior of single flow plane solar heaters with gas radiation effect has been analyzed by Foruzan Nia et al. [16]. for the first time. In that study, the set of governing equations for the forced convection gas flow and the conduction equation for the solid parts solved by numerical methods. Numerical results revealed that the thermal efficiency of solar gas heaters is greatly affected by gas radiation, in such a way that the performance of the system increases considerably with the increase of gas optical thickness. Since, in the proposed solar gas heater, radiating gases are used, a closed cycle for working gas should be designed. Therefore, an extra heat exchanger is needed to transfer the thermal energy of high temperature gas flow into a second working fluid for using in many engineering applications. [17, 18].

In the present study, which is the continuation of the previous work reported in literature [16], the gas radiation effect on the performance of double flow gas heaters is investigated for the first time. It is expected that this type of solar heater with radiating working gas will operate very efficiently. The second target of the present research work is comparing the thermal performances of single and double flow solar heaters with considering gas radiation at different optical thicknesses. The literature review by the authors shows that this problem has not been studied before in any research work.

Based on the applied mathematical model, the conservation equations of mass, momentum and energy for the gas flow and the conduction equations for the glass cover, absorber plate and insulation layer for both single and double flow gas heaters solved, numerically. Radiation computations are based on the numerical solution of the radiative transfer equation (RTE) with the discrete ordinate method (DOM). The discretized forms of the governing equations obtained by the finite volume method (FVM) and solved with the CFD technique along with three diagonal matrix Algorithm (TDMA) via an iterative procedure. The authors performed the numerical simulations by writing a Fortran computer code. Results presented in the forms of temperature contours inside the whole computational domain including all parts of heaters, and the gas temperature distribution in the heater ducts. Besides, the effect of gas optical thickness on the rate of energy conversion and thermal efficiency is thoroughly explored.

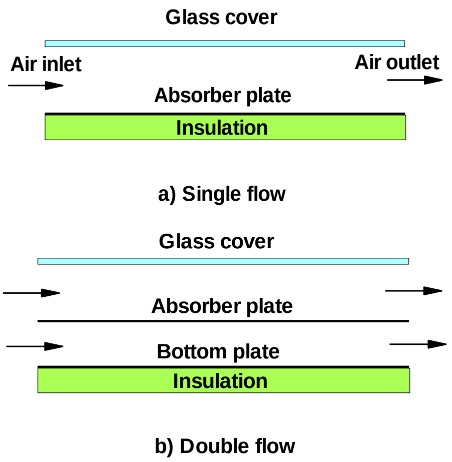


Figure 1. Schematics of single flow and double flow solar air heaters

2. PROBLEM STATEMENT

The solar gas heater investigated in this study is schematically depicted in Fig. 2. Although, the same equations govern the phenomena in single and double flow heaters, the analysis of double flow heaters is more complicated. therefore, for simplicity, only the simulation and mathematical model of double flow type is explained in this section. The flow of radiating working gas passes both above and below the absorbing plate in order to increase the surface area for heat transfer. These two flows with equal mass flow rate enter into the heater with uniform velocity V_{in} and uniform temperature T_{in}. All geometrical parameters of the heater including the glass cover, absorber, bottom plate and insulation layer are shown in Fig. 2. In both upper and lower ducts, the gas flows are assumed to be laminar, keeping the Reynolds number, defined as $Re = \rho V b/\mu$, below 2000. As the solar heater is inclined, the buoyancy effect in the gas flow also considered into account by the Boussinesq approximation. A major part of the incoming short-wave solar irradiation is transmitted across the glass cover and an amount equal to $\alpha_g . q''_{sun}$ is absorbed. Accordingly, the conduction equation with heat generation term should be solved for temperature computation in this element.

2. 1. Basic Equations

In the analysis of double flow solar gas heater, the set of governing equations for two dimensional steady and incompressible laminar mixed convection flow of radiating gas with employing the Boussinesq approximation is as follows [16]:

i) Flow equations

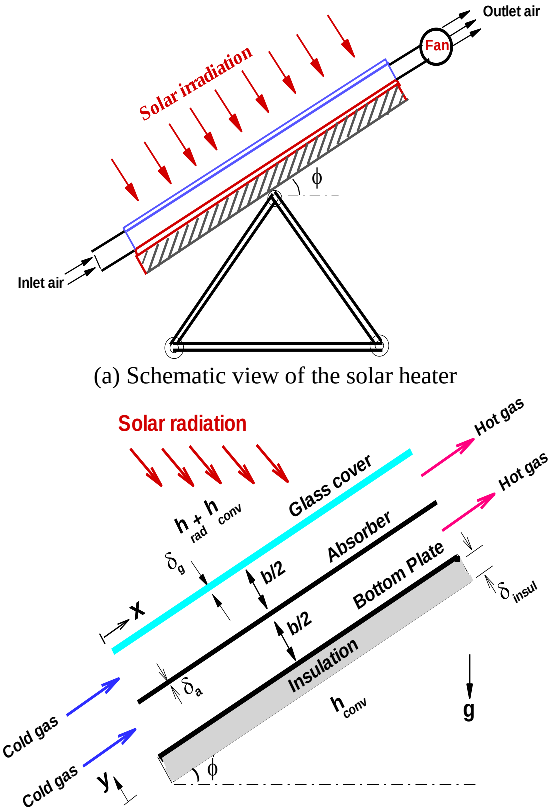
Continuity:

$$\nabla.\vec{V} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

x-momentum:

$$\vec{V}.\nabla u = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu \nabla^2 u + g\beta(T - T_0)\sin\phi \tag{2}$$

y-momentum:



(a) Schematic view of the solar heater

(b) Layout of the gas flow in heater's duct

Figure 2. Geometry of the double flow solar gas heater

$$\vec{V}.\nabla v = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu \nabla^2 v + g\beta(T - T_0)\cos\phi \tag{3}$$

Energy:

$$\vec{V}.\nabla T = \alpha \nabla^2 T - \frac{1}{\rho c_P}\nabla \cdot \vec{q}_r \tag{4}$$

ii) Glass cover conduction equation

$$\nabla^2 T_g + \frac{\alpha_g . q''_{sun}}{\delta_g . k_g} = 0 \tag{5}$$

iii) Conduction equation for absorber, bottom plate and insulation

$$\nabla^2 T_a = 0 \tag{6}$$

$$\nabla^2 T_p = 0 \tag{7}$$

$$\nabla^2 T_{insul} = 0 \tag{8}$$

Since the flow equations are temperature-dependent because of the buoyancy terms, all of the governing equations (Equations (1)-(8)) should be solved simultaneously.

2. 2. Radiation Computations The divergence of radiative heat flux presented in the gas energy equation depends on to temperature and radiant intensity distributions inside the participating medium as follows [19]:

$$\nabla.\vec{q}_r = \sigma_a.(4\pi\sigma T^4(\vec{r}) - \int_{4\pi} I(\vec{r},\hat{s})d\Omega) \tag{9}$$

The distribution of radiation intensity $I(\vec{r},\hat{s})$ can be computed using the RTE, which is the following integro-differential equation [19]:

$$\vec{s}.\nabla I(\vec{r},\vec{s}) = -\beta I(\vec{r},\vec{s}) + \sigma_a I_b(\vec{r}) + \frac{\sigma_s}{4\pi}\int_{4\pi} I(\vec{r},\vec{s})\varphi(\vec{s},\vec{s}')d\Omega' \tag{10}$$

The radiant intensity distribution along the boundary walls has the role of boundary condition for solving the RTE via the following relation [19]:

$$I(\vec{r}_w,\vec{s}) = \varepsilon_w I_b(\vec{r}_w) + \frac{(1-\varepsilon_w)}{\pi}\int_{\vec{n}_w.\vec{s}'<0} I(\vec{r}_w,\vec{s})|\vec{n}_w.\vec{s}'|d\Omega' \qquad \vec{n}_w.\vec{s} > 0 \tag{11}$$

The details of the discrete ordinate method in numerical solution of the radiative transfer equation is omitted here to save space, and readers are referred to literature [14-16] for details.

2. 3. Boundary Conditions In numerical computations, six sub-domains including the glass cover, two gas flows, absorber, bottom plate, and insulation layer, exist inside the computational domain of double flow gas heater. The flow equations, including the conservation of mass, momentum and energy solved for the gas flows and heat conduction equation for four solid parts of the heater. In numerical solution of flow equations, no slip condition employed at the solid-gas interface. The gas flow has uniform velocity and temperature distributions at inlet section, while the gas velocity at the outlet section is corrected based on the continuity requirement and zero axial conduction $\partial^2 T / \partial x^2$ considered in gas temperature computation. Besides, the continuity of temperature and heat flux imposed at the gas-solid interfaces. In the radiating gas, the total heat flux is the sum of conductive and radiative terms. Therefore, the following boundary condition according to the continuity of heat flux employed on the interfaces of gas flow with the glass cover and solid plates [15]:

$$-k_{solid}\frac{\partial T_{solid}}{\partial n} = -k_{gas}\frac{\partial T_{gas}}{\partial n} + \varepsilon_w\left(\pi I_b(\vec{r}_w) - \sum_{\vec{n}_w.\vec{s}_i<0} I(\vec{r}_w)\left|\vec{n}_w.\vec{s}_i\right|w_i\right) \tag{12}$$

Finally, on the outer surfaces of the heater exposed to the surrounding, the convection boundary condition with equivalent radiation- convection coefficient is applied in the mathematical model [16].

3. OVERALL SOLUTION PROCEDURE

In the analysis, the discretized forms of the governing equations were obtained by integrating over each control volumes with nonuniform staggered grids in the computational domain by the well-known Finite Volume Method (FVM). The first-order upwind scheme and the central differencing method were employed for discretizing the convective and diffusion terms, respectively. Navier Stokes equations were numerically solved using the SIMPLE algorithm of Patankar [20]. The strategy of calculating each dependent variable was based on the line-by-line procedure of the tri-diagonal matrix algorithm (TDMA).

In radiation computations, the discretized form of RTE is obtained by the FVM and solved by the DOM. In the present analysis, S6 approximation was employed in the numerical solution of RTE. In total, thirteen equations (four conduction equations for solid element, eight flow equations for two gas flows and the RET) had to be solved, simultaneously.

Different mesh sizes used in the grid study to arrive at a grid independent converged solution. Accordingly, an optimum grid of 800$\times$160 was chosen, with clustering in both x and y-directions in the regions with high temperature and velocity gradients (Fig. 3). In radiation computations, the same grid size inside the flow domains was considered. In Table 1, the effects of grid size on calculations of maximum velocity and gas bulk temperature at the outlet section and the maximum temperature of absorber plate of the double flow solar air heater whose parameters are reported in Table 2, were investigated. Accordingly, the optimum discretized computational domain 800×160 determined and used in all subsequent test cases. It should be noted that in the construction of double flow solar heaters, the absorber and the bottom plate are identical with the same geometrical and physical properties.

Figure 4 shows the flow chart of computations. In iterative solution of flow equations, the converged velocity distribution was considered to be achieved when the sum of mass residual at each control volume became less than 10^{-4}. Besides, the following criteria was used for obtaining the converged solution in temperature and radiant intensity computations:

$$ErrorI = Max\left|\frac{I_p^n - I_p^{n-1}}{I_p^n}\right| \le 10^{-4} \quad (13)$$

$$ErrorT = Max\left|\frac{T_p^n - T_p^{n-1}}{T_p^n}\right| \le 10^{-4} \quad (14)$$

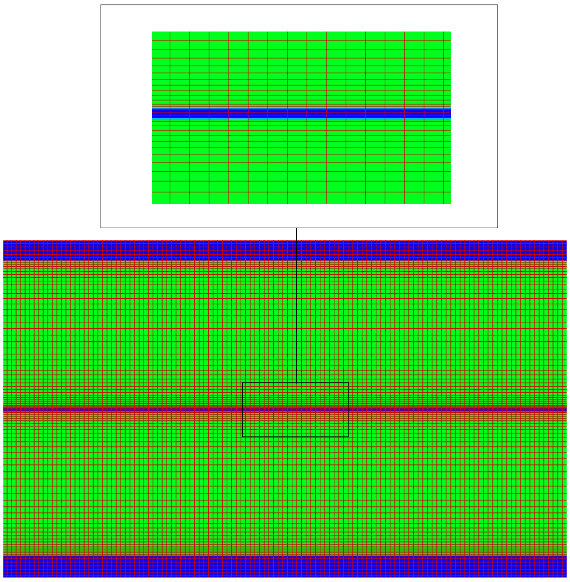


Figure 3. Structure of the grid on the computational domain

TABLE 1. The effect of grid size on converged solutions

Grid size	320*100	750*120	800*160	850*160
$T_{out}[^oC]$	300.1	330.2	334.7	335.1
$T_{max}[^oC]$	355	371	375.7	376.1
$u_{max}/\bar{V}$	1.390	1.463	1.497	1.498

TABLE 2. Values of parameters used in numerical simulation

Parameter	Value	Parameter	Value
δ_g	3 mm	δ_a	1.2 mm
ε_g	0.9	ε_a	0.95
α_g	0.05	k_a	80 W/mK
τ_g	0.9	T_{in}	35 ^oC
k_g	0.78 W/mK	δ_{insul}	2 cm
k_{insul}	0.037 W/mK	b	2 cm
$\bar{V}_{air}$	0.4 m/s	$\dot{m}$	0.01 kg/s
L	70 cm	B	50 cm
T_∞	35 ^oC	ϕ	30 ^{0}

In Equations (13) and (14), the subscript ‘p’ and superscript ‘n’ denote to the grid point and iteration level, respectively.

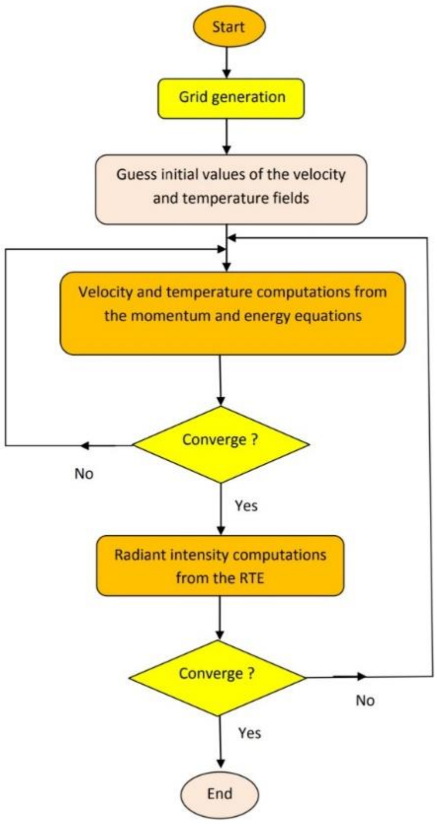


Figure 4. Flow chart of numerical procedure

4. VALIDATION

In order to validate the mathematical model and numerical strategy used in the present study with experimental data, the double flow SAH which was experimentally studied in literature [10] is simulated and the numerical results are compared with the experiment in Table 3. The air mass flow rate is 0.03 kg/s and the values of all of geometrical parameters of the heater with the thermo-physical and radiative properties of all parts are given in that reference. In Table 3, the operating conditions of the heater on the test day from 9 am to 4 pm including the air inlet and outlet temperatures as well as the solar radiative flux are tabulated. In the last three columns, the computed air temperature at the outlet is compared with experimental data reported in literature [10] and the relative error is also reported. It is apparent that the present numerical simulation over-estimates the air outlet temperature which may be due to the two dimensional analysis, but the maximum error is lower than 4.3%. In another test case, the plane solar air heater studied theoretically by Chand et al. [9] and experimentally by Karwa et al. [21] is simulated and its thermal efficiency versus air mass flow rate is drawn in Fig. 5. The values of all input data for simulating this test case have been reported in literature [9, 21]. Figure 5 shows an increasing trend for thermal efficiency with increasing in the air mass flow rate. Besides, good consistencies are seen between the values predicted in the proposed numerical simulation and those reported in literature.

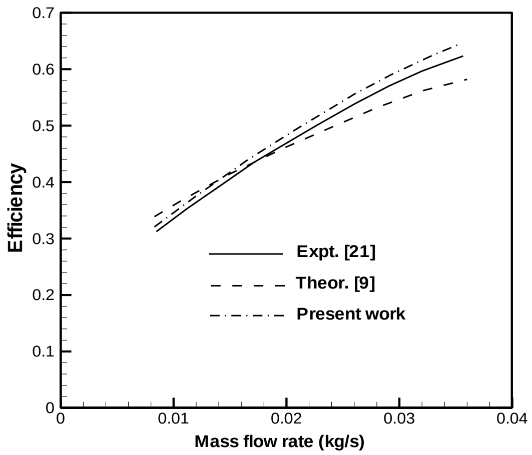


Figure 5. Variation of thermal efficiency with air mass flow rate, ($\eta = \dot{m}c(T_{out} - T_{in}) / q''_{Sun}A$)

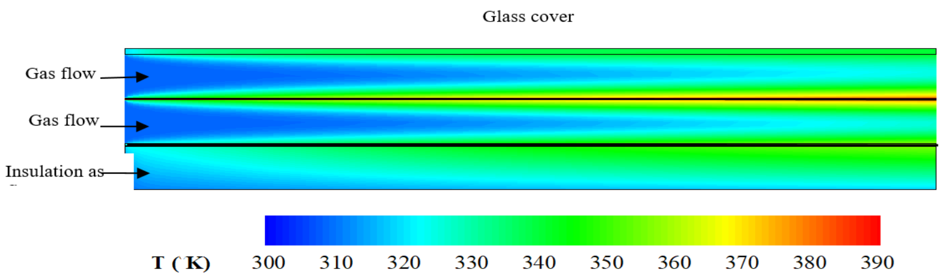
5. RESULTS AND DISCUSSION

The results presented in this section are obtained from the numerical simulation of the double flow solar gas heater whose geometrical parameters are reported in Table 2. The total mass flow rate of the working gas is equally divided into the upper and lower ducts of the heater with the same conditions in the inlet section. The Reynolds number of the gas flows according to the data given in Table 2 becomes less than 2000 and the Rayleigh number is in the order of 10^5, assuming laminar flow. Also, the Richardson number, $Ri = Gr / \mathrm{Re}^2$, is in the order of one, for considering the mixed convection flow. The value of the incoming solar heat flux is considered to be 1100 W / m^2 in all numerical simulations. In the solar gas heater under study, the absorber and the bottom plate are diffusely opaque and the working gas is considered to be participating medium. The glass cover transmits a major part of the short-wave incoming solar irradiation, but it is opaque against the long-wave thermal radiation emitted from low temperature bodies.

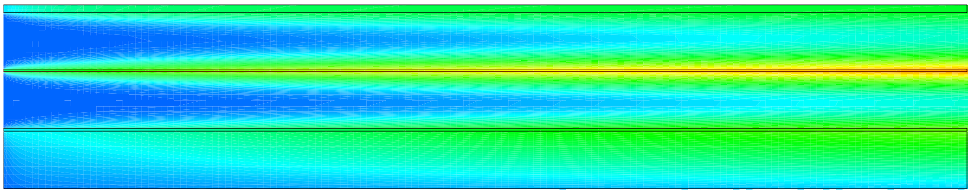
The temperature contours for both double and single flow SAH are visualized in Figure 6 at three different values of gas optical thickness, including the non-radiating case ($\tau_0 = 0$). For non-radiating working gas in double flow heaters, it is seen that the upper flow is heated along the heater through convection heat transfer by the absorber and slightly by the glass cover, which absorbs some of the incoming solar radiation equal to $\alpha_g . q''_{sun}$. As physically expected, the maximum temperature inside the heater is reached on the absorber and this element plays the main role in generating the high temperature gas flow at the outlet. Besides, more temperature increase in the upper gas flow takes place as it passes through the heater in comparison with the lower gas flow, especially when the working gas is radiative and has high optical thickness. This is due to the fact that the upper gas flow receives higher rate of convection heat transfer from high temperature absorber surcease and also absorbs directly a part of short-wave solar radiation, such that the lower gas flow is not exposed to this radiative source. The gas radiation has a similar effect in

TABLE 3. Comparison between the computed air outlet temperatures with experiment [10]

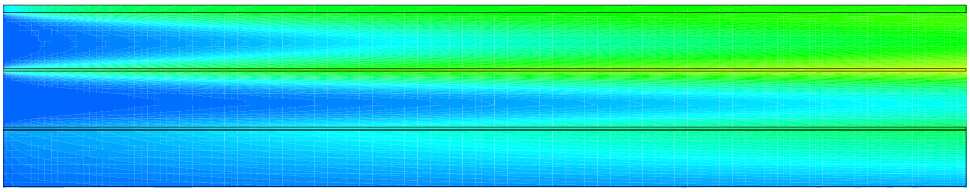
Time (h)	$T_{in}\,(^{o}C)$	$q''_{Sun}\,(W/m^2)$	$T_{Out}\,(^{o}C)$ (Expt.)	$T_{Out}\,(^{o}C)$ (Theor.)	Relative Error%
9	23.5	420	28	29.2	4.3
10	31	630	38	38.8	2.1
11	35	800	46	47.2	2.6
12	37.5	900	53	55.3	4.3
13	39	950	57.5	58.6	1.9
14	37	910	53.5	55.1	3.0
15	34	800	46.5	48.2	3.6
16	29	660	38	39.2	3.1



i) $\tau_0 = 0$

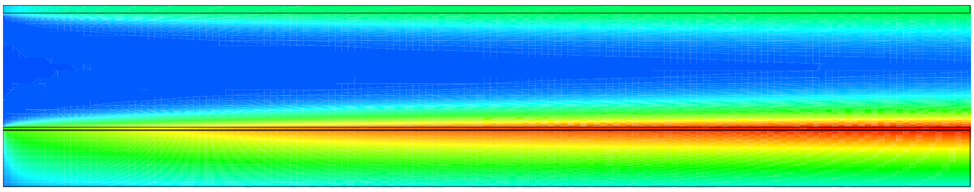


ii) $\tau_0 = 0.1$

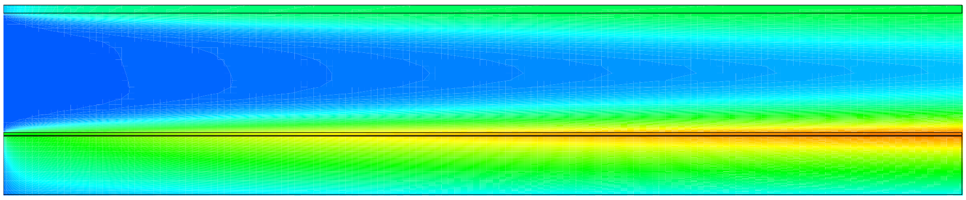


iii) $\tau_0 = 1$

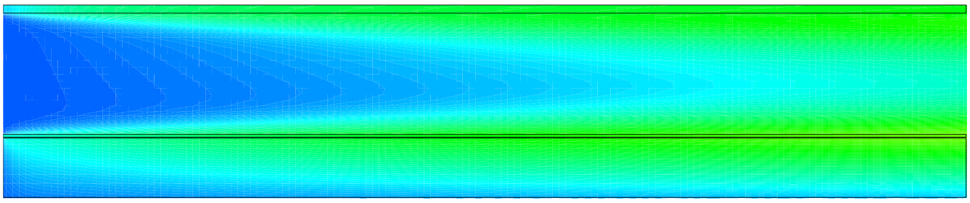
a) Double flow



i) $\tau_0 = 0$



ii) $\tau_0 = 0.1$



iii) $\tau_0 = 1$

b) Single flow

Figure 6. Temperature contours inside the single and double flow gas heaters at different optical thickness

single flow SAHs, a higher energy conversion takes place in the heater in the case of using radiating working gas. Besides, Figure 6 demonstrates that the maximum absorber temperature decreases by gas radiation, especially when the optical thickness gets higher.

To show the temperature pattern inside the heaters more clearly, the temperature distributions along the y-direction at different axial sections are drawn in Figure 7 for single and double flow heaters operating under different optical thicknesses. This figure shows clearly, how the gas flow gets thermal energy from solar irradiation by both convection and radiation mechanisms. It seen that the high temperature region in the heater is due to the absorber and the hottest point happens on this element at the outlet section. Figure 7 depicts that the major part of heat loss takes place from the insulation layer in which, large temperature gradient in y-direction exists at its boundary adjacent to surrounding. It is also seen that in double flow gas heaters, the temperature increase in the upper gas flow is greater than the lower one, especially at high optical thickness condition. This behavior was also seen in the previous figures. Furthermore, it can be seen that the upper flow is more sensitive to gas radiation because it is exposed to two strong radiative fluxes from its upper and lower surface boundaries. These two heat fluxes are the incoming solar radiation and the emitted radiant energy from absorber plate. The temperature distributions drawn for single flow heater show that the temperature of absorber plate in these heaters is much higher than the double flow ones, because less energy conversion from solar radiation into gas enthalpy takes place in these systems. Also, Figures 7 (a) and (b) visualize that in both types of heaters, the temperature distribution along the y-direction for each axial section become more uniform, when radiating working gas is used. This is due to more thermal energy penetration into the gas flow by combined radiation-convection heat transfer.

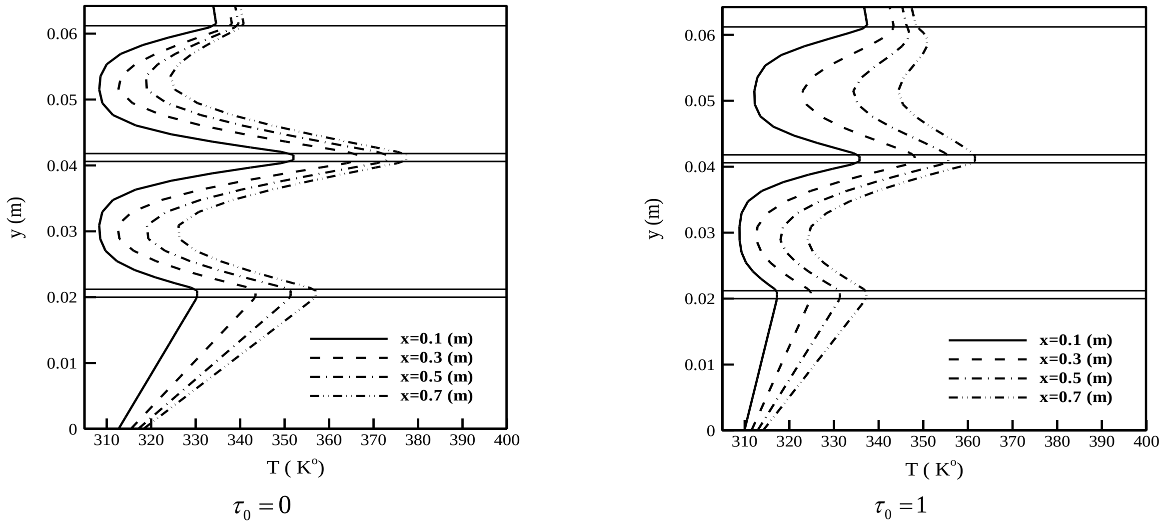
This energy transfer is enhanced in double flow heaters in which the absorber is adjacent to gas flows from both its upper and lower surfaces. This behavior led to more reversible heat transfer and then higher thermal performance.

Figure 8 shows the variation of gas bulk temperature along the channel of a single flow heater at different values of the gas optical thickness. It is seen that the bulk temperature distribution in the x-direction is almost linear, so that greater temperature increase takes place in the radiating working gas with high optical thickness. This behavior was seen before in the previous work by the author and it was concluded that the performance of single flow heaters is improved by using optically thick gas flows [16]. Figure 9 shows the variation of gas bulk temperature along the upper and lower channels in double flow solar heater at different values of the gas optical thickness. For the upper flow, greater temperature increase along the heater takes place in the case of using radiating working gas. This is due to this fact that in the case of using radiating working gas, a part of solar incoming radiation is absorbed directly by the gas flow and the mechanisms of energy transfer from heater to the gas flow takes place by both convection and radiation. But for the lower gas flow inside the heater, opposite behavior is seen, such that radiating working gas receives much less energy. It should be recalled that weather the performance of double flow solar heater improves by using radiating working gas or nor, the effect of gas optical thickness on thermal efficiency should be studied. The performance of solar gas heaters can be evaluated by defining their thermal efficiency which can be computed as follows:

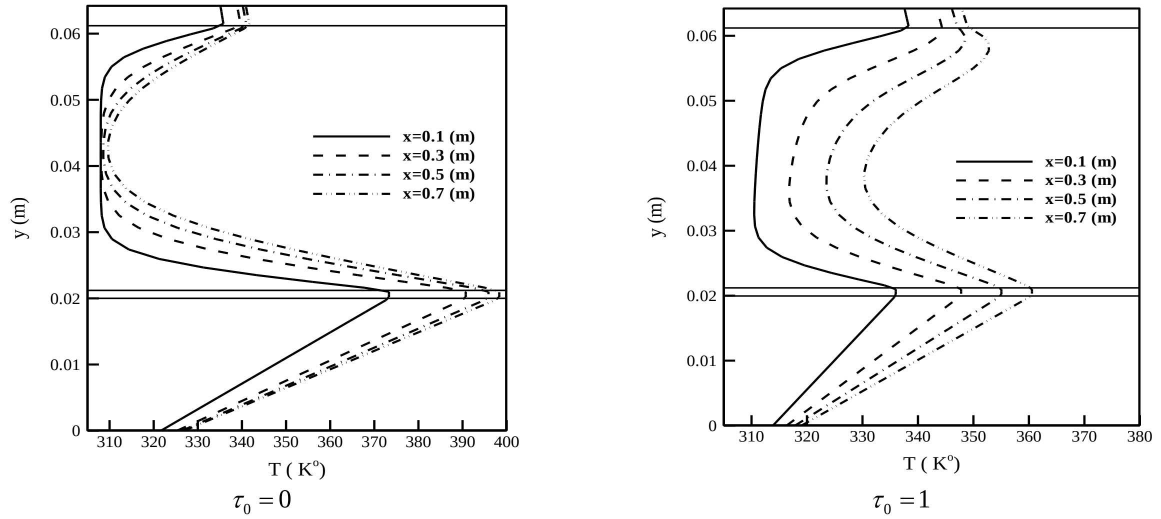
$$\eta = \frac{\sum_{i=1}^{2} \dot{m}_i c (T_{out} - T_{in})_i}{q''_{sun} . A} \tag{15}$$

In Equation (15), $\dot{m}_i$ is the gas mass flow in the upper and lower duct of double flow heater, and for single flow heaters, the numerator only has one term. The variations of double flow and single flow efficiencies as a function of optical thickness are drawn in Figure 10. As physically expected, there is an increasing trend for thermal efficiency of single flow heater with optical thickness. It is visualized in Figure 10 that using radiating gas with $\tau = 2$, yields to 80% thermal efficiency. However, for double flow heaters, there is an optimum value of optical thickness, say τ =0.8, for having the best performance, corresponds to $\eta = 80\%$.. To the best of the author's knowledge within the well-documented techniques in the open literature, such high efficiency has not yet been reported. Besides, it is seen from Figure 10 that the double flow heater has higher efficiency than the single flow one in a wide range of gas optical thickness $0 \le \tau \le 1.4$, and the maximum difference between the efficiencies of these heaters happens in the case of non-radiating working gas corresponds to $\tau = 0$.

As noted before, the efficiency of SAHs has been found to be low because of low convective heat transfer coefficient between absorber plate and the flowing air which increases the absorber plate temperature, leading to higher heat losses to the environment. Due to the main role of absorber in SAHs, the surface temperature variation of this element in axial direction for both single and double flow heaters are drawn in Figure 11 taking into account the gas radiation effect. This figure depicts the increasing trend of absorber temperature along x-direction that is due to growing temperature boundary layer thickness, leading to decrease in convection coefficient. Therefore, it is expected that the absorber's maximum temperature takes place at the outlet section, as it can be seen in Figure 11. Because, the absorber plate in double flow heaters is exposed to convection from both



(a) Double flow



(b) Single flow

Figure 7. Temperature variations in all parts of solar heaters along the y-direction at different axial sections

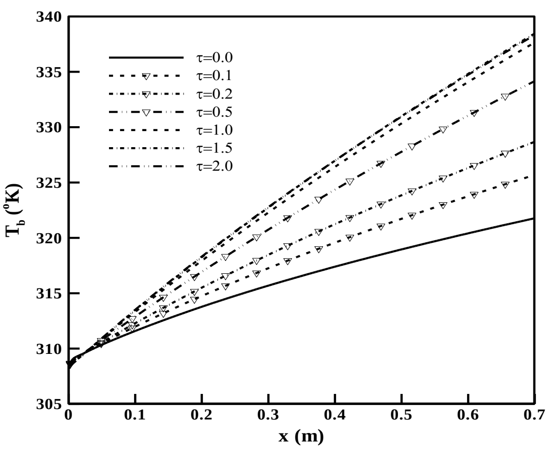
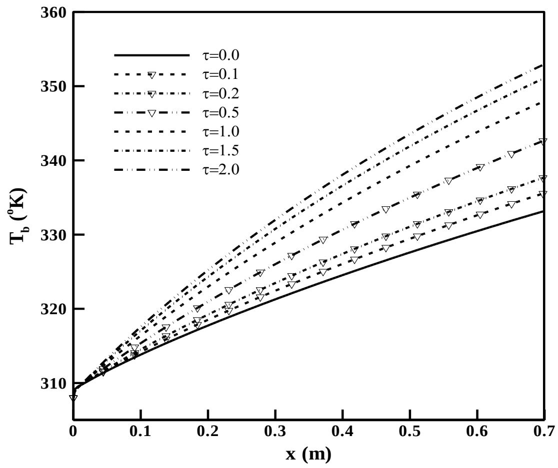
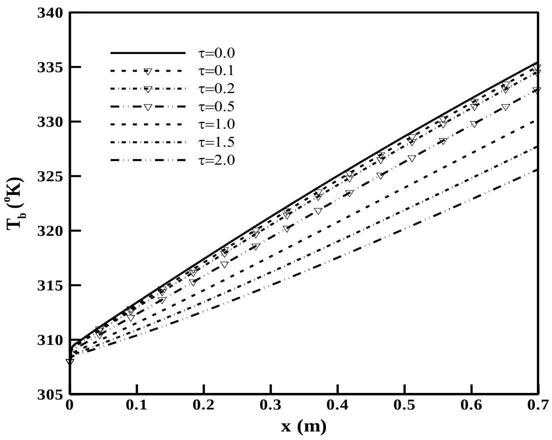


Figure 8. Gas bulk temperature distribution along the single flow gas heater



(a) Upper gas flow



(b) Lower gas flow

Figure 9. Gas bulk temperature distribution along the double flow gas heater

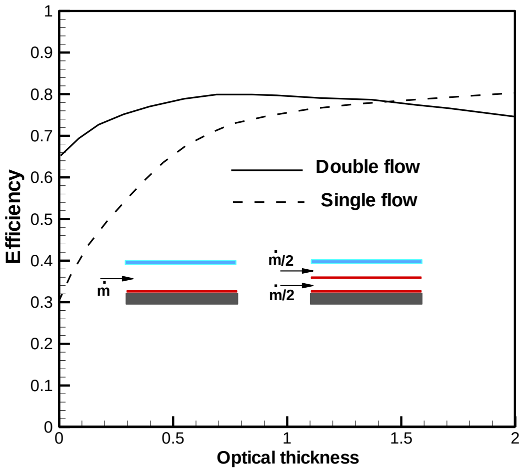


Figure 10. Comparison between the efficiencies of single and double flow heaters

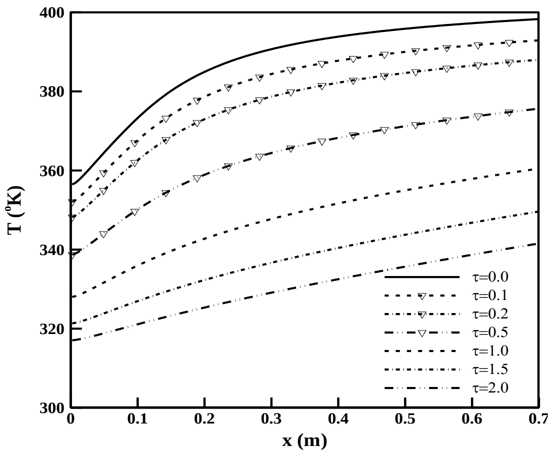


Figure 11. Absorber surface temperature distributions at different optical thickness

its upper and lower surfaces, the temperature of this element is lower that the single flow heater. It leads to more reversible convection heat transfer and then higher performance. By enhancing the rate of heat transfer into the gas flow from pure convection into the combined radiation-convection heat transfer with using radiative working gas, the absorber plate temperature decreases as it is demonstrated in Figure 11, especially when the gas optical thickness gets higher.

6. CONCLUDING REMARKS

In the present investigation, the main motive is to improve the performances and efficiencies of the single and double flow plane solar gas heaters based on using radiating working gas. For this purpose, these types of solar heaters are simulated and analyzed numerically. For solid elements in the heaters, including the glass cover, absorber, bottom plate and insulation layer, the conduction equation and for the gas flows, the continuity, momentum and energy equations were considered as governing equations and solved by FVM. The computed temperature field in double flow gas heaters revealed that more rate of energy conversion from solar irradiation into gas enthalpy takes place in this type of solar heater, and this behavior enhances with gas radiation. In the test cases, more than 50% increase in thermal efficiency in single flow haters was also seen with using radiating gas flow with $\tau = 2$ instead of non-radiating working fluid $(\tau = 0)$. On the other hand, numerical results revealed that double flow heaters have lower sensitivity to optical thickness, because the opposite effect of gas radiation in temperature increase inside the upper and lower gas flows. So, there is an optimum value of optical thickness, say $\tau = 0.7$, for having the maximum thermal efficiency, which is about 80%. It is a very high efficiency for plane solar gas heaters. Besides, numerical analysis revealed that in a wide range of optical thickness $0 \le \tau \le 1.4$, double flow heaters work more efficiently in comparison to single flow ones, and the maximum difference in their efficiencies happens at $\tau = 0$, corresponds to non-radiating working gas.

7. REFERENCES

1. Menni, Y., Azziz, A. and Chamkha, A., "A review of collectors: Models and applications, ***Journal of Applied and Computational Mechanics***", Vol. 4, No. 4, (2018), 375-401.

2. Sengupta, A. R., Gupta, R. and Biswas, A., "Computational fluid dynamics analysis of stove systems for cooking and drying of Muga Silk", ***Emerging Science Journal***, Vol. 3, No. 5, (2019), 285-292.

3. Esen H., "Experimental energy and energy analysis of a double-flow solar air heater having different obstacles on absorber plates", ***Build Environment***, Vol. 43, No. 6, (2008), 1046-1054.

4. Ravi Kant, R. and Rajeshwer Prasad, S., "A review on different techniques used for performance enhancement of double pass SAHs", ***Renewable and Sustainable Energy Review***, Vol. 56, (2016), 941-952.
5. Chabane, F., Moummi, N. and Benramache, S., "Experimental study of heat transfer and thermal performance with longitudinal fins of solar air heater", ***Journal of Advance Research***, Vol. 5, (2014), 183-192.
6. Dhiman, P., Thakur NS and Chauhan SR. "Thermal and thermo-hydraulic performance of counter and parallel flow packed bed solar air heaters", ***Renewable Energy***, Vol. 46, (2012), 259-268.
7. Akpinar, E. K. and Koçyiğit, F.," Experimental investigation of thermal performance of solar air heater having different obstacles on absorber plates", ***International Communication in Heat and Mass Transfer,*** Vol. 37, (2010), 416-421.
8. Saha, S. N. and Sharma, S. P., "Performance Evaluation of Corrugated Absorber Double Flow Solar Air Heater Based on Energy, Effective and Exergy Efficiencies", ***International Journal of Mechanical and Mechatronics Engineering,*** Vol.17, No. 1, (2017), 63-76.
9. Chand, S, and Chand, P., "Performance evaluation of solar air heater equipped with louvered fins", ***International Journal of Heat and Technology,*** Vol. 36, No. 2, (2018), 741-751.
10. Ozgen, F., Esen, M., and Esen, H., "Experimental Investigation of Thermal Performance of a Double-Flow Solar Air Heater Having Aluminum Cans", ***Renewable Energy***, Vol. 34, (2009), 2391-2398.
11. Mohitkumar, G. G, Amarsingh, B. and Kanasem, P.,"Experimental analysis of double flow solar air heater with multiple C shape roughness", ***Solar Energy***, Vol. 155, (2017), 1411-1416.
12. Tyagia V.V, Panwarb N.L, Rahima N.A. and Kotharic R.,"Review on solar air heating,system with and without thermal energy storage system", ***Renewable and Sustainable Energy Review,*** Vol. 16, (2012), 2289-2303.
13. Kabeela, A. E., Hamedb, M. H., Omarab, Z. M. and Kandeal, A. W., "Solar air heaters: Design configurations, improvement methods and applications – A detailed review", ***Renewable and Sustainable Energy Reviews***, Vol. 70, (2017), 1189-1206,
14. Atashafrooz, M. and Gandjalikhan Nassab, S. A., "Simulation of three-dimensional laminar forced convection flow of a radiating gas over an inclined backward-facing step in a duct under bleeding condition", ***Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,*** Vol.227, No. 2, (2013), 332-345.
15. Foruzan Nia, M and Gandjalikhan Nassab, S. A., "Conjugate Heat Transfer Study of ombined Radiation and Forced Convection Turbulent Separated Flow". ***International Journal of Non Nonlinear Sciences and Numerical Simulation***, Vol. 18, (2017), 29-39.
16. Foruzan Nia, M. Gandjalikhan Nassab, S. A. and Ansari, A. B., "Numerical Simulation of Flow and Thermal Behavior of Radiating Gas Flow in Plane Solar Heaters", ***ASME Journal of Thermal Science and Engineering Applications,*** Vol. 12, (2020), 0310081-8.
17. Zhang, W., Wang, T., Zheng, S., Peng, X. and Wang, X.," Experimental study of the gas engine driven heat pump system for space heating and cooling", ***Civil Engineering Journal,*** Vol. 15 No. 10, (2019), 2282-2295.
18. Ahmed, B. M. and Alhialy, N. F. F.," Optimum efficiency of PV panel using genetic algorithms to touch proximate zero energy house (NZEH)", ***Civil Engineering Journal***, Vol. 5, No. 8, (2019), 1832-1840.
19. Modest, M. F., "Radiative heat transfer", 2nd edition, Academic press, New York (2013).
20. Patankar, S. V., Spalding, B. D. "A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows", ***International Journal of Heat and Mass Transfer***, Vol. 15, (1972), 1787-1806.
21. Karwa R. and Chitoshiya, G.," Performance study of solar air heater having v-down discrete ribs on absorber plate", ***Energy,*** Vol. 55, (2013), 939-955.

Persian Abstract

چکیده

در مقاله‌ی حاضر، مشخصات حرارتی گرم‌کن‌های خورشیدی صفحه‌ای با در نظرگرفتن اثرات تابشی گاز به صورت عددی مورد مطالعه شده است. در این راستا جریان جابه‌جایی ترکیبی و آرام گاز با روش دینامیک سیالات محاسباتی و استفاده از روش حجم محدود حل شده است. معادلات حاکم به منظور شبیه‌سازی گرم‌کن شامل معادلات پیوستگی، مومنتم و انرژی برای جریان گاز و معادله‌ی هدایت حرارتی برای سایر اجزای جامد گرم‌کن به طور هم‌زمان به جواب رسیده‌اند. از آن‌جا که گازتوانایی صدور و جذب تابشی را دارد، معادله‌ی انتقال تابش (RTE) به روش جهات مجزا (DOM) به منظور محاسبه شار تابشی حل شده است. نتایج عددی نشان‌دهنده‌ی وابستگی زیاد عملکرد گرم‌کن‌های یک‌جریانه به تابش گاز بوده و این تاثیر همواره مثبت ارزیابی شده است. نتایج گواه بر ۵۰٪ افزایش راندمان در صورت استفاده از جریان گاز تابشی با ضخامت اپتیکی معادل ۲ می‌باشد. اما در مورد گرم‌کن‌های دوجریانه، به واسطه‌ی تاثیر معکوس تابش گاز بر ازدیاد دمای جریان بالایی و پایینی در این مبادله‌کن‌های حرارتی، ضخامت اپتیکی بهینه‌ای برای داشتن بیشترین راندمان به دست آمده است. همچنین در مواردی که شبیه‌سازی شده‌اند معادل ۱۵٪ افزایش راندمان در صورت استفاده از گاز تابشی دیده شده است. مقایسه نتایج عددی کار حاضر با یافته‌های دیگر پژوهش‌گران رضایت‌بخش بوده است.