Experimental Study on a Solar Air Heater with Various Perforated Covers and Bed Heights

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ABSTRACT

In this study, the thermal performance of the single and double pass solar air heaters with normal glass cover, Plexiglas cover, quarter and half perforated covers were investigated experimentally. In this system, the conventional absorber plate was replaced with fourteen steel wire mesh layers. The solar air collector was tested with four different perforated covers. On two perforated covers the holes were made on the first quarter at the top side of the cover in an area of 100 × 36 cm^2. On the other two covers, half of the cover area (i.e. 100 × 72 cm^2) on the top side was perforated. The holes made on one of the quarter and one of the half perforated covers had the center-to-center distance (d_c) of 20D (6cm) and on the other two covers d_c was 10D (3cm). D was the hole diameter that is fixed to be 0.3cm. The air mass flow rate was varied between 0.011 kg/s and 0.037 kg/s. The solar collector was also tested with three different bed heights (3, 5.5 and 8cm) in order to examine the effect of duct height on the efficiency of the air heater. The height of upper channel was 2cm in double pass collector. In this research the effects of different mass flow rates, various perforated covers and different bed heights on the outlet temperature and thermal efficiency were studied.

The obtained results show that as the mass flow rate increases, the thermal efficiency also increases but the temperature difference between the outlet and inlet air, ΔT, decreases. The efficiency of the double pass collector with glass cover was always greater than the single pass collector with the same cover by 5 - 22.7% for the same air mass flow rates. In case of solar air heater with the quarter perforated cover, it was found that, the efficiency of the air heater with the 10D quarter perforated cover is slightly higher than the one with 20D quarter perforated cover for both single and counter flow collectors and that is because the 10D cover was cooler than 20D cover during the tests and this reduces the heat lost from 10D cover to the ambient.

It was found that the solar air heater with quarter perforated cover reaches to higher ΔT than with the half perforated or normal Plexiglas cover. At mass flow rate ($\dot{m}$) of 0.032 kg/s, the maximum efficiency of the double pass solar collector with quarter perforated covers 20D and 10D were, 57.60% at 13:00h and 60.49% at 15:00h, respectively while at the same $\dot{m}$, for the same collector with half perforated covers 20D and 10D the maximum value of efficiency obtained were 52.66% at 12:00h and 57.93% at 15:00h, respectively.

The results show that the thermal efficiency of the solar air heater decreases by increasing the bed height of the collector. The collector with duct height of 3cm was shown higher performance compared with the one with bed height of 5.5 or 8 cm.

Keywords: Solar air heater, perforated cover, packed bed, thermal efficiency

ÖZ

Bu çalışmada, normal cam örtülü, pleksiglas örtülü, çeyrek ve yarı delikli örtülü tek ve çift geçişli güneş hava ısıtıcılarının ısıl performansı deneysel olarak incelenmiştir. Bu sistemde, geleneksel emici levha, on dört çelik tel örgü tabaka ile değiştirildi. Güneş hava kolektörü dört farklı delikli örtü kullanılarak test edildi. İki örtüde delikler örtünün üst çeyreğindeki 100 × 36 cm^2 lik alana açılmıştır. Diğer iki örtüde, örtü alanını üst yarısı (100 × 72 cm^2) delinmiştir. Çeyrek ve yarı alanı delinen iki örtünün deliklerinin merkezden-merkeze uzaklıkları (d_c) 20D (6 cm) diğer iki örtünün deliklerinin merkezden-merkeze uzaklıkları ise 10D (3 cm) dir. D delik çapı olup 0.3 cm olarak sabitlendi. Hava debisi 0.011 kg/s ve 0,037 kg/s arasında değiştirilmiştir. Güneş kolektörü, kanal yüksekliğinin hava ısıtıcısının verimliliğine etkisini incelemek amacıyla üç farklı kanal yüksekliğinde (3, 5.5 ve 8 cm) test edilmiştir. Üst kanal yüksekliği çift geçişli kolektörde 2 cm dir. Bu araştırmada farklı kütle akış hızlarının, çeşitli delikli örtülerin ve kanal yüksekliklerinin çıkış sıcaklığına ve ısıl verimliliğine olan etkileri çalışılmıştır.

Elde edilen sonuçlara göre kütle akış hızı arttıkça ısıl verimlilik artar, ancak çıkış ve giriş havası arasındaki sıcaklık farkı, ΔT, azalır. Aynı hava kütle akış hızı için cam örtülü çift geçişli kolektörün verimliliği, aynı örtülü tek geçişli kolektörün verimliliğinden % -22.7 daha büyüktür. Çeyrek delikli örtülerde,10D çeyrek delikli örtülü hava ısıtıcısının verimliliği tek ve çift geçişlerde 20D çeyrek delikli ötülü hava ısıtıcısının verimliliğinden daha yüksek bulunmuştur, bunun nedeni, yapılan testlerde 10D çeyrek delikli örtünün 20D çeyrek delikli örtüye göre sıcaklığının daha düşük olmasından dolayı çevreye olan ısı kaybını azaltmasına bağlanmaktadır.

Çeyrek delikli örtülü güneş hava ısıtıcısının, yarı delikli veya normal pleksiglas örtülü hava ısıtıcılarına göre daha yüksek ΔT ye ulaştığı tespit edilmiştir. Kütle akış hızı ($\dot{m}$) 0.032 kg/s olduğunda, 20D ve 10D çeyrek delikli örtülü hava ısıtıcısında maksimum verimlilik saat 13:00 ve 15:00 da sırasiyle %57.60 ve %60.49 dur; Aynı kolektör için 20D ve 10D yarı delikli örtü kullanıldığında hava ısıtıcısındaki maksimum verimlilik saat 12:00 ve 15:00 da sırasıyla %52.66 ve %57.93 tür.

Sonuçlar, güneş hava ısıtıcısının ısıl verimliliğiin kolektör kanal yüksekliğini artması durumunda azaldığını göstermektedir. (Kanal yüksekliği 3 cm olduğunda elde edilen ısıl verimlilik 5,5 veya 8 cm kanal yüksekliği kullanıldığında elde edilen ısıl verimliliklerden daha yüksektir).

Anahtar kelimeler: Güneş hava ısıtıcısı, delikli örtü, gözenekli yatak, ısıl verimlilik

To My Life
My Husband
Nima

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A_c	Collector area (m^2)
c_p	Specific heat of air, (kJ/kg.K)
D	Diameter of the hole on the perforated cover (D = 0.3cm)
d_c	Holes center-to-center distance, (cm)
I	Solar radiation, (W/m^2)
$\dot{m}$	Mass flow rate of air, (kg/s)
خ	Volumetric flow rate, (m^3/s)
T_{air}	Film air temperature between the outlet and inlet, (°C)
T_{in}	Inlet air temperature, (°C)
T_{out}	Outlet air temperature, (°C)
$T_{Plexiglas}$	Temperature of Plexiglas cover, (°C)

Greek symbols

η	Thermal efficiency of collector
ρ	Density of air, (kg/m^3)
ΔP	Pressure difference, (N/m^2)
ΔT	Temperature difference (T_{out} - T_{in}), (°C)
ω	Uncertainty
Φ	Porosity

Subscripts

in	Inlet
out	Outlet

Chapter 1

INTRODUCTION

High energy prices, depleting of the earth's conventional fuels resources and the global warming increased the human need of renewable sources of energy. Among all different renewable energy resources, solar energy is one of the valuable heat sources with variety of applications such as space heating and cooling and electricity generation.

Basically solar air heater is a heat exchanger, which takes the incident solar radiation, converts it into heat and finally transfers this heat to a working fluid for an end use system (Banal *et al.,* 1983). In general, air heaters are used in drying applications for the heating or preheating of air. Air collectors can be classified into two different types with several different design features each. The first types are the conventional solar air collectors with an absorber plate being over- or /and underflow by the working fluid (air). The other types are the matrix air collectors in which the working fluid flows through the absorber-matrix (Kolb *et al.,* 1999). More details about solar collectors and their applications are presented by Duffie and Beckman (2013).

The advantages of solar air collectors compared with the ones which use liquid heat transfer media are mainly associated with eliminating the freezing and boiling problems. Also with such systems the heated air can be used directly and there is no need for external fluid loop. Significant reduction in corrosion is another benefit of these systems (Qenawy and Mohammad, 2007).

1.1 A Brief on Solar Air Heaters

In general solar air-heating collectors can be classified into two types: bare-plate and covered-plate solar collectors. In covered-plate solar collectors, heat losses from solar air heaters are minimized by the use of one or more transparent covers parallel to the absorber plate. The cover prevents convective heat losses from the absorbing plate and reduces long-wave radiative heat losses. At moderate temperature elevations covered-plate solar air heaters operate at higher efficiencies than bare-plate solar air heaters (Ekechukwua and Norton, 1999).

Bare-plate (Non-covered) solar air collectors consist of an air duct and an absorber plate with the rear surface insulated. These collectors are used widely in crop drying operations (both for natural and forced-convection systems). Bare-plate solar collectors have huge thermal losses through the exposed surface. Consequently, they have low thermal efficiencies at moderately elevated temperatures.

Unglazed transpired solar air heater is a kind of non-covered collectors. Such solar air heater consists of an unprotected or unglazed but perforated black metallic surface placed over a plenum on a southern surface. Although the solar collector is unprotected, its perforations allow the ventilation air to collect heat lost by convection at its surface (Sebastien and Suzelle, 2011). It is also found that the efficiency of the unglazed solar air heater depend on the wind velocity. Bare-plate solar collectors have simple structures and cost less compared to covered-plate solar collectors. The most widely used collectors are covered-plate solar collectors.

The solar air heater can be classified on the basis of extended surface, energy storage, numbers of covers, and tracking axis. Tyagi *et al*. (2012) mentioned that it is not an easy task to classify solar air heaters in a proper manner, solar air heaters can be classified on the basis of mode as presented in Fig. 1.1.

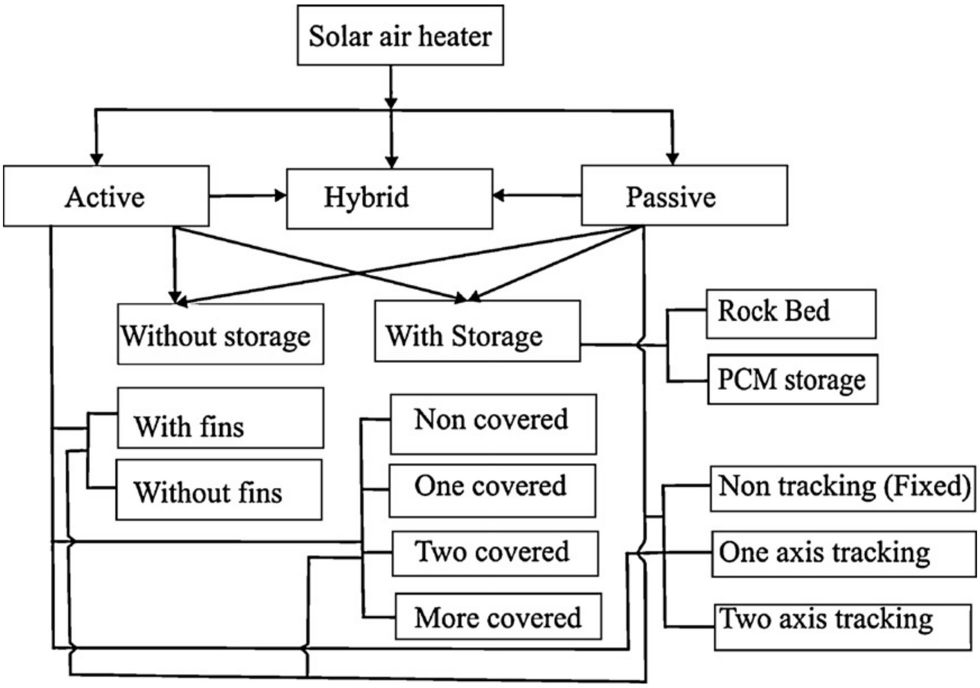


Figure 1.1: Classification of solar air heaters (Tyagi *et al*., 2012)

1.2 Thesis Objectives and Organization

The available literature on solar air heaters show that many considerable research works are performed on such systems in order to increase the performance of the air heaters; however further modifications can prove worthwhile in the optimization of the overall performance also reducing the construction costs of collectors. In many experimental studies porous media are used as absorber plates (Tian *et al.,* 2004; Mittal and Varshney, 2006; Omojaro, 2010) but, studies where large quantities of the packed materials used in a small bed height of the collector are very few. It is also known that the cover of solar collector plays a vital role in the collector efficiency

(Ekechukwua and Norton, 1999) as substantial amount of heat loss occurs through the cover. There are very few studies available in the literature attempting to reduce the cover losses by making modifications.

As discussed in section 1.1, efficiency of unglazed transpired solar air heaters (non-covered) depends on wind velocity and perforations on the absorber part allow the ventilation air to collect heat lost by convection at its surface. The working principles of transpired solar air heaters motivated this study to use perforation on the cover of the solar collector. It is obvious that the perforated cover reduces the heat losses from the top cover of collector as the air is continuously drawn through the perforations convective heat loss is almost eliminated. Also the sucked air keeps the cover plate temperature low thus, radiant heat loss is minimized.

In covered-plate solar air heaters, cover prevents convective heat losses from the absorber plate and reduces long-wave radiative heat losses. In present study the purpose is to improve the performance of the solar air heater and to achieve this goal the cover and absorber plate of the conventional solar collectors are modified. In order to increase the heat transfer area between the air and the absorber part, wire mesh layers are used instead of an absorber plate. Using wire meshes instead of an absorber sheet metal reduces the construction cost of the collector as wire meshes are cheaper compared with the sheet metal.

The main objective of this work is to investigate the performance of the single and double pass solar air collectors with partially perforated covers and porous media in a small duct height of 3cm. To the best of our knowledge such solar system has not been tested yet. Also it is aimed to test the same solar collector with the partially perforated covers and porous media at different bed heights. As mentioned earlier there is no absorber plate in the proposed solar air heater. The steel wire mesh layers in the lower channel (collector bed) are acting as an absorber plate. The porous media are arranged in a way to give high porosity (around 0.83) and low pressure drop across the collector. The solar air heater is tested with various quarter and half perforated covers which were made of Plexiglas and had different distances between the hole centers.

The main objectives of this study can be summarized as follows:

1. To construct a solar air heater which can be tested as a single or counter flow air collector.
2. To replace the absorber plate with steel wire mesh layers (porous media) to reduce the construction cost and increase the heat transfer area.
3. To test the solar air heater with different partially perforated covers and investigate the effect of perforated cover on the thermal performance of solar air heater.
4. To change the collector’s bed height and examine the effect of the duct height on the thermal performance of the solar collector.
5. To accomplish the experimental work under the same weather condition of Famagusta, north Cyprus in order to compare the collected data and recommend the best arrangement to achieve the highest efficiency.

The thesis is organized into five chapters. In chapter one a brief introduction about solar air heaters and the main objectives of the work are presented.

In chapter two the literature review on solar air heaters is presented. The research works which are related to the thesis topic are discussed.

The experimental set up of the solar air collector and the equipment used in collecting data are described in chapter three.

The obtained experimental results from the solar air heater with different configurations are presented in chapter four. The collected data at various days of the tests are illustrated with figures and are discussed in details.

In chapter five the findings of this research work are concluded. Recommendation for future works is also presented in this chapter.

Chapter 2

LITERATURE REVIEW

Solar air collectors are simple devices that utilize solar energy to heat air. Panel, air duct and a glass cover are the main parts of a typical solar air heater. The active solar system has an air blower as well. The wooden or metallic air duct consists of an absorber plate. The thermal insulation covers the sides and bottom of the duct.

The efficiency of the solar air heater is affected by the length and bed height of collector, the type of the absorber plate, glass cover, wind speed and many other parameters. Among these factors, the cover and the absorber plate are the most effective ones in the design of solar collectors (Omojaro and Aldabbagh, 2010).

It is obvious that the major heat losses from a normal solar air collector are through the top cover which reduce the thermal efficiency of the system also, the low heat transfer coefficient between the air stream and the absorber plate is another reason of low thermal efficiency in solar air heaters. Various studies were performed in order to increase the thermal performance of the solar collectors by modifying the absorber plate configuration. Using fin between the wire mesh (as an absorber plate) to increase the path of the air flow inside the channel (El-khawajah *et al.,* 2011), adding porous material inside the collector (Tian *et al.,* 2004), making a cross-corrugated absorber plate (Wenxian Lin *et al.,* 2006), and using counter flow solar air heater

(Sopian *et al.,* 1999; Paisarn, 2005a, 2005b; Sopian *et al.,* 2009) are few examples of these modifications.

The performance of the single and double pass solar collectors with fins and wire mesh layers were investigated experimentally by Omojaro and Aldabbagh (2010). They used seven steel wire mesh layers and the range of the air mass flow rate was between 0.012 kg/s and 0.038 kg/s. The distance between the glass and the bottom of the collector used in their study, was 7 cm. According to their study the maximum efficiency for the single and double pass air collectors were 59.62% and 63.74%, respectively for mass flow rate ($\dot{m}$) of 0.038 kg/s.

To achieve high thermal efficiency and reduce heat losses from the cover, a novel solar air collector of pin-fin integrated absorber was designed by Donggen *et al.* (2010). In their design the gap between the glazing and the absorber plate was 5 cm. According to their experimental results, the average thermal efficiency of pin-fin arrays collector reaches 50 - 74% compared to the solar transmittance of 83% for the glazing, for the air volume flow rate of 19m^3/h.

The investigations on a packed bed solar air heater having its duct packed with blackened wire screen matrices of different geometrical parameters, wire diameter and pitch, were performed by Mittal and Varshney (2006) and their resulting values of effective efficiency clearly indicate that the thermal gain of packed bed collectors is relatively higher as compared with smooth collectors, although the pressure drop across the duct increases significantly.

A single-glazed solar matrix air collector was tested by Kolb *et al.* (1999). This collector consists of two parallel sheets of black galvanized industrial woven, fine-meshed wire screens made of copper. Their results show that at the duct height of 4 cm and mass flow rate of 0.04 kg/s, the thermal efficiency of the solar air heater was around 70%.

Ho-Ming Yeh *et al.* (2000) have designed a solar air heater in which the absorber plate was constructed with fins on it and the baffles were attached to the fins to create turbulence and extend the heat transfer area. In their work, the distance between the glass and the absorber plate in the lower channel was 5.5 cm and it was indicated that the efficiency of baffled solar air heaters is greater than that of flat plate air heaters without fins and baffles.

The thermal performance of cross-corrugated solar air collector was studied by Wenxian *et al.* (2006). The cross-corrugated collector consists of a wavelike absorbing plate and a wavelike bottom plate, which are crosswise positioned to form the air flow channel. In their study, the mass flow rate ($\dot{m}$) changes in the range of 0.001- 0.25 kg/m^2s. Their results show that the efficiency of collectors increase monotonically and dramatically with $\dot{m}$, therefore, to achieve a better thermal performance of the solar air collectors it is essential to maintain a higher air mass flow rate.

Several configurations of copper screen meshes were investigated experimentally by Tian *et al.* (2004). They found that the overall heat transfer depends on porosity and the surface area.

Some researchers (Martin and Fjeld, 1975; Prasad *et al.,* 2009) suggested using double glazing on the solar collectors in order to minimize the heat losses through the top cover to improve the thermal efficiency. In other studies (Sopian *et al.,* 1999; Paisarn, 2005a, 2005b; Sopian *et al.,* 2009) the absorber plate was inserted into the panel to make a double pass channel where the air flows from above and then below the absorber plate. The same method was used by Yeh *et al.* (2002) , Ozgen *et al.* (2009) and Esen H. (2008) with this difference that in their work the air was passing from above and below the absorber plate at the same time.

A counter-flow solar air heater was analyzed for cold climate by Qenawy and Mohammad (2007), a double pass solar air heater with and without porous media in the lower channel was studied by Mohammad (1997). It was indicated that the efficiency of the mentioned solar air heater with porous media exceeded 75%.

An unglazed solar air pre-heater consisting of perforated corrugated siding was examined by Sebastien and Suzelle (2011) and it was found that the efficiency of the unglazed solar air heater depended on the wind velocity, as the efficiency was found to be 65% for wind velocities under 2 m/s and dropped below 25% for wind velocities exceeding 7 m/s.

Experimental study on the perforated baffles with various open area ratio in a rectangular duct, a system similar to a solar air heater, was shown that the baffles with 46.8% open area ratio give the best performance (Rjendra *et al.,* 2005).

Chapter 3

EXPERIMENTAL SET UP AND EQUIPMENT

Solar air collectors are simple devices that utilize solar energy to heat air. Air duct, absorber plate and glass cover are the main parts of a typical solar air heater. The active solar system has an air blower as well. In the present study, some modifications are performed on the conventional air heater. In this chapter the construction and experimental set up of the air heater with different covers (normal or perforated), various bed heights and without absorber plate are presented. In addition, the uncertainty analysis for the mass flow rate and thermal efficiency are also presented in this chapter.

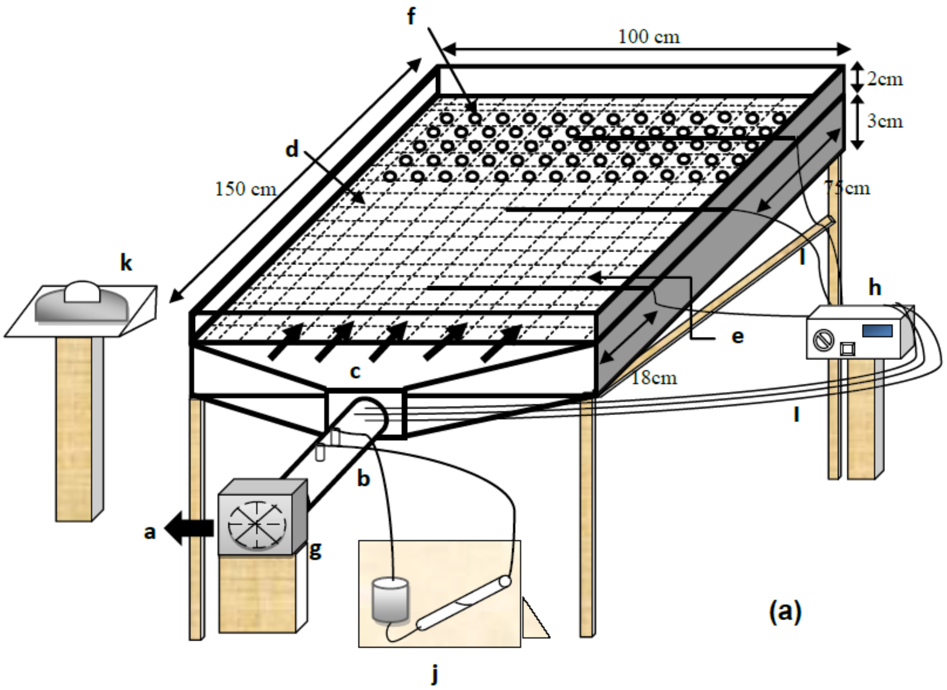
3.1 Solar Air Heater with Various Arrangements

In order to investigate the performance of the new modified solar air heater twelve different set ups were examined. Different set ups of the solar air heater are listed in Table 3.1.

The main components used in each set up are the bed or duct of various heights, wire mesh layers, glass or Plexiglas or perforated cover. The schematic of the manufactured solar air collector with perforated cover and the sectional view of the system are shown in Fig. 3.1 and Fig. 3.2. The schematic of the solar air collector with different bed heights is shown in Fig. 3.3.

Table 3.1: Different set-ups of the solar air heater

#	Collector	Type of cover	Bed height (cm)	Number of mesh layers
1	Single and double pass	Normal glass cover	3	14
2	Single and double pass	Quarter perforated cover 20D	3	14
3	Single and double pass	Quarter perforated cover 10D	3	14
4	Single and double pass	Half perforated cover 20D	3	14
5	Single and double pass	Half perforated cover 10D	3	14
6	Single and double pass	Normal Plexiglas cover	3	14
7	Single and double pass	Normal glass cover	5.5	14
8	Single and double pass	Quarter perforated cover 10D	5.5	14
9	Single and double pass	Half perforated cover 10D	5.5	14
10	Single and double pass	Normal glass cover	8	14
11	Single and double pass	Quarter perforated cover 10D	8	14
12	Single and double pass	Half perforated cover 10D	8	14



a. Outlet air
b. Orifice meter
c. Inlet air
d. Glass cover
e. Wire mesh layers
f. Perforated cover
g. Centrifugal fan
h. Thermometer
l. Thermocouples
j. Inclined manometer (θ =15°)
k. Pyranometer

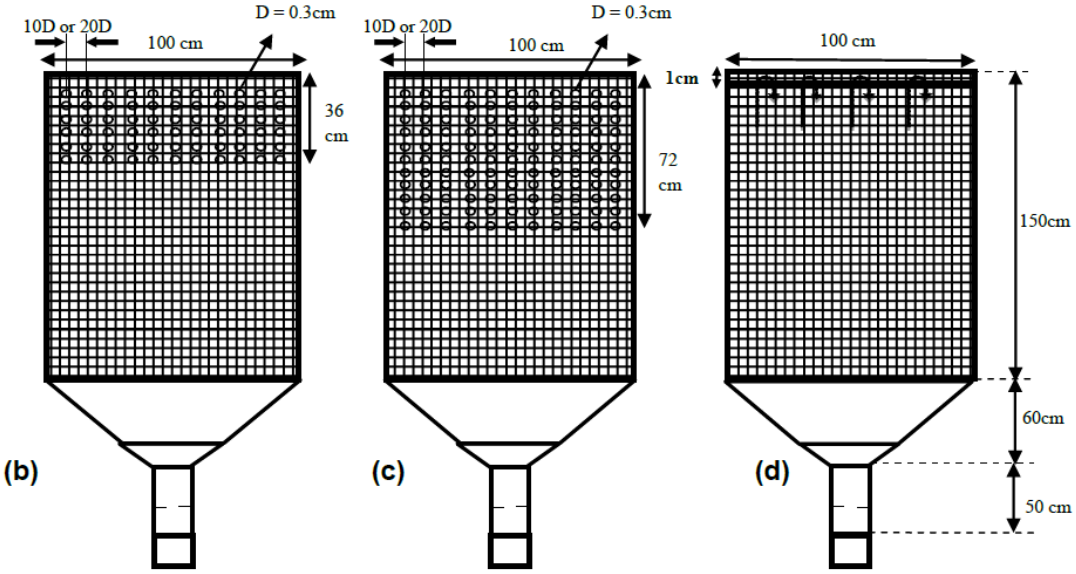


Figure 3.1: Schematic assembly of the manufactured solar air heater, (a) Schematic view of the solar collector, (b) With quarter perforated cover, (c) With half perforated cover, (d) With normal glass or Plexiglas cover

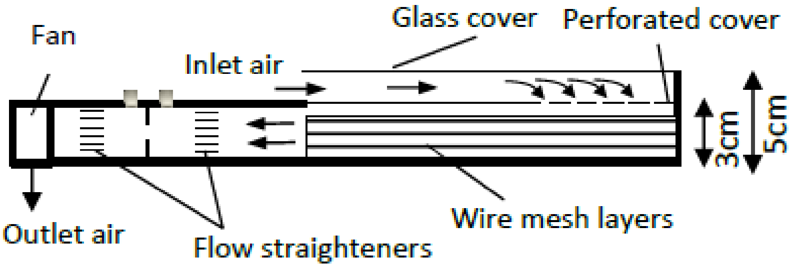


Figure 3.2: Section view of the double pass solar air collector with perforated cover

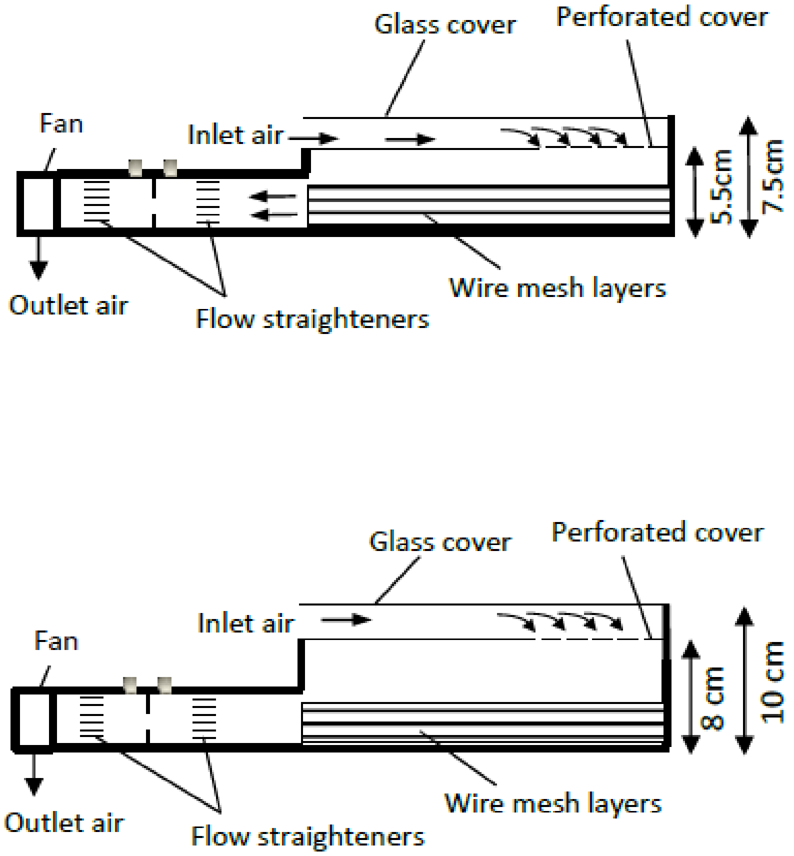


Figure 3.3: Schematic view of collector with different bed heights (5.5cm and 8cm)

The pictorial views of the air heater with normal glass cover and with quarter perforated cover are shown in Figs. 3.4 and 3.5, respectively.

Figure 3.4: Pictorial view of the experimental set up of solar air heater

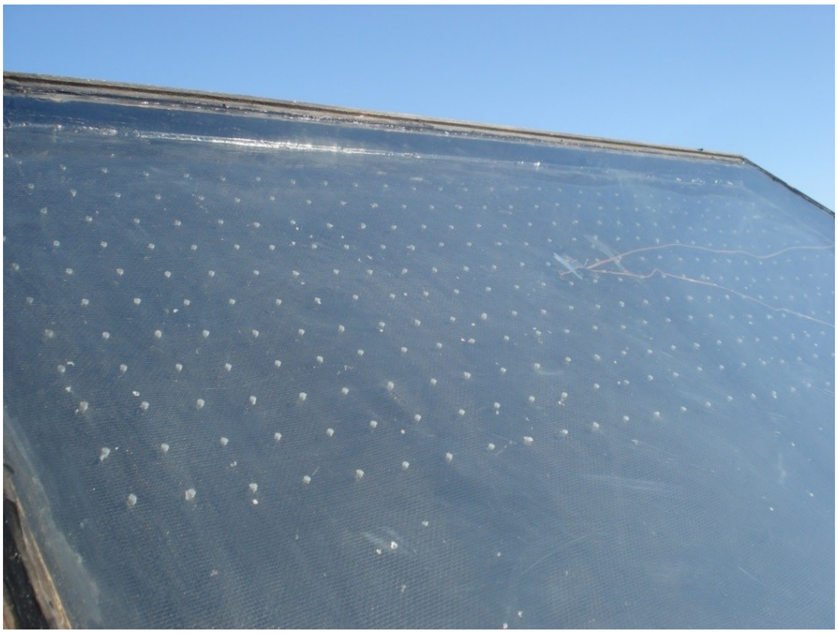


Figure 3.5: Pictorial view of the double pass solar air heater with quarter perforated cover 10D

3.1.1 The Collector's Bed or Duct

The frame of the solar collector was made from plywood of 1.8cm thick and the whole frame was painted in matt black. In all the different set ups the same frame was used. The collector length and width were 150cm and 100cm, respectively. The distance between the second cover and the bottom of the collector, duct (bed) height, was 3cm and it was changed to 5.5cm and 8cm to examine the effect of duct height on performance of the air heater.

To minimize the heat losses, the sides and bottom of the frame were insulated with 3cm thick Styrofoam. The distance between the second glass cover and the first cover was 2cm in double pass solar collector. By removing the first glass the collector becomes a single pass air heater.

3.1.2 Wire Mesh

Although absorber plate is one of the major components of a solar air heater, in this study absorber plate was replaced by wire meshes which were acting as an absorber plate and as a result the cost of the solar air heater was reduced significantly as the wire mesh is much cheaper compared with sheet metal plate and is readily available in the market.

Fourteen steel wire mesh layers, 0.2 × 0.2 cm in cross section opening and 0.025 cm in diameter, were fixed inside the collector's duct parallel to the glazing. The wire meshes used in this collector are similar to the ones which were used by (Omojaro and Aldabbagh, 2010; El-khawajah *et al.,* 2011; Aldabbagh *et al.,* 2010).

The arrangement of the wire mesh layers is as follows: 6 wire mesh layers were attached to each other, as one matrix, and placed at the bottom of the collector, 5 more layers were attached with each other and placed at the middle and the last 3 meshes were connected to each other and located on top of the other layers. The distance between the three sets of wire meshes were fixed to be 0.5 cm. Moreover, 0.5 cm spacing was left between the second glazing and the upper layers. In addition, the new arrangement of the wire mesh layers in the collector that gives high porosity, $\Phi = 0.83$, reduces the pressure drop through the collector. In order to increase the absorptivity of the mesh layers, they were painted in black.

3.1.3 Glass, Plexiglas and Perforated Covers

In this experimental work, specific attention was paid to the cover, as it was known that the major heat loss from flat-plate collectors is through the cover. To minimize the heat losses through the cover and to cool it, the normal cover was replaced with the perforated one. In this case the ambient air will have two functions: to cool the cover while penetrating through it as well as supplying air to the solar air heater. The velocity of the air is low enough through and around the hole to prevent the heat transfer by conduction or by convection.

For simplicity of making the holes on the cover, transparent Plexiglas was used instead of normal glass. The length, width and thickness of the Plexiglas were 150cm, 100cm and 0.3cm, respectively.

Four different perforated covers were used in the experiments. Their differences were due to the number of holes made on them and the space between the hole to hole centers. On the two perforated covers the holes were made on the first quarter at the top side of the cover, on the opposite side of the outlet flow, in an area of $100 \times 36\text{cm}^2$. On the other two covers, half of the cover area (i.e. $100 \times 72\text{cm}^2$) on the top side was perforated. The holes were arranged in line format. The hole diameter, D, was fixed to be 0.3cm.

To examine the effect of hole to hole spacing on the solar air heater performance, the holes made on one of the quarter and one of the half perforated covers had the center-to-center distance (d_c) of 20D (6cm) and on the other two covers d_c was 10D (3cm).

In counter flow solar collector a normal glass with 0.4cm thickness, was used on top of the perforated cover to reduce the heat losses from the top side of the collector. The second or upper channel height was 2cm.

As it was aimed to compare the obtained results of the solar air heater with the perforated cover with the one with normal cover, the same solar collector was tested with a normal Plexiglas as its glazing. The air was entered to the collector through an opening made on the top side of the collector as shown in Fig. 3.1 (d). The opening area was 100 cm^2.

3.2 Experimental Equipment

3.2.1 Pyranometer

Every hour the solar intensity was measured with an Eppley PSP(Precision Spectral Pyranometer), which was coupled with a voltmeter of model HHM1A digital Omega with resolution of ±0.5%.

The solar collector was faced toward south in order to receive the maximum radiation and its tilt angle was fixed at 39.5° due to the geographical location of Cyprus (35.125 °N latitude and 33.95 °E longitude).

3.2.2 Thermometer and Thermocouples

T-type thermocouples were used to measure the air temperatures at the inlet, outlet and at different places inside the solar collector and on the glazing. Three thermocouples were located at the outlet of the solar collector inside the galvanized pipe before the orifice meter in order to measure the outlet temperature, T_{out}, of the air. The ambient or inlet temperature, T_{in}, was measured by three thermocouples placed underneath the collector. Three thermocouples were also placed at the top, middle and bottom of the glazing and the bed (inside the wire mesh layers) to record their temperatures hourly through the day. A Ten-channel Digital Thermometer (MDSSi8 Series digital, Omega, ±0.5°C accuracy) was used to record the temperature readings.

3.2.3 Orifice Meter

The orifice meter was designed according to the principles recommended by Holman (1989) and placed in a steel pipe with diameter of 8 cm and length of 50 cm. The pipe was located between the converging section of the collector and a single inlet centrifugal fan. The fan type was OBR 200 M-2K.

3.3 Experimental Procedure

The experimental work on the single and double pass solar air heaters with different set ups were conducted at a geographic location of Cyprus in the city of Famagusta. The tests were performed in summer time, 2011 and 2012 with clear sky condition.

The tests and readings started at 8 AM and continued till 5 PM at each day of experiment. The outlet and inlet (ambient) temperatures of the air, the bed and the glazing temperatures were recorded hourly at each experiment. In addition, the solar radiation and the incline tube manometer reading were read as well. Wind speed and humidity values were taken hourly from the Northern Cyprus Department of Meteorology's webpage (T.R.N.C. Department of Meteorology, 2011).

Flow straighteners were placed before and after the orifice meter to create uniform flow through it. These straighteners were plastic straw tubes of 0.46cm in diameter and 2cm in length.

The pressure difference through the orifice was measured by an inclined tube manometer of 15° angle. In order to increase the accuracy of the inclined manometer, a low density fluid such as alcohol, 803 kg/m^3, was used.

Different air mass flow rates can be achieved by using a speed controller. The speed controller was connected to the fan to allow the user to adjust the speed on the desired value.

3.3.1 Solar Air Heater with Normal Glass Cover and Bed Height of 3cm

As it is mentioned in the earlier sections, the air heater was tested with different set ups. In all the different arrangements the same frame was used. The first set up included testing the system with normal glass cover on the collector with fourteen steel wire mesh layers, as absorber, and bed height of 3cm. The air was entered to the collector through an opening made on the top side of the collector. The opening area was 100cm^2. To examine the thermal performance of the air heater, the system was tested at different days with several air mass flow rates which were varied from 0.011 to 0.037 kg/s.

Normal window glass of 0.4cm thickness was used as glazing. The collector was manufactured in a way to operate as a single or double pass air heater. The distance between the second glass and the first glass was 2cm. By removing the first glass the collector became a single pass air heater.

3.3.2 Solar Air Heater with Quarter Perforated Cover and Bed Height of 3cm

In order to examine the effect of perforated cover on the performance of the solar air heater, the glass cover was replaced with quarter perforated cover. The same fourteen wire mesh layers and frame were used in this set up and the duct height was kept as 3cm. In this case the ambient air will have two functions, to cool the cover while penetrating through it as well as supplying air to the solar air heater. For simplicity of making the holes on the cover the second glass cover was replaced by a transparent Plexiglas. The length, width and the thickness of the Plexiglas were 150cm, 100cm and 0.3cm, respectively. The holes were made on the first quarter at the top side of the cover in an area of 100 × 36 cm^2 and they were arranged in line format. The hole diameter, D, was fixed to be 0.3 cm.

Two different set of experiments were carried with two different quarter perforated covers to investigate the effect of hole to hole spacing on the solar air heater performance. The holes made on one of the covers had the center-to-center distance (d_c) of 20D (6cm) and on the other cover d_c was 10D (3cm). In counter flow solar collector a normal glass with 0.4cm thickness was used on top of the perforated cover to reduce the heat losses from the top side of the collector. The collector was tested with two mass flow rates of 0.011 kg/s and 0.032 kg/s.

3.3.3 Solar Air Heater with Half Perforated Cover and Bed Height of 3cm

The next step in the experiment was to increase the number of holes on the cover and examine its effect on the efficiency of the solar collector. To achieve this goal the quarter perforated cover was replaced with half perforated one. Therefore the same collector with the same steel wire mesh layers and 3cm duct height was tested with two new half perforated covers. On the two new covers, half of the cover area (i.e. 100 × 72 cm^2) on the top side was perforated. The holes were arranged in line format. The hole diameter, D, was fixed to be 0.3cm, same as the ones on the quarter perforated covers. The holes made on one of the covers had the center-to-center distance (d_c) of 20D (6cm) and on the other cover d_c was 10D (3cm). The hole to hole spacing on the quarter and half perforated covers were kept the same in order to be able to compare the obtained results from all the tests.

In the double pass solar collector a normal glass cover with 0.4cm thickness was used on top of the half perforated cover to reduce the heat losses from the top side of the collector. The collector was tested with two mass flow rates of 0.011 kg/s and 0.032 kg/s.

3.3.4 Solar Air Heater with Normal Plexiglas Cover and Bed Height of 3cm

The solar air collector was tested with various covers such as normal glass cover, quarter and half perforated covers. The perforated covers were made of Plexiglas because it was easier to make hole in this material than in glass. As it was aimed to compare the obtained experimental results from different set ups, the system was tested with normal Plexiglas cover of 0.3cm thickness as well. The air was entered to the collector through an opening made on the top side of the collector. The opening area was 100 cm^2. The collector was tested with two mass flow rates of 0.011 kg/s and 0.032 kg/s.

3.3.5 Solar Air Heater with Bed Height of 5.5cm and Various Covers

At the same mass flow rate, by decreasing the cross sectional area of the duct the velocity of air inside the duct increases and as a result heat transfer coefficient between the air and absorber increases. Therefore, the duct height has considerable effect on the performance of the air heater.

In this study the duct height (space between the bed and the lower glazing) was fixed at 3cm and the solar collector was tested with various normal and perforated covers. In order to investigate the effect of changes in the channel depth on the efficiency of the solar air heater, it was decided to increase the bed height to 5.5cm and repeat the same experiments which were performed with the 3cm duct height collector. Therefore, the solar collector with bed height of 5.5cm was tested with normal glass, quarter and half perforated covers and all other characteristics of the collector were kept unchanged. In case of counter flow collector the height of the upper channel was fixed at 2cm.

3.3.6 Solar Air Heater with Bed Height of 8cm and Various Covers

Although solar collector was tested with the duct heights of 3cm and 5.5cm, in order to have a general idea about the effect of duct height on the performance of the solar air heaters, the bed height was increased to 8cm and results were compared with the ones achieved from the collector with lower bed heights. The collector with the new bed height was tested with all different covers (normal and perforated). Rather than the bed height and the cover, the other characteristics of the solar air collector were kept unchanged.

3.4 Uncertainty Analysis

The uncertainty of the air mass flow rate and the thermal efficiency are demonstrated in this section. The mass flow rate ($\dot{\imath}$), is calculated by equation (1),

$$\dot{\imath} \qquad (1)$$

where, ρ is the density of air and Q is the air volume flow rate. The pressure difference through the orifice, which is measured from the inclined tube manometer, is used to find the volume flow rate.

The mass flow rate fractional uncertainty, $\omega_{\dot{m}}/\dot{m}$, is calculated according to Holman (1989) and Esen (2008):

$$\frac{\omega_{\dot{m}}}{\dot{m}} = \left[\frac{1}{4}\left(\frac{\omega_{T_{air}}}{T_{air}}\right)^2 + \frac{1}{4}\left(\frac{\omega_{\Delta P}}{\Delta P}\right)^2\right]^{1/2} \tag{2}$$

where, T_{air} is the film air temperature between the outlet and inlet.

The ratio of energy gain to solar radiation incident on the collector plane is the efficiency of solar collector, η, and is:

$$\eta = \frac{\dot{m}\, c_p (T_{out} - T_{in})}{IA_c} \tag{3}$$

where, I is the solar intensity, c_p is the specific heat of the fluid and A_c is the area of the collector. According to Eq. (3), the fractional uncertainty of efficiency, ω_η/η, is a function of ΔT, $\dot{m}$ and I. A_c is 1.5 m^2 and c_p, ranges between 1.007 and 1.008 kJ/kg°C.

$$\frac{\omega_\eta}{\eta} = \left[\left(\frac{\omega_{\dot{m}}}{\dot{m}}\right)^2 + \left(\frac{\omega_{\Delta T}}{T}\right)^2 + \left(\frac{\omega_I}{I}\right)^2\right]^{1/2} \tag{4}$$

In order to calculate the fractional uncertainties of mass flow rate and efficiency, the uncertainties associated with the measurements are used in the calculations. The average values of all parameters for all days of experiment are calculated separately. The mean values of ΔT, T_{in}, T_{out}, T_{air}, $\dot{m}$, I and η for all days are found to be 23.7°C, 31.3°C, 55.1°C, 43.2°C, 0.021 kg/s, 718.6 W/m^2 and 42%, respectively. The percent uncertainties in mass flow rate and efficiency are calculated to be 1.4% and 2.7%, respectively.

Chapter 4

EXPERIMENTAL ANALYSIS OF THE MODIFIED SOLAR AIR HEATER

This chapter presents the findings of the experimental study on the modified solar air heater. The tests were performed between 13.08.2011 and 29.09.2011 and continued during next summer from 17.07.2012 to 20.09.2012. The air heater with various configurations is constructed and examined in the city of Famagusta, 35.125 °N latitude and 33.95 °E longitude, in Cyprus. The solar collector was examined with different covers (i.e. normal glass, normal Plexiglas, quarter and half perforated covers), various duct heights (3, 5.5 and 8 cm) and fourteen steel wire mesh layers instead of an absorber plate. The tests and readings started at 8 AM and continued till 5 PM at each day of experiment. The readings and measurements were recorded at time interval of 1 hour each day.

4.1 Solar Air Heater with Glass and Quarter Perforated Covers and Bed Height of 3cm

The performance analysis of 4 different configurations for a solar air heater are performed experimentally in the city of Famagusta, 35.125 °N latitude and 33.95 °E longitude, which is located in Cyprus. The mean value of wind speed as measured hourly during the data's collection is 5.65 m/s. Two configurations include testing the single and double pass solar air heaters with the packed bed and normal glass cover. The other two set-ups of the system include testing the single and double pass solar air heaters with the packed bed and quarter perforated cover. The distance between the hole centers are selected to be 10D (3cm) and 20D (6cm), where D is the hole diameter (D = 0.3cm). The thermal efficiency of all different arrangements of solar air heater with wire mesh layers as absorber plate and small duct height of 3 cm, at different mass flow rates is studied. The mass flow rate of the air is varied between 0.011 to 0.037 kg/s.

The solar intensity versus time of the day for all days of experiment is shown in Figs. 4.1(a-c). The highest daily solar radiation obtained with counter flow solar air heater with glass cover, which was at the mass flow rate of 0.024 kg/s (day 10), was 1092 W/m^2 at 13:00 h. The same amount of solar radiation (1092 W/m^2) was also measured at day sixteen at 12:00 h, when the single pass solar collector with the quarter perforated cover, 10D, was tested. For each day the mean solar intensity is calculated. The average solar intensity for all days of experiment was 717.6 W/m^2 and 730.3 W/m^2 for single and double pass solar air heaters with the packed bed and normal glazing. For the single and double pass collectors with quarter perforated cover, the mean solar intensity of all days was 715.8 W/m^2 and 724.5 W/m^2, respectively. It is found that all the average values of solar intensity were within the close range during the experiment. The solar intensity increased from morning to a peak value at midday, and then decreased gradually afterwards. The inlet ambient temperature, T_{in}, versus time of the day for all days of experiment, is shown in Fig. 4.2(a-c). It is found that the ambient temperature increases during the day until afternoon and minor fluctuations happened in some of the days depending on wind speed of that day.

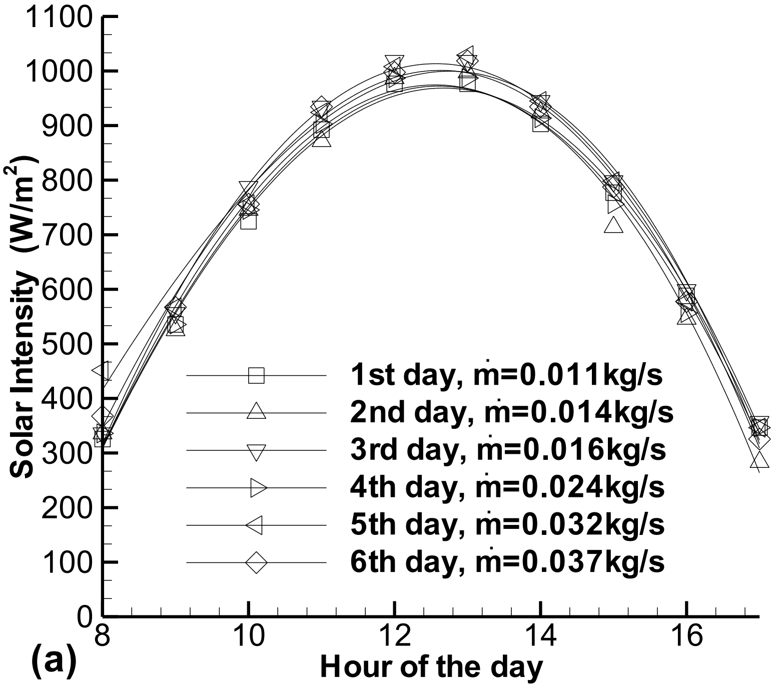


Figure 4.1(a): Solar intensity versus time of the day for single pass solar air heater with glass cover

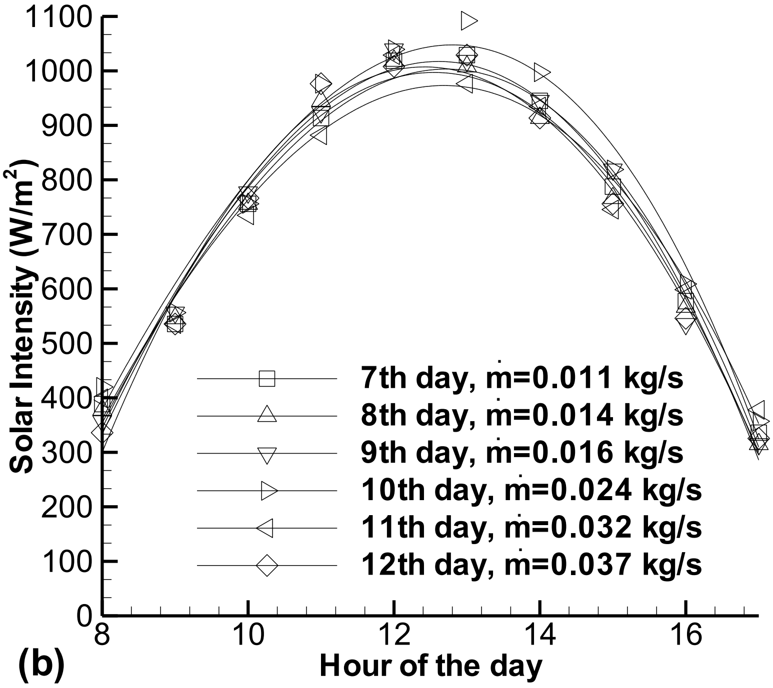


Figure 4.1(b): Solar intensity versus time of the day for double pass solar air heater with glass cover

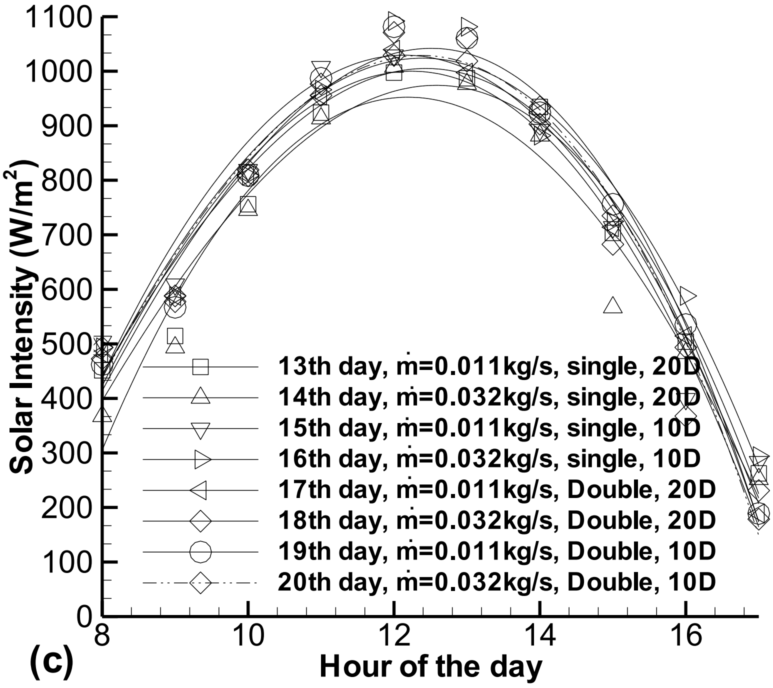


Figure 4.1(c): Solar intensity versus time of the day for single and double pass collectors with quarter perforated covers (10D & 20D)

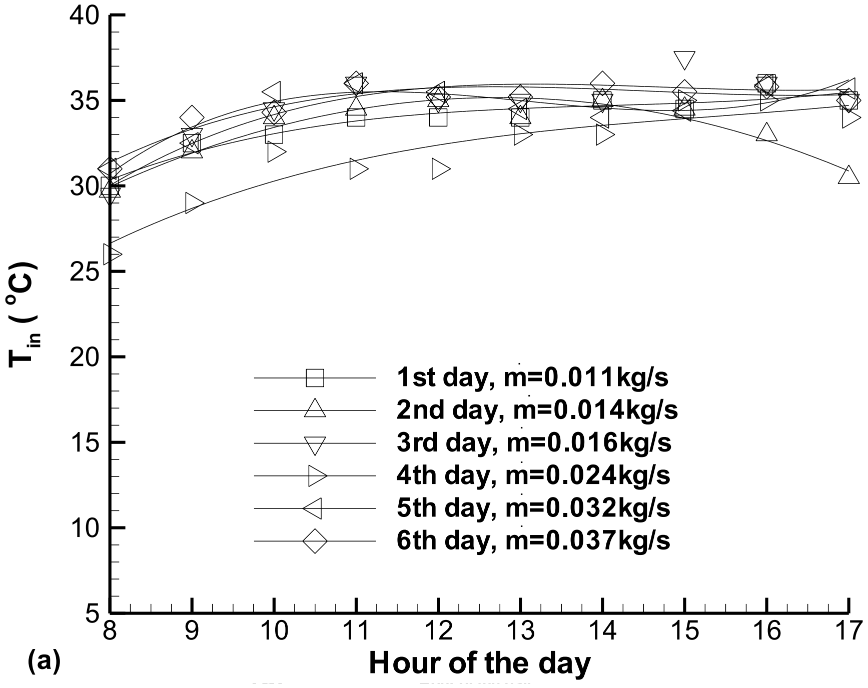


Figure 4.2(a): Inlet temperature versus time of the day for single pass solar air heater with glass cover

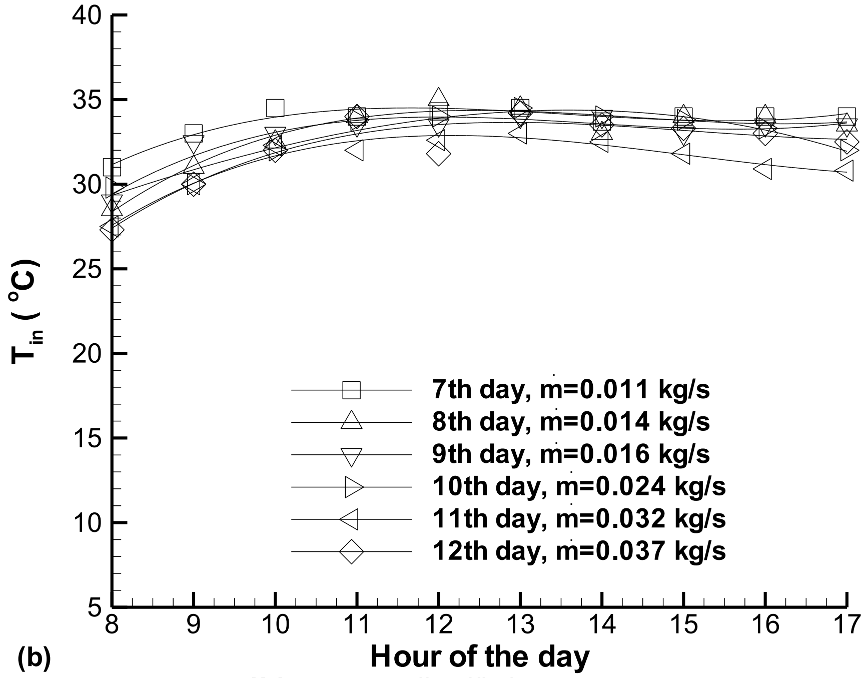


Figure 4.2(b): Inlet temperature versus time of the day for double pass solar air heater with glass cover

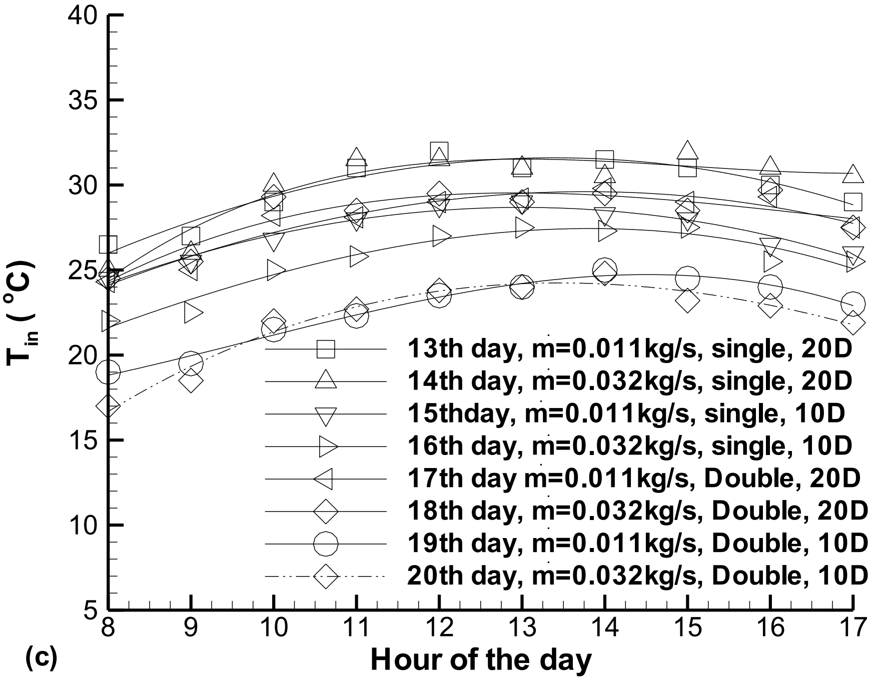


Figure 4.2(c): Inlet temperature versus time of the day for single and double pass collectors with quarter perforated covers (10D & 20D)

The temperature differences, $\Delta T = T_{out} - T_{in}$, versus time of the day at different air mass flow rates for single and double flow solar air collectors with normal glazing and with the quarter perforated Plexiglas covers are shown in Figs. 4.3 - 4.6. In general, ΔT decreases with increasing air mass flow rate. Moreover, the temperature difference was increasing from morning to a peak value at noon and then was decreasing in the afternoon until sunset, in a similar manner as the solar radiation. For the single pass air heater the maximum temperature difference was about 45.8 °C at 13:00 h and it was obtained at the minimum mass flow rate of 0.011 kg/s (Fig. 4.3). The maximum temperature difference obtained from the double pass solar air at $\dot{m} = 0.011$ kg/s was 53°C at 14:00 h (Fig. 4.4). Moreover, the maximum temperature difference is not affected too much by replacing the normal glazing with the quarter perforated Plexiglas cover in a single pass solar air heater (Fig. 4.5). The maximum temperature difference decreased to 43.1°C at 13:00 h when quarter perforated cover with 20D hole to hole spacing was used (Fig. 4.5). In addition, increasing the number of holes using 10D hole to hole distances has increased the maximum temperature difference (Figs. 4.5 & 4.6).

The maximum temperature difference obtained from this work with single pass solar air heater and 10D hole to hole distances cover is 46.25°C at 13:00 h with $\dot{m} = 0.011$ kg/s. While at the same mass flow rate, the maximum temperate difference obtained with single pass collector with normal glazing is 45.8°C. For the same mass flow rate, the temperature differences for single and double pass solar air heaters with normal glazing are very close in magnitude to that of with 10D quarter perforated cover. Aldabbagh *et al.* (2010) investigated a single pass solar air heater with 10 wire mesh layers used as an absorber plate and the channel height of 10 cm and they found that the maximum value of ΔT was around 27°C at the mass flow rate of 0.012 kg/s. A double pass solar air heater with packed bed iron scraps placed below the absorber plate and channel height of 12 cm was investigated by by El-Sebaii *et al*. (2007) and the maximum value of ΔT which was obtained by this air heater was 48°C at $\dot{m}$ = 0.0105 kg/s.

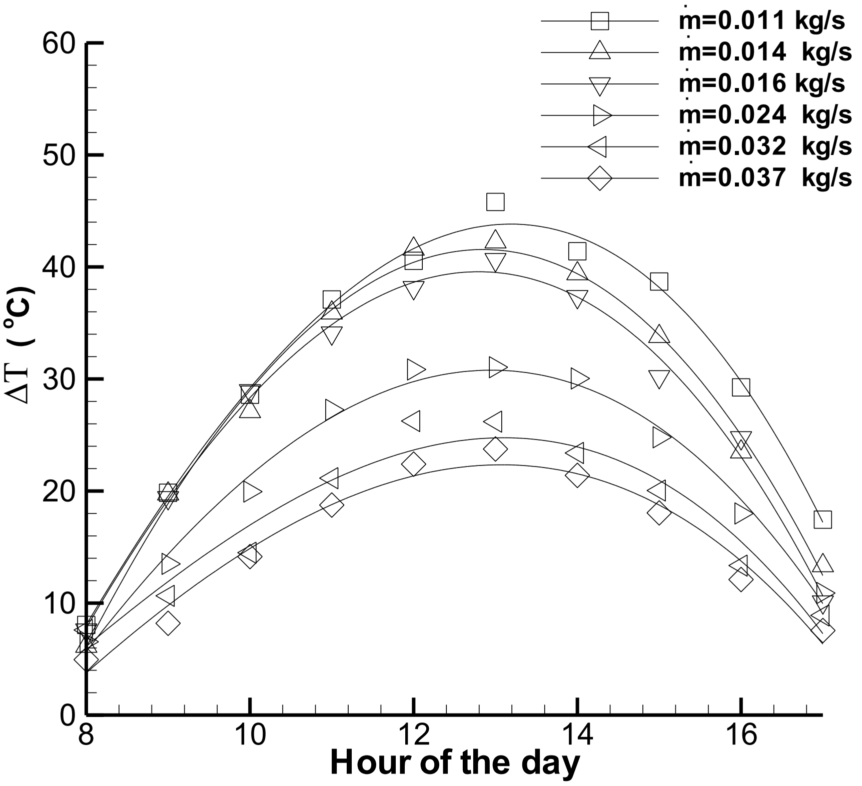


Figure 4.3: Temperature difference versus time of the day at different mass flow rates for single pass solar air heater with normal glass cover

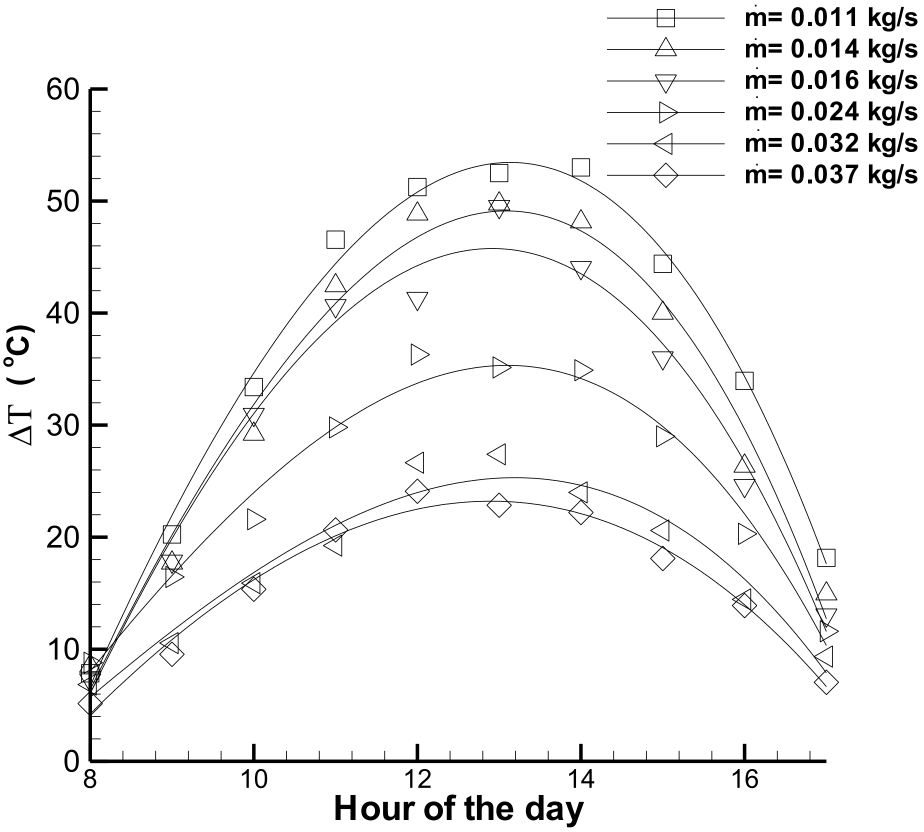


Figure 4.4: Temperature difference versus time of the day at different mass flow rates for double pass solar air heater with normal glass cover

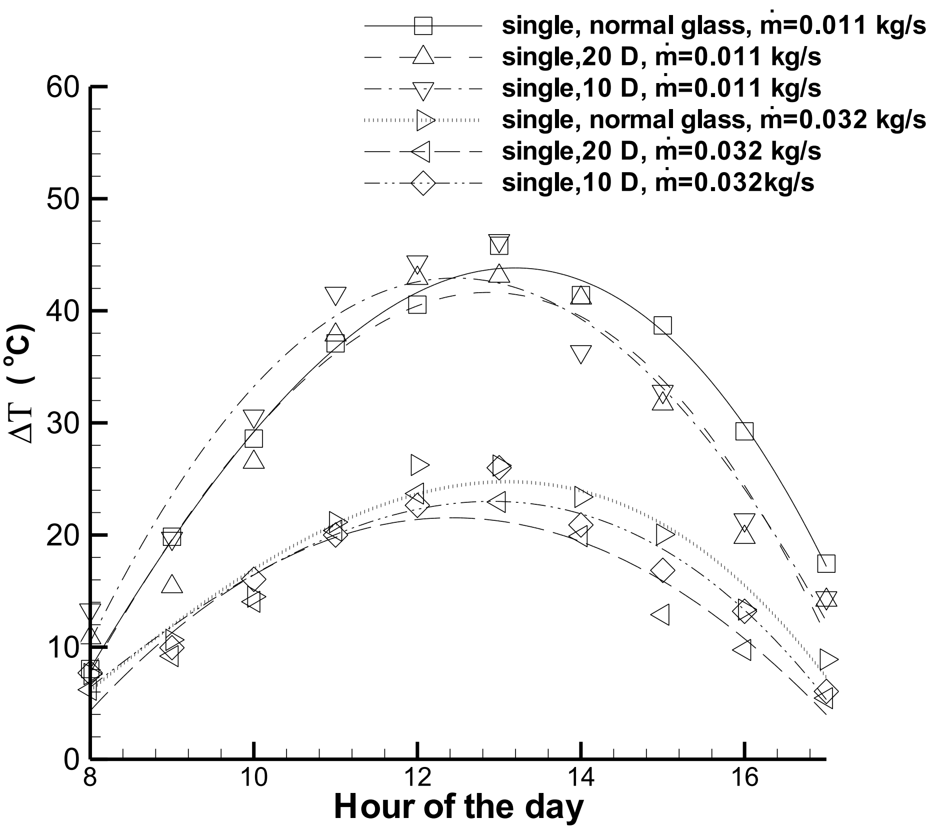


Figure 4.5: Temperature difference versus time of the day at different mass flow rates for single pass collector with quarter perforated covers (20D & 10 D)

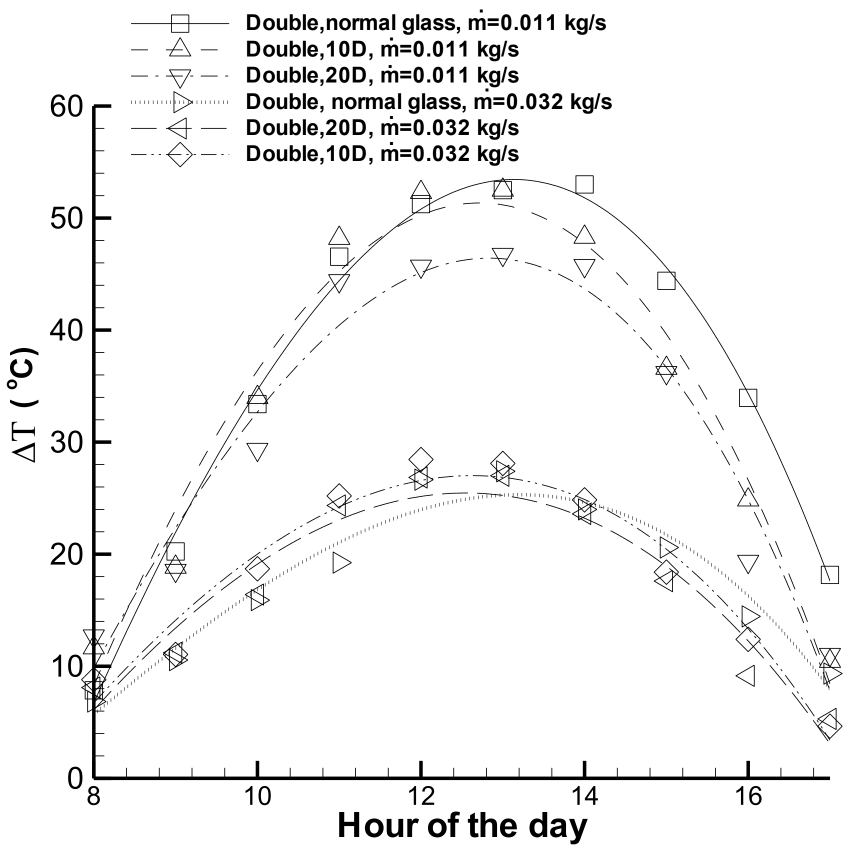


Figure 4.6: Temperature difference versus time of the day at different mass flow rates for double pass collector with quarter perforated covers (20D & 10D)

The thermal efficiency versus time of the day at different mass flow rates of air for the single and double pass air heaters with and without perforated cover are shown in Figs. 4.7 - 4.10. In most of the tests, the behavior of efficiency was similar to that of inlet temperature as it was increasing from morning until 13:00 PM with slight decrease in the afternoons. The thermal efficiency of the solar air heater is depended to the ambient temperature. Due to lower ambient temperature in the morning compared with the afternoon more heat losses occur in the early hours of the day. In all the tests, the thermal efficiency increases as the air mass flow rate increases.

Depending on the air mass flow rate, the double pass shows between 5 and 22.7% higher efficiency than the single pass solar collector. The efficiency of the single and double pass solar air heaters with normal glazing and the efficiency of the solar air heater with the perforated cover at two different mass flow rates are presented in Figs. 4.9 and 4.10. For the same mass flow rate, the efficiency of the solar air heater with the 10D perforated cover is slightly higher than 20D perforated cover for both single and double pass solar air heaters. In Table 4.1 the maximum thermal efficiencies obtained from single and double pass solar air heaters with different covers are presented.

El-Sebaii *et al*. (2007) indicated that by increasing the mass flow rate up to 0.05 kg/s the efficiency of the solar air heater also increases but the higher amount of mass flow rate does not affect the efficiency very much. Ramadan *et al*. (2007) recommended to operating the system with or without the packed bed, with the mass flow rate of 0.05 kg/s or lower to have a lower pressure drop across the system and a reasonably high thermal efficiency, more than 70%.

Table 4.1: Maximum thermal efficiency of the solar air heater with different covers at $\dot{m} = 0.032$ kg/s

Solar air heater	**Maximum efficiency (%)**	**Cover**	**Time (hour)**
Single pass	55.52	Normal glass	12:00
Double pass	60.18	Normal glass	13:00
Single pass	51.07	Quarter perforated 20D	13:00
Single pass	52.56	Quarter perforated 10D	13:00
Double pass	60.49	Quarter perforated 10D	15:00
Double pass	57.60	Quarter perforated 20D	13:00

The average efficiency for the single and double pass solar air heaters with different covers are listed in Table 4.2. Obtained results show that the average efficiency of single pass solar air heater with normal glazing is higher than with 20D perforated cover and the average efficiencies of both are higher than the one for single pass solar air heater with 10D perforated cover. The reason is the mixture of the air flows entering to the solar air heater through the holes with various positions on the cover. The obtained results from double pass solar air heater are different. The average efficiency of double pass solar air heater with 10D perforated cover is higher than with 20D perforated cover and the average efficiencies of both are higher than the one for double pass solar air heater with normal glazing because, the inlet air is preheated in the upper channel (space between the first and second covers) before it enters to the lower channel (duct) through the holes.

Table 4.2: Average thermal efficiency of solar air heater with different covers at $\dot{m} = 0.032$ kg/s

Solar air heater	Average efficiency (%)	Cover
Single pass	49.36	Normal glass
Double pass	51.70	Normal glass
Single pass	46.54	Quarter perforated 20D
Single pass	46.40	Quarter perforated 10D
Double pass	54.76	Quarter perforated 10D
Double pass	51.38	Quarter perforated 20D

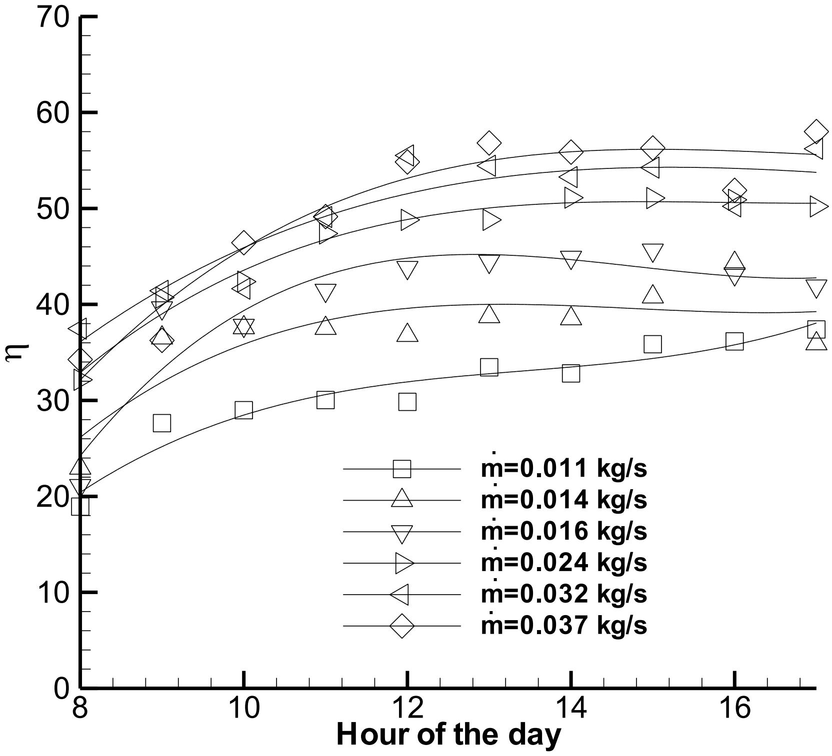


Figure 4.7: Efficiency versus time of the day at different mass flow rates for single pass solar air heater with normal glass cover

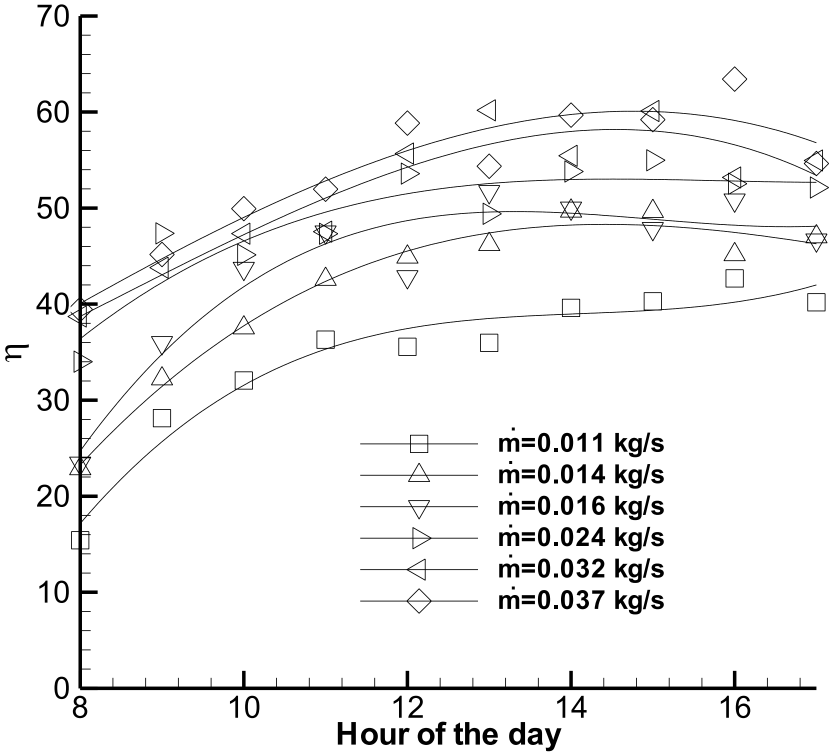


Figure 4.8: Efficiency versus time of the day at different mass flow rates for double pass solar air heater with normal glass cover

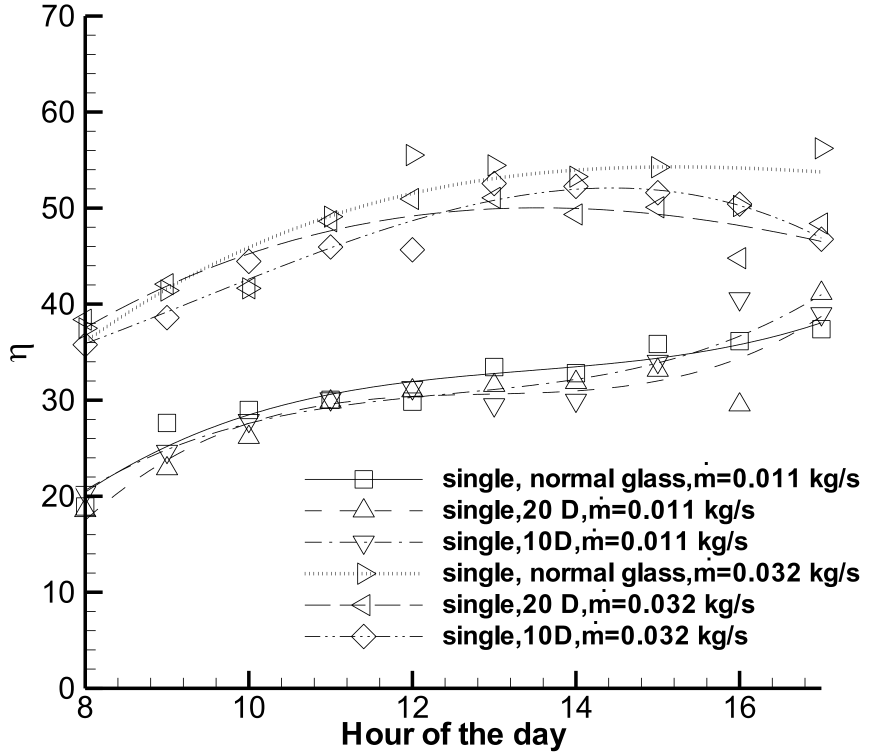


Figure 4.9: Efficiency versus time of the day at different mass flow rates for single pass collector with glass cover, quarter perforated covers 20D & 10D

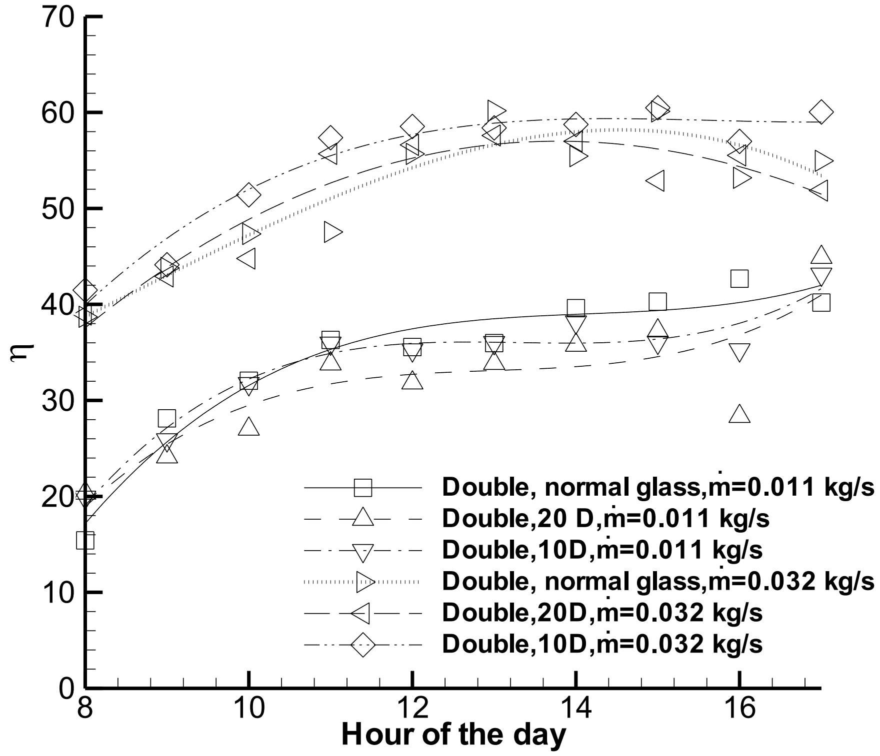


Figure 4.10: Efficiency versus time of the day at different mass flow rates for double pass collector with glass cover, quarter perforated covers 20D & 10D

As it has been mentioned earlier, in order to improve the efficiency of the solar air heater and also minimize the heat losses through the top cover, the normal glass cover is replaced by the perforated Plexiglas cover. The holes on the cover have two functions, firstly they are used as the passages for the inlet air; secondly, they decrease the temperature of the cover which led to reduce the heat lost from the cover to the environment. The effect of using various numbers of holes on the temperature of collector's cover can be seen from Figs. 4.11 – 4.14.

For both single and double pass solar air heaters with the perforated cover 20D, the temperature differences ($T_{Plexiglas}$ - T_{in}) at mass flow rate of 0.011 and 0.032 kg/s are compared with the ones when 10D perforated cover is used on the solar collector (Figs. 4.11 - 4.14). The temperatures of the cover at top, middle and bottom of the Plexiglas are measured hourly with thermocouples fixed on the cover from inside the channel. The top and bottom thermocouples are placed 18 cm from the upper and lower sides of the collector frame and the middle thermocouple is placed between these two, 75cm away from upper frame.

It is found that the bottom of cover, which is close to the outlet air, has higher temperature than the middle and top side of it. The temperatures measured on the 10D cover were always lower compared with the 20D cover at the same mass flow rate, for both single and double pass solar air heaters. That is the reason the solar air heater with quarter perforated cover 10D has higher thermal efficiency than with the cover with less number of holes on it (20D). In the same time, the temperature difference of the cover with double pass found to be higher than that of single pass solar air heater for $\dot{m}$= 0.011 kg/s. However, the temperature differences of the cover for both single and double pass solar air heaters are very close but higher in double pass solar air heater at $\dot{m}$= 0.032 kg/s. The increases in the temperature difference of the cover for double pass solar air heater are expected. In double pass solar collectors, the upper channel preheats the inlet air before it enters to the lower channel also; the inlet air is heated by the high temperature portion of the cover, bottom of Plexiglas (Figs. 4.13 &4.14) at the outlet of the lower channel as well as by the solar intensity.

Finally, the pressure drop versus the mass flow rate for this small channel height study is shown in Fig. 4.15. In general, the pressure drop through the proposed solar air heater was not very significant compared with published data. The obtained results show that increasing the air mass flow rate increases the pressure drop inside the solar air heater. The difference in pressure drop between the single pass and double pass is not high, and in general, the pressure drop is higher through double pass solar air heater.

As it is mentioned in the uncertainty section, T_{air} is the film air temperature between the outlet and inlet. From Figs. 4.16(a-d), it is evident that the slopes of the efficiency curves increase with increase of mass flow rate in addition, the thermal efficiency of solar air heater increases as $(T_{air} - T_a)/I$ ratio increases. Similar results are obtained by Karmare and Tikekar (2009).

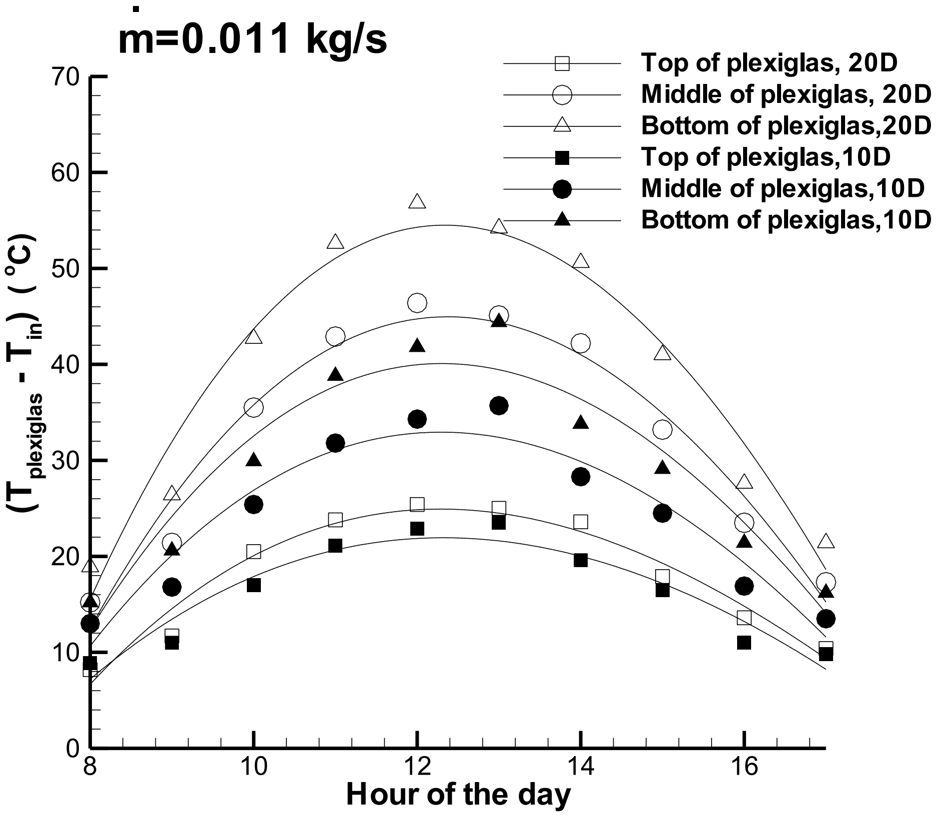


Figure 4.11: Quarter perforated cover temperature differences ($T_{Plexiglas} - T_{in}$) versus time of the day for single pass solar collector, ṁ=0.011 kg/s

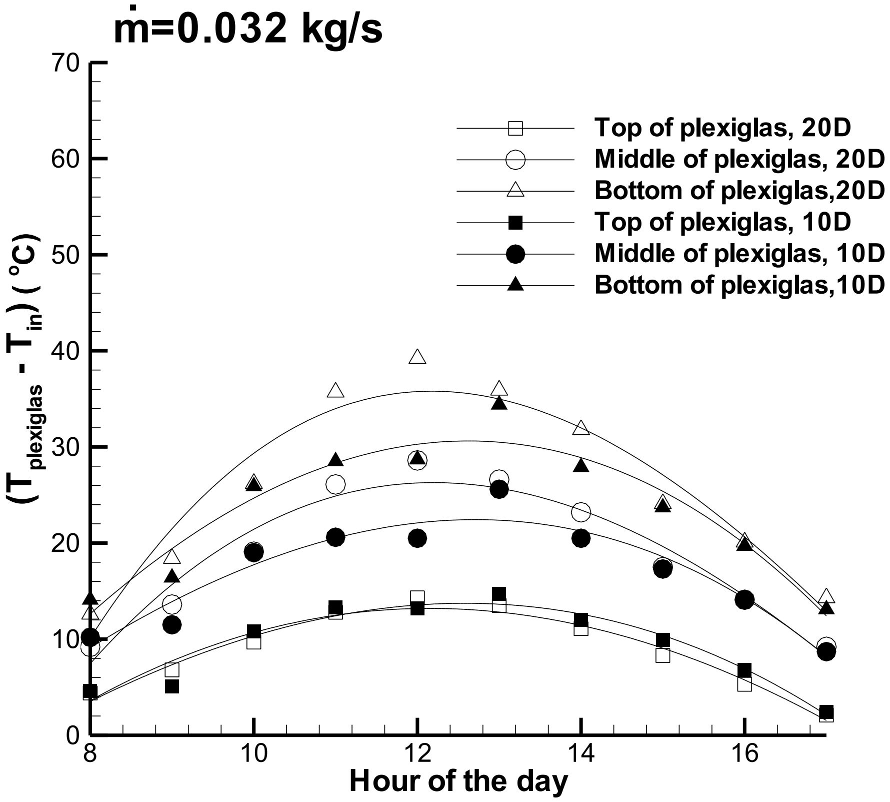


Figure 4.12: Quarter perforated cover temperature differences (T $_{\text{Plexiglas}}$ – T_{in}) versus time of the day for single pass solar collector, ṁ=0.032 kg/s

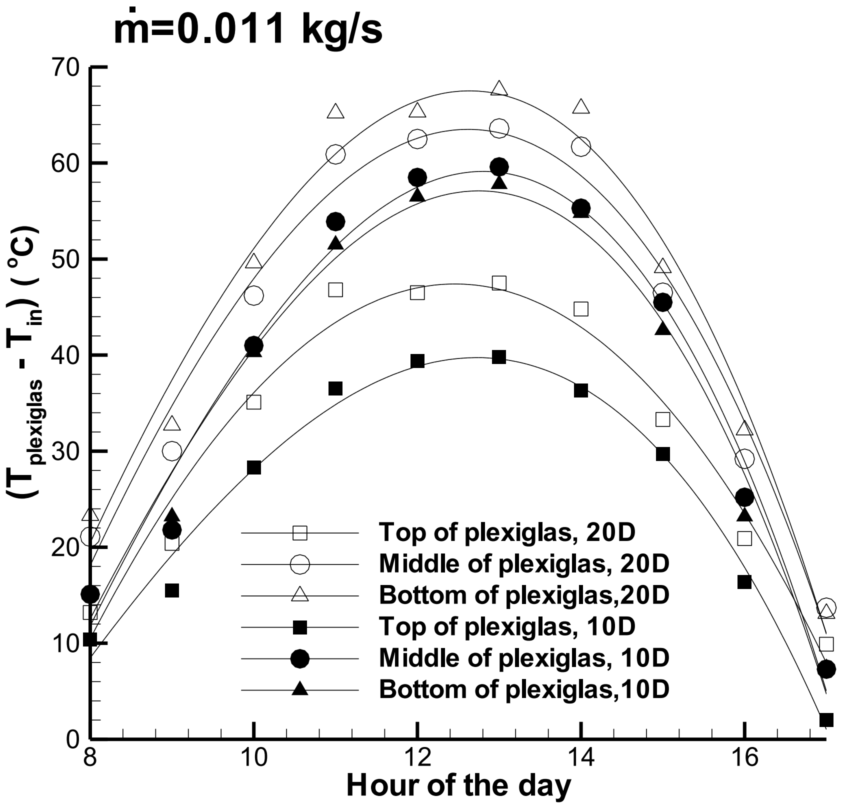


Figure 4.13: Quarter perforated cover temperature differences ($T_{Plexiglas} - T_{in}$) versus time of the day for double pass solar collector, ṁ=0.011 kg/s

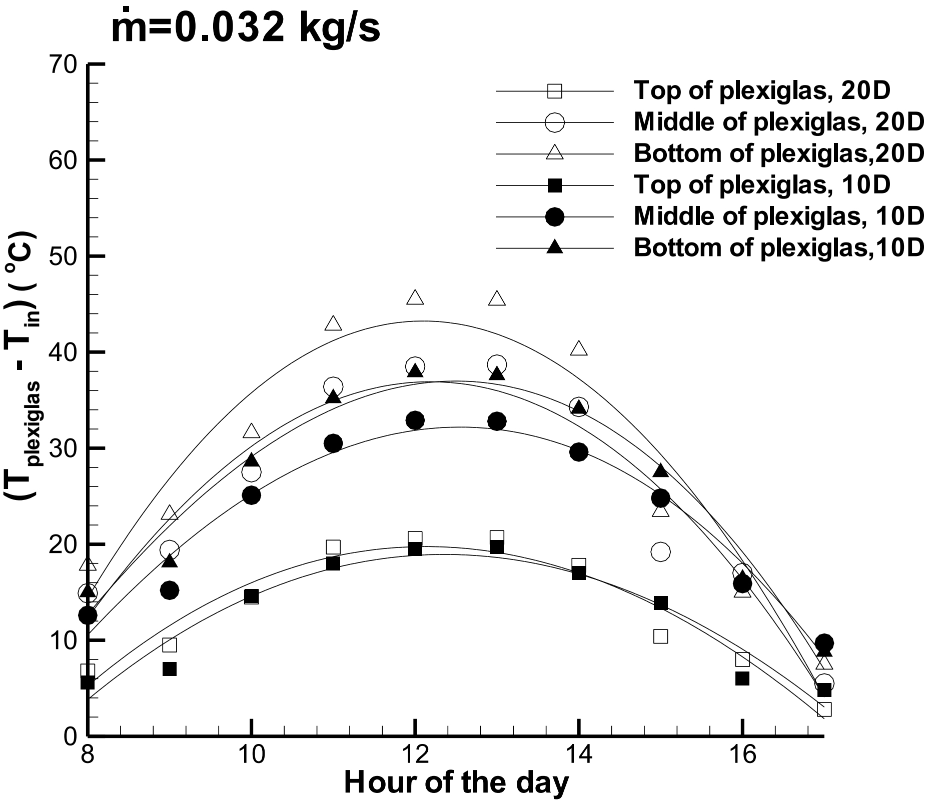


Figure 4.14: Quarter perforated cover temperature differences ($T_{Plexiglas} - T_{in}$) versus time of the day for double pass solar collector, ṁ=0.032 kg/s

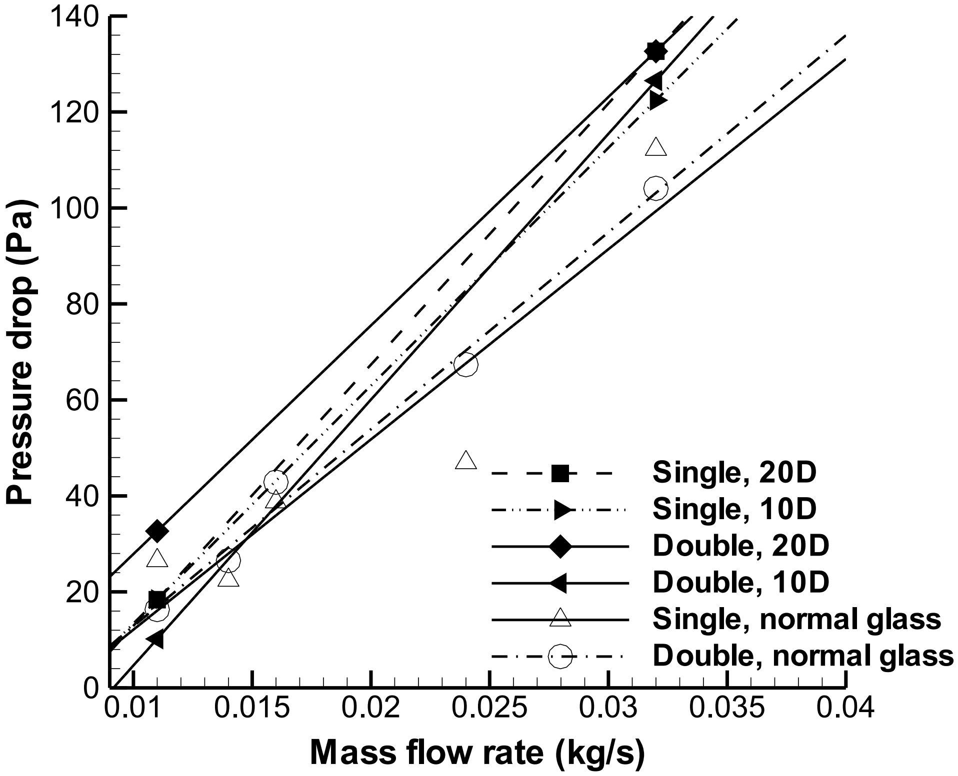


Figure 4.15: Pressure drop versus mass flow rate for single and double pass solar air heaters with normal glass, and single and double pass solar air heaters with quarter perforated covers (20D &10D)

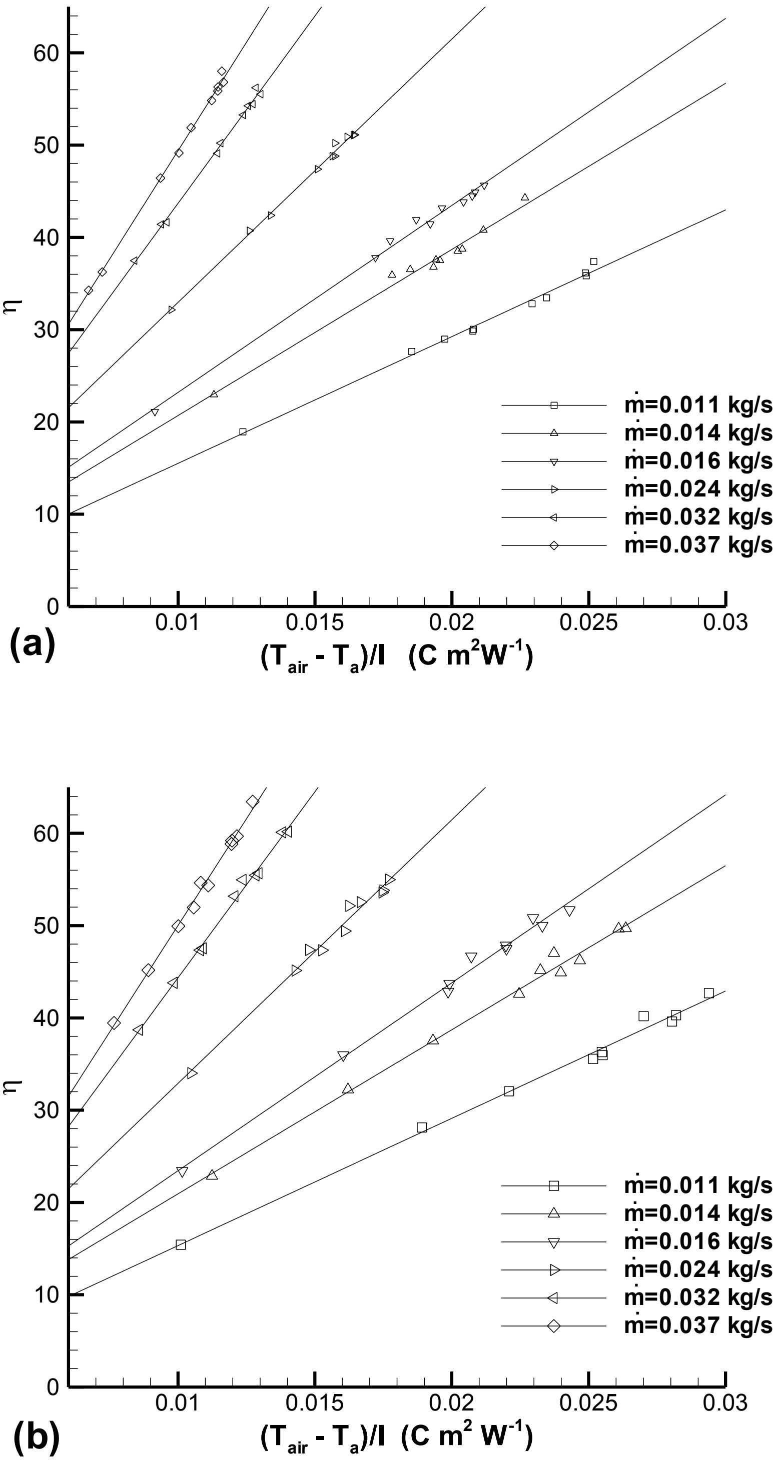


Figure 4.16: Efficiency versus (T_{air} - T_a)/I ratio at different mass flow rates for (a) Single pass solar air heater, (b) Double pass solar air heater

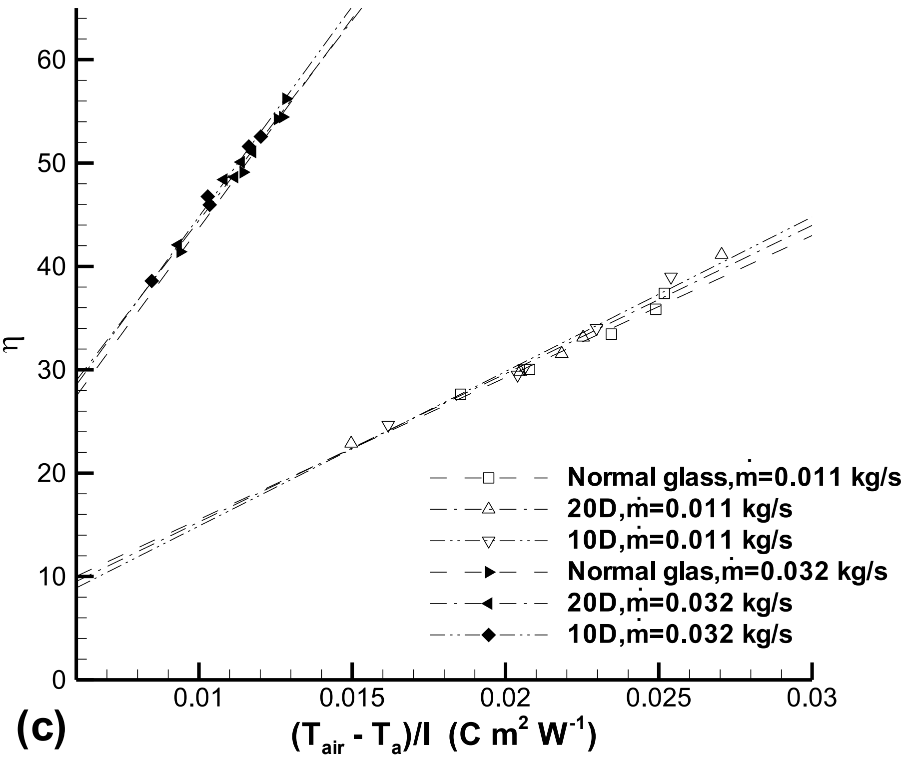


Figure 4.16(c): Efficiency versus (T_{air} - T_a)/I ratio at different mass flow rates for single pass solar air heater with perforated covers (20D & 10D)

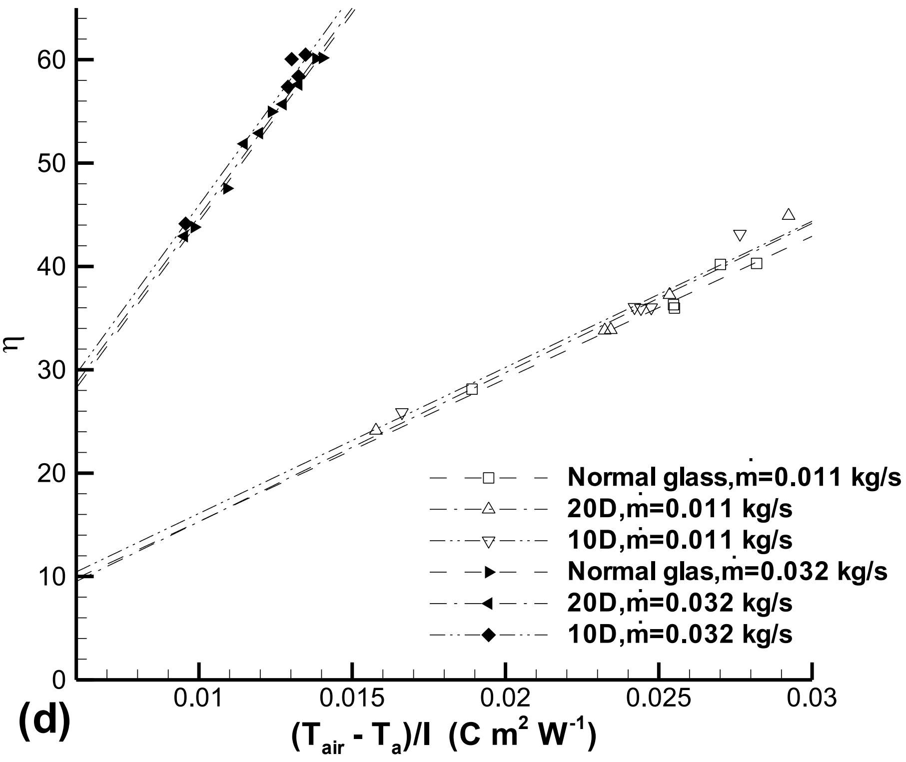


Figure 4.16(d): Efficiency versus (T_{air} - T_a)/I ratio at different mass flow rates for double pass solar air heater with perforated covers (20D & 10D)

4.2 Solar Air Heater with Normal Plexiglas, Quarter and Half Perforated Covers and Bed Height of 3cm

Four different perforated covers, two quarter perforated and two half perforated covers with 10D and 20D center-to-center distance between the holes were used in the tests. The perforated covers were made of Plexiglas.

On two perforated covers the holes were made on the first quarter at the top side of the cover in an area of 100 × 36 cm^2. On the other two covers, half of the cover area (i.e. 100 × 72 cm^2) on the top side was perforated. No holes were made near the outlet or in the lower half side of cover as it was believed that, the air entering to the collector through the holes on the lower side of the cover may reduce the temperature of outlet air and the thermal performance of collector. The cold air, ambient air, entering from the lower side of cover has no time to carry heat from the bed due to the short path length and, it may reduce the temperature of outlet air as it mixes with it. As a result the thermal performance of collector may reduce. The hole diameter, D, was 0.3 cm. The holes made on one of the quarter and one of the half perforated covers had the center-to-center distance (d_c) of 20D (6 cm) and on the other two covers d_c was 10D (3cm). The solar air collector was also tested with a normal Plexiglas cover in which the air was entered to the collector through an opening made on the top side of the cover. The opening area was 100 cm^2. All the different covers were examined on both single and double pass solar air collector in order to find the best arrangement which leads to highest thermal performance.

The tests are performed in summer time with clear sky condition. The mean value of wind speed as measured hourly during all days of experiment is 4.86 m/s. The thermal efficiency of all different arrangements of solar air heater with wire mesh layers as absorber plate and small duct height of 3 cm, at two different air mass flow rates of (0.011 and 0.032 kg/s) is studied.

The solar intensity versus time of the day for all days of experiment are shown in Figs 4.17(a-c). The highest daily solar radiation was 1155 W/m^2 and it was measured on single pass solar air heater with normal Plexiglas cover at 13:00 h. Similar amount of solar radiation (1134 W/m^2) was also measured at 13:00 h, when the single pass solar collector with quarter perforated cover, 10D, was tested. The average solar intensity on single and double pass solar air heaters with packed bed and normal Plexiglas cover were 740.2 W/m^2 and 709.3 W/m^2, respectively during all days of experiment. For the single and double pass collectors with quarter perforated covers, the mean solar intensity of all days was 715.8 W/m^2 and 724.5 W/m^2, respectively while for the single and double pass collectors with half perforated covers, it was measured to be 708.7 W/m^2 and 690.6 W/m^2, respectively. It is found that all the average values of solar intensity were within the close range during the experiment.

Figs. 4.18(a-c) show the inlet ambient temperature, T_{in}, versus time of the day for all days of experiment. It can be seen in Fig. 4.18 that in general the ambient temperature increases during the day and slight reduction occurs at 5 PM also, minor fluctuations happened in some of the days depending on wind speed of that day. As for the solar intensity, the average values of inlet temperature at different days were also within the close range with each other.

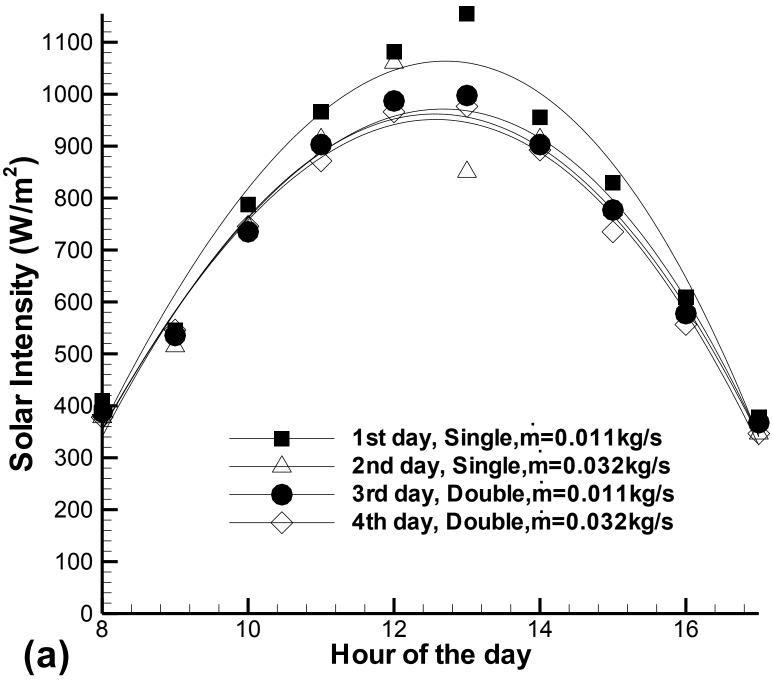


Figure 4.17(a): Solar intensity versus time of the day for single and double pass solar air collector with normal Plexiglas cover

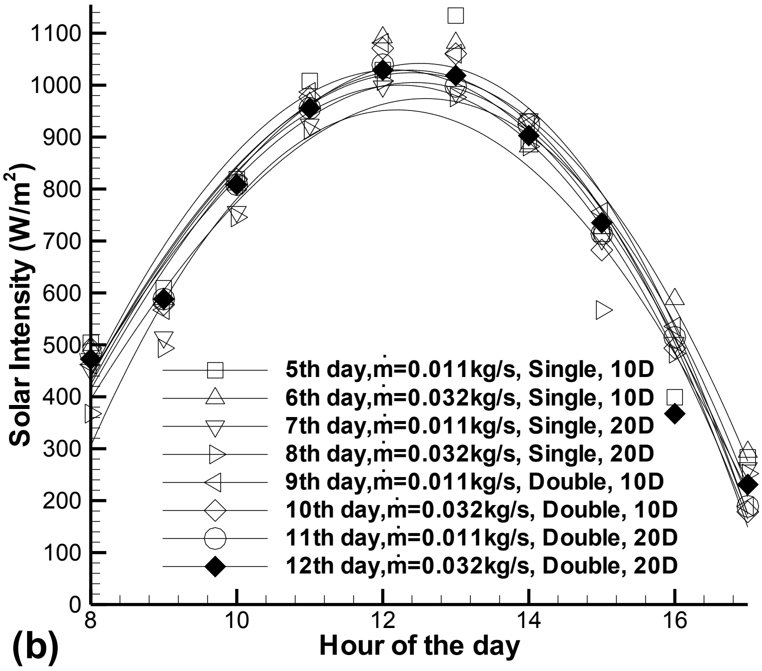


Figure 4.17(b): Solar intensity versus time of the day for single and double pass solar air collector with quarter perforated covers (10D & 20D)

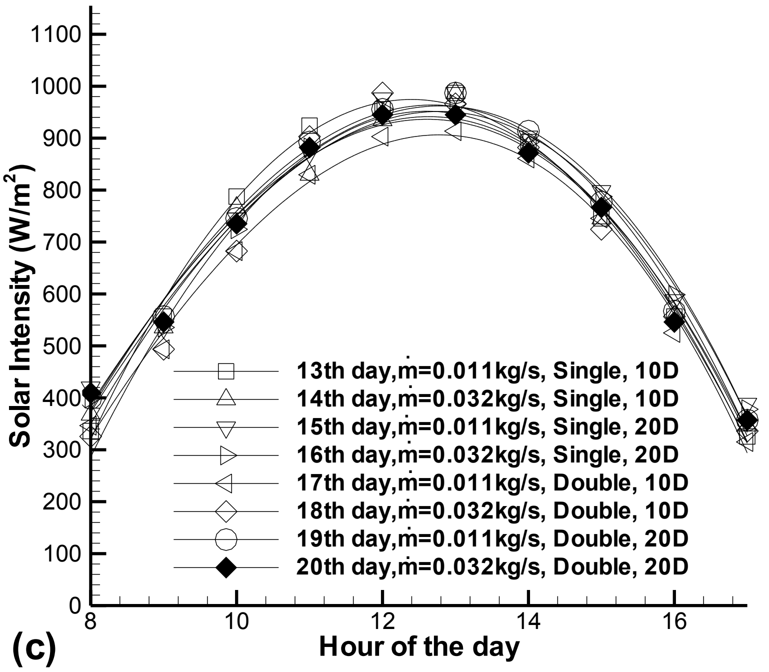


Figure 4.17(c): Solar intensity versus time of the day for single and double pass solar air collector with half perforated covers (10D & 20D)

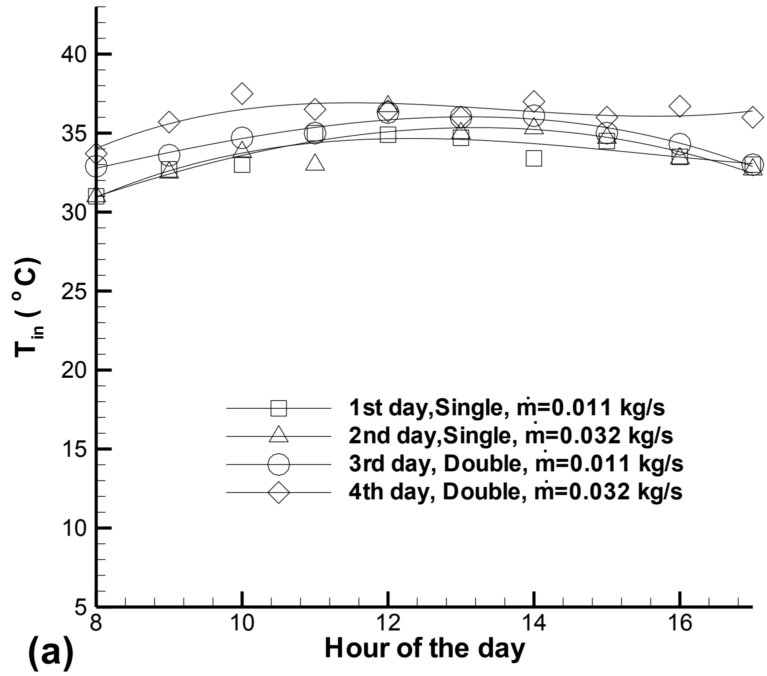


Figure 4.18(a): Inlet temperature versus time of the day for single and double pass solar air collector with normal Plexiglas cover

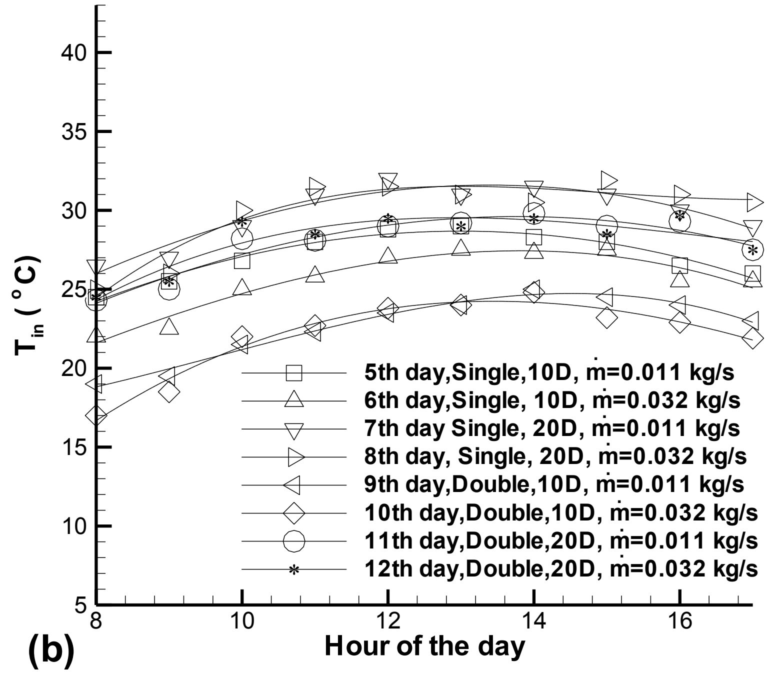


Figure 4.18(b): Inlet temperature versus time of the day for single and double pass solar air collector with quarter perforated covers (10D & 20D)

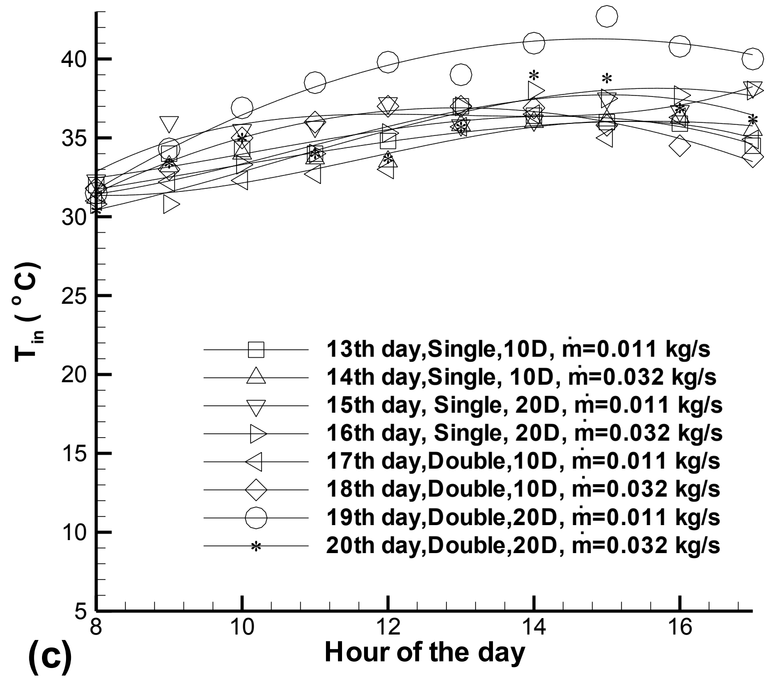


Figure 4.18(c): Inlet temperature versus time of the day for single and double pass solar air collector with half perforated covers (10D & 20D)

The temperature difference between the outlet and inlet air, $\Delta T = T_{out} - T_{in}$, versus time of the day at two different air mass flow rates, for single and double pass solar air collectors with normal Plexiglas cover and with quarter and half perforated covers are shown in Figs. 4.19 - 4.22. It is found that the solar air heater with quarter perforated cover reaches to higher ΔT than with the half perforated or normal Plexiglas cover. The temperature difference of both single and double pass solar collectors with either quarter or half perforated covers at low mass flow rate ($\dot{m}$=0.011 kg/s) were higher than the ones with normal Plexiglas cover. Only the single pass collector with half perforated cover 10D (Fig. 4.19), had shown lower ΔT than the one with normal Plexiglas cover at the same $\dot{m}$. The reason of this can be explained as follow. The air enters to the collector through the upper holes and absorbs heat from the mesh layers as it propagates inside the collector. At the time the hot air reaches to the holes close to the middle of the collector, the ambient air with lower temperature enters to the collector through the middle holes on the cover and mixes with the hot air which comes from the top side of bed. As a result of mixing the air temperature decreases. In the case of double pass collector the low temperature ambient air preheats in the upper channel before it enters to the lower channel via the holes as a result ΔT increases. At $\dot{m}$ = 0.032 kg/s, the ΔTs obtained from single pass collector with normal cover, quarter and half perforated covers were similar to each other.

The maximum temperature difference obtained with single pass air heater with quarter perforated cover of 10D pitch spacing was 46.25°C at 13:00 h, at $\dot{m}$ of 0.011 kg/s (Fig. 4.19). At the same mass flow rate the ΔT increases more by using the double pass solar air heater. The maximum temperature difference was 52.5°C at

13:00 h when the double pass collector was tested with the quarter perforated cover 10D at $\dot{m}$ of 0.011 kg/s (Fig. 4.21). Generally the highest ΔT was obtained at the lowest flow rate of air. The maximum amount of ΔT obtained for the counter flow collector with normal Plexiglas cover at $\dot{m}$ of 0.011 kg/s was 34.8°C at 12:00 h. For the same mass flow rate, the temperature difference for single and double pass solar air heaters with quarter perforated cover is higher compared to that of normal Plexiglas cover.

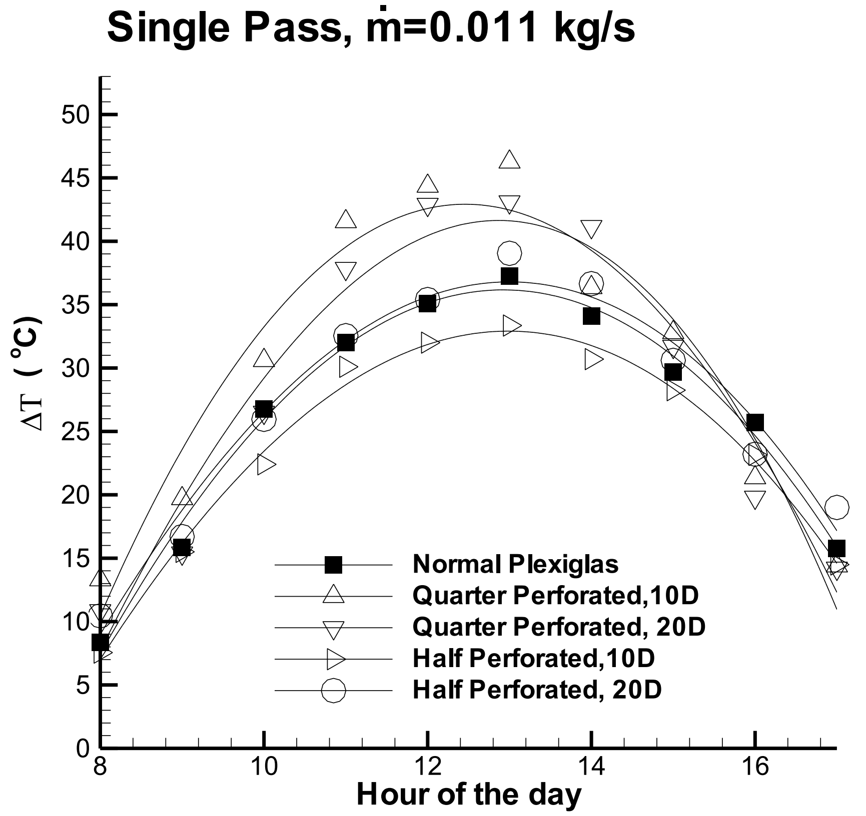


Figure 4.19: Temperature difference versus time of the day for single pass solar air collector with normal Plexiglas cover, quarter and half perforated covers (10D & 20D) at ṁ = 0.011 kg/s

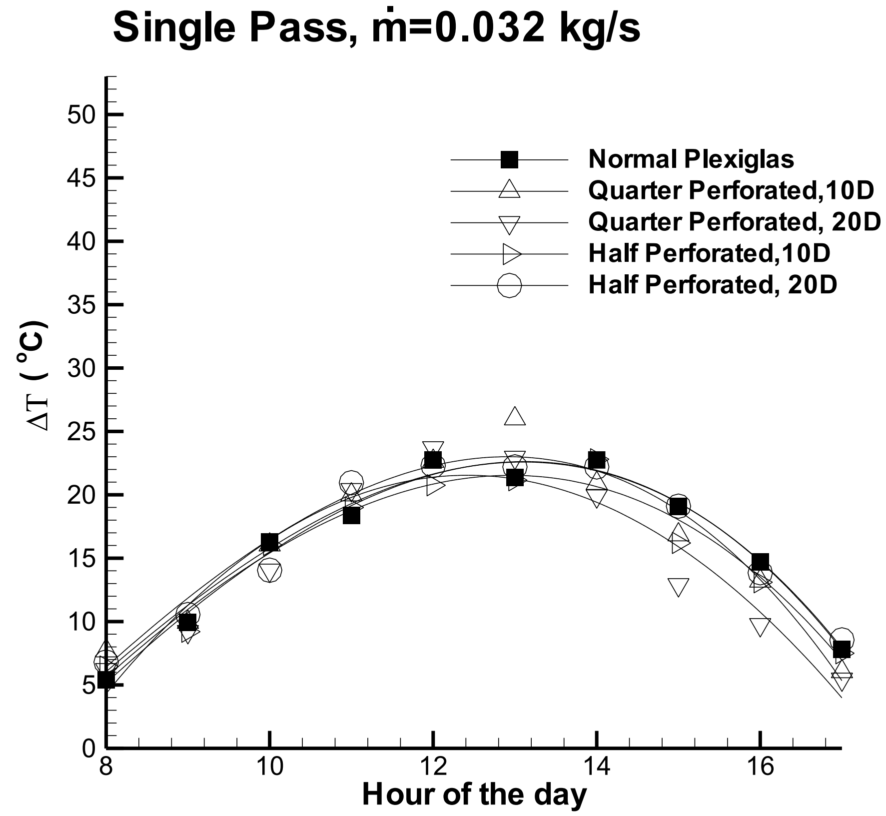


Figure 4.20: Temperature difference versus time of the day for single pass solar air collector with normal Plexiglas cover, quarter and half perforated covers (10D & 20D) at ṁ = 0.032 kg/s

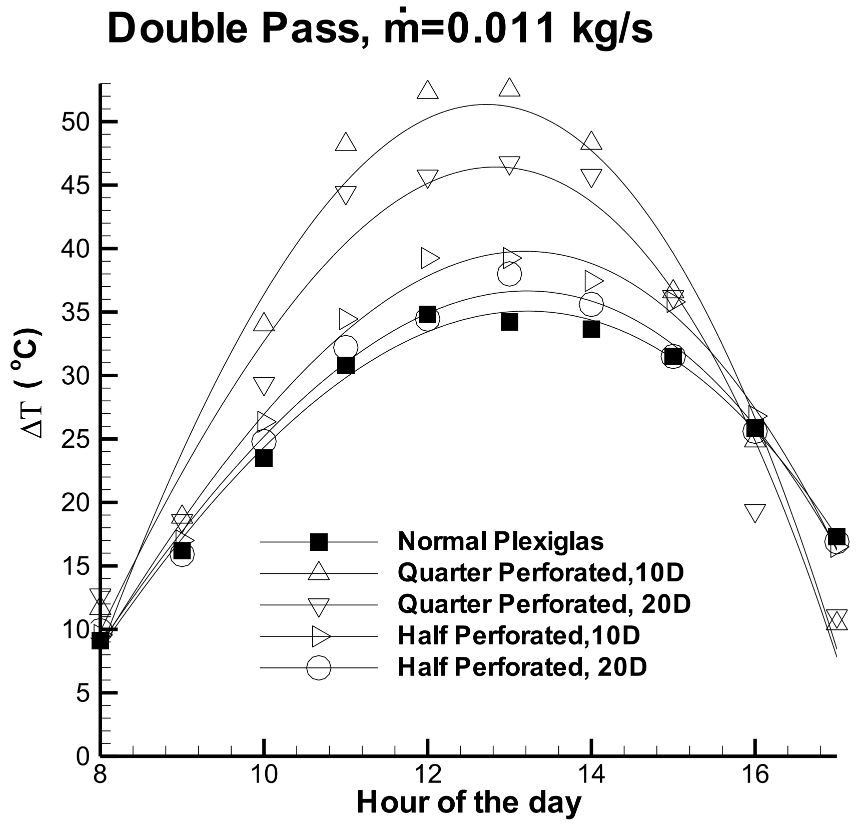


Figure 4.21: Temperature difference versus time of the day for double pass solar air collector with normal Plexiglas cover, quarter and half perforated covers (10D & 20D) at ṁ = 0.011 kg/s

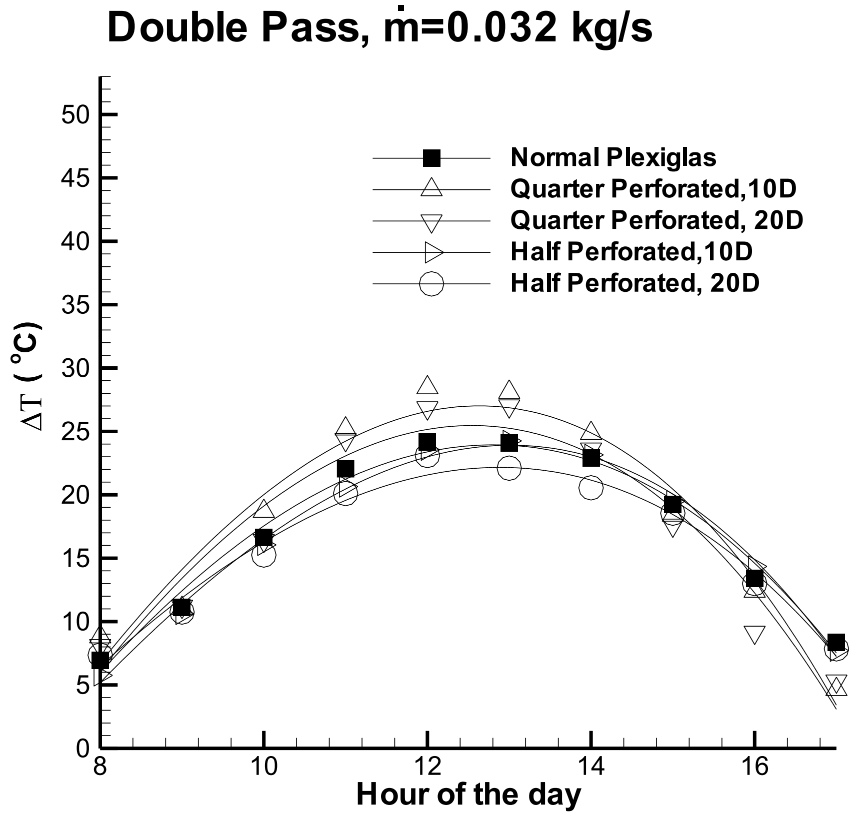


Figure 4.22: Temperature difference versus time of the day for double pass solar air collector with normal Plexiglas cover, quarter and half perforated covers (10D & 20D) at ṁ = 0.032 kg/s

The thermal efficiency versus time of the day at two different air mass flow rates, for single and counter flow solar air collectors with normal Plexiglas cover and with quarter and half perforated covers are shown in Figs. 4.23 – 4.26. In general at high air mass flow rate ($\dot{m}$=0.032 kg/s) thermal efficiency increases from morning until around 13:00 PM and then it shows slight decrease in the afternoons. At low $\dot{m}$ the efficiency continues to increase even throughout the afternoon because more heat losses occur in the early hours of the day due to lower ambient temperature in the morning compared with the afternoon. Similar results were reported by El-khawajah *et al.,* 2011; Omojaro *et al.* 2010 and Aldabbagh *et al.* 2010. In all the experiments, thermal efficiency increased as the air mass flow rate was increased. The maximum thermal efficiency of the single and double pass solar air heaters with normal Plexiglas cover at the mass flow rate of 0.032 kg/s are found to be 54.62% at 16:00 h and 56.36% at 15:00 h, respectively (Figs. 4.24 & 4.26). As it is shown in Fig. 4.26, at mass flow rate of 0.032 kg/s, the maximum efficiency of the double pass solar collector with quarter perforated covers 20D and 10D are, 57.60% at 13:00h and 60.49% at 15:00h, respectively. For the same mass flow rate and the same collector with half perforated covers 20D and 10D the maximum value of efficiency obtained was 52.66% at 12:00h and 57.93% at 15:00h, respectively.

The average efficiency of the single and double pass solar air heaters with normal Plexiglas cover and different quarter and half perforated covers are listed in Table 4.3.

Table 4.3: Average thermal efficiency of solar air heater with different covers at ṁ = 0.032 kg/s

Solar air heater	Average efficiency (%)	Cover
Single pass	47.67	Normal Plexiglas
Double pass	50.92	Normal Plexiglas
Single pass	46.54	Quarter perforated 20D
Single pass	46.40	Quarter perforated 10D
Double pass	54.76	Quarter perforated 10D
Double pass	51.38	Quarter perforated 20D
Single pass	47.86	Half perforated 20D
Single pass	46.72	Half perforated 10D
Double pass	48.21	Half perforated 20D
Double pass	51.17	Half perforated 10D

As it is shown in Fig. 27(a and b), the average thermal efficiency of the solar air heater with different covers increases as mass flow rate increases. The maximum average efficiency was 54.8% at mass flow rate of 0.032 kg/s and it was obtained from double pass solar collector with quarter perforated cover 10D while, the maximum average efficiency obtained from the double pass solar collector with normal Plexiglas cover was 50.9% at the same mass flow rate.

Fig. 4.28(a and b) shows the pressure drop versus mass flow rate for both single and double pass solar air haters with various covers. The obtained results show that increasing the air mass flow rate increases the pressure drop inside the collector. Usually, at the same mass flow rate, the pressure drop is higher in a double pass solar collector compared with the single pass. In addition, pressure drop inside the single pass solar collector increases as a perforated cover is used but for a double pass collector with either normal or perforated cover, the pressure drop values are very close.

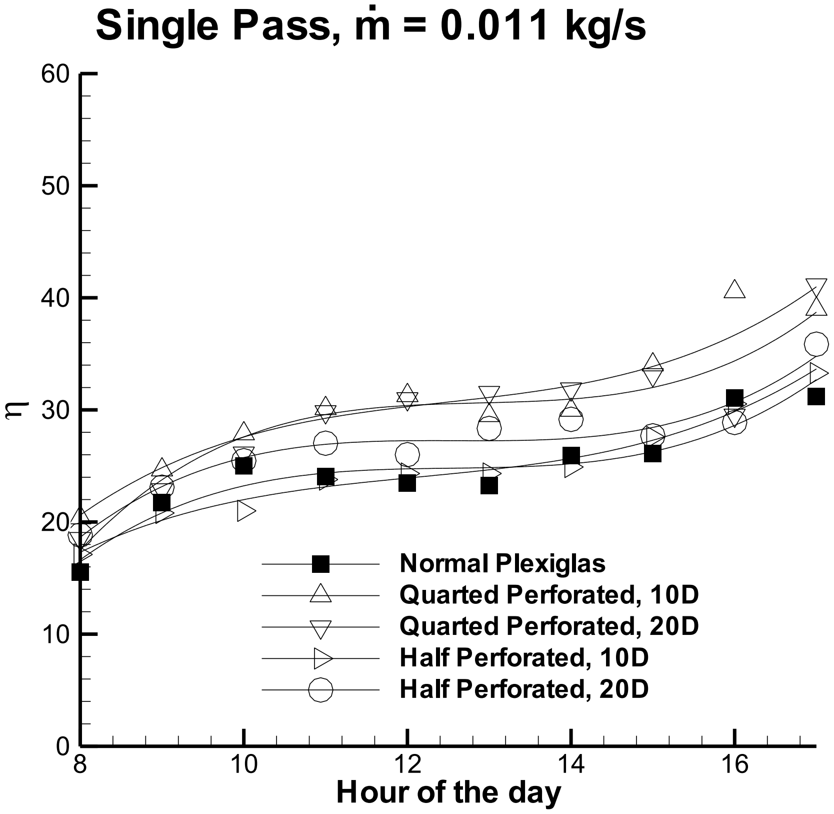


Figure 4.23: Efficiency versus time of the day for single pass solar air collector with normal Plexiglas cover, quarter and half perforated covers (10D & 20D) at ṁ = 0.011 kg/s

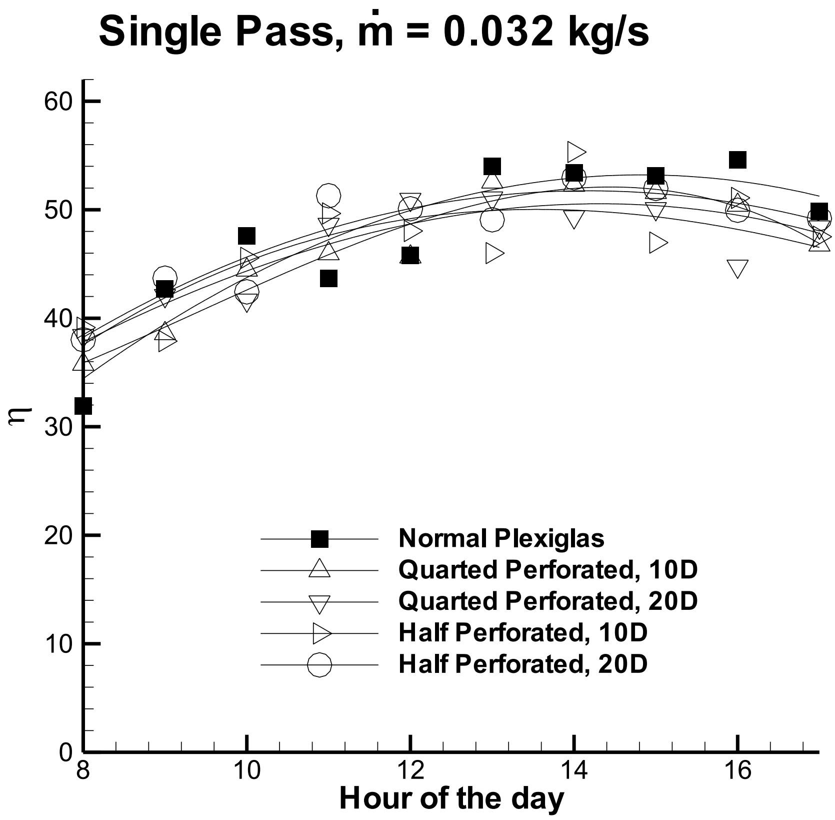


Figure 4.24: Efficiency versus time of the day for single pass solar air collector with normal Plexiglas cover, quarter and half perforated covers (10D & 20D) at ṁ = 0.032 kg/s

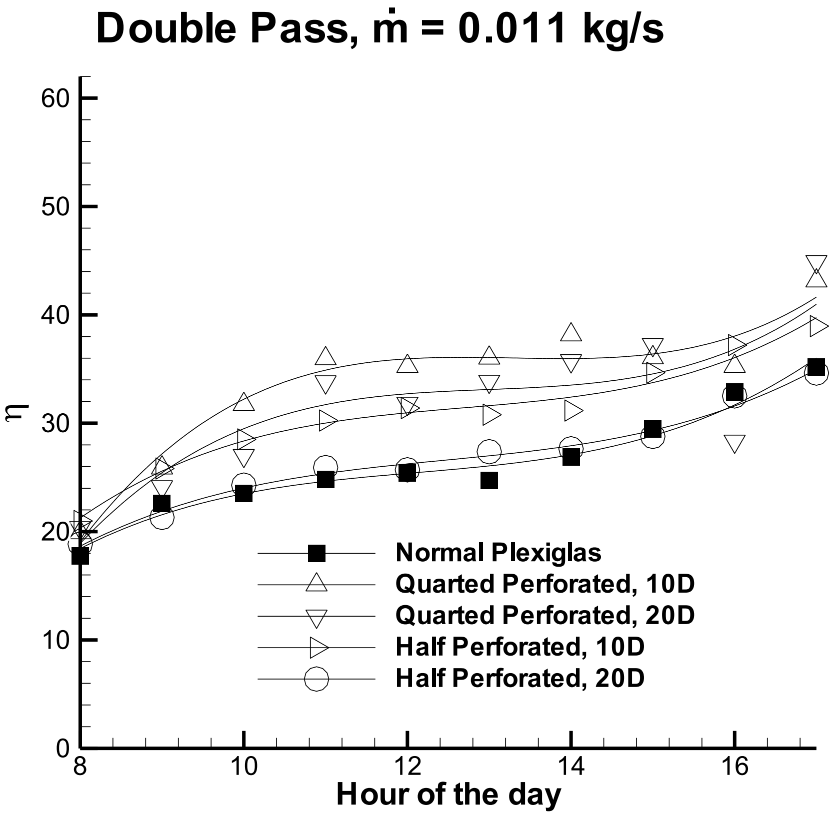


Figure 4.25: Efficiency versus time of the day for double pass solar air collector with normal Plexiglas cover, quarter and half perforated covers (10D & 20D) at ṁ = 0.011 kg/s

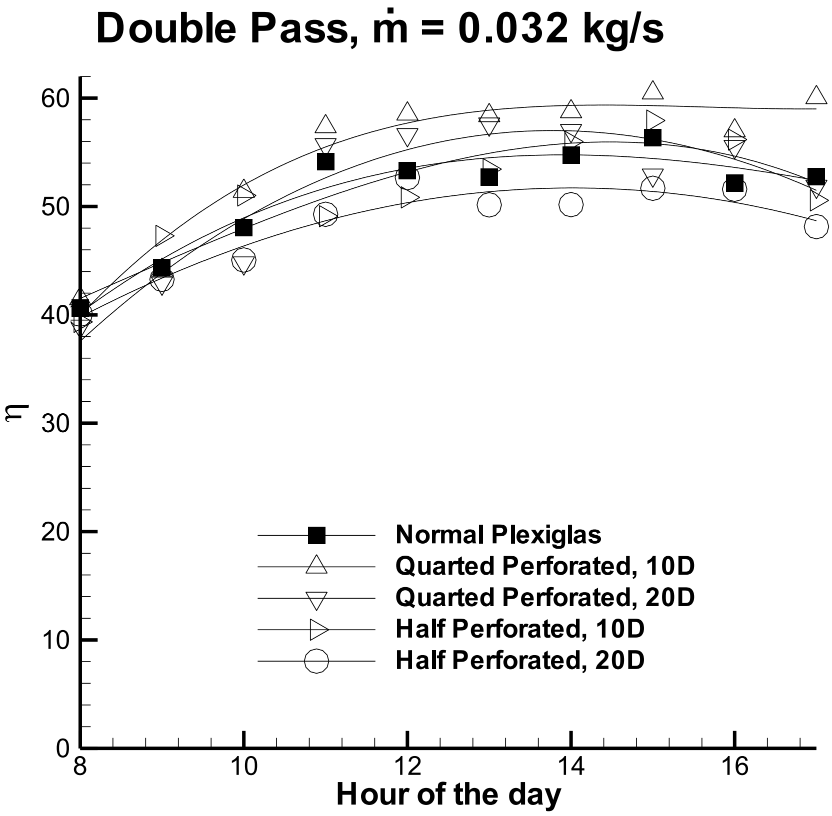
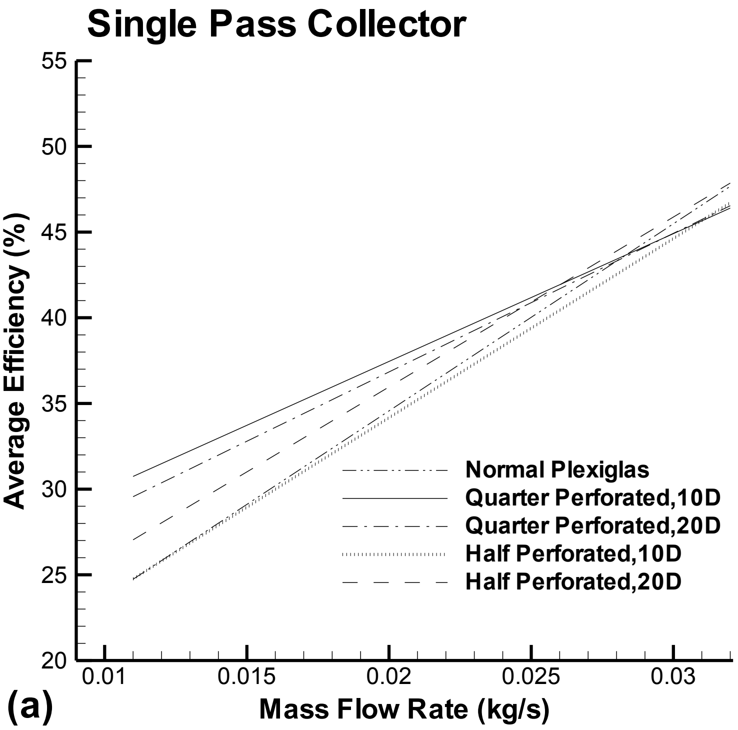


Figure 4.26: Efficiency versus time of the day for double pass solar air collector with normal Plexiglas cover, quarter and half perforated covers (10D & 20D) at ṁ = 0.032 kg/s



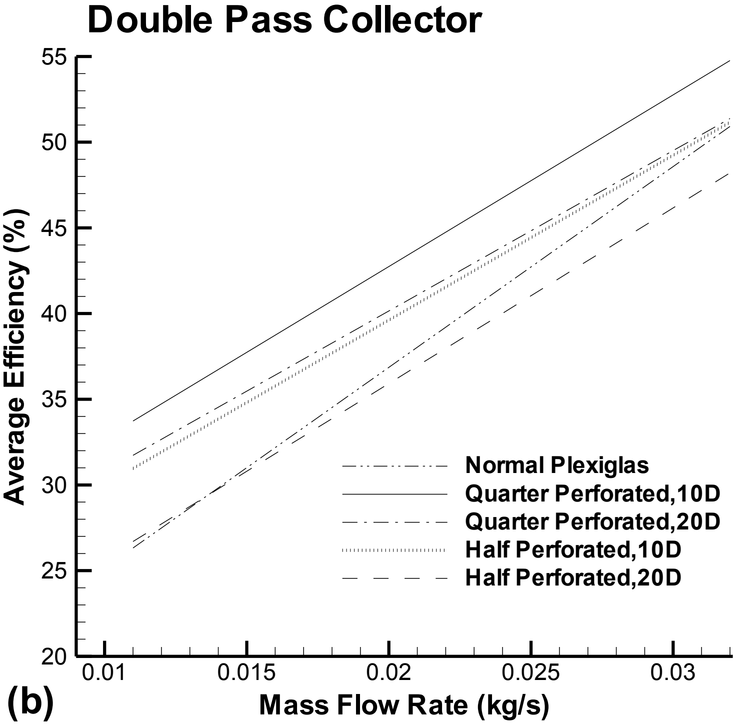
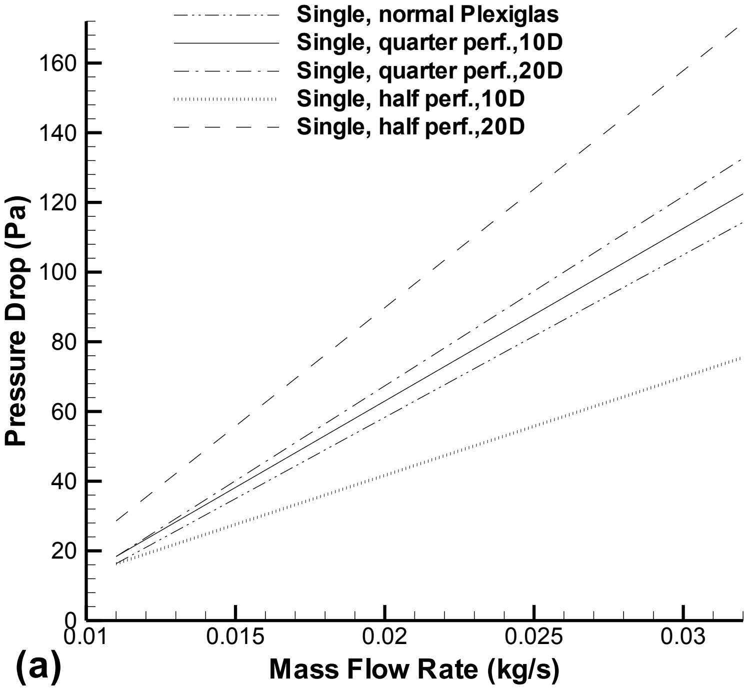


Figure 4.27: Average efficiency versus mass flow rate for, (a) Single pass, (b) Double pass solar air heaters with normal Plexiglas cover, quarter and half perforated covers (10D & 20D)



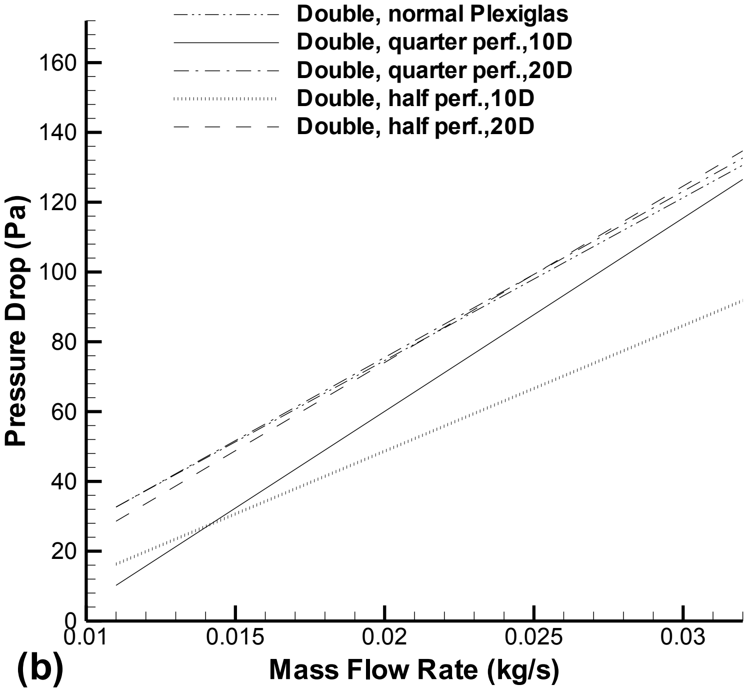


Figure 4.28: Pressure drop versus mass flow rate for, (a) Single pass, (b) Double pass solar air heaters, with normal Plexiglas cover, quarter and half perforated covers (20D &10D)

4.3 Solar Air Heater with Various Normal and Perforated Covers and Different Bed Heights (3, 5.5 and 8 cm)

In order to examine the effect of bed height on thermal performance of the solar air heater, the collector is tested with different bed heights and the obtained results are compared with the ones from the solar collector with 3cm bed height. In these experiments the solar collector is examined with various bed heights of 3cm, 5.5cm and 8cm. The collectors with different bed heights are tested with normal, quarter and half perforated covers at two mass flow rates (0.011kg/s and 0.032 kg/s). The perforated covers used in the previous experiments are also used for the new experiments. In case of double pass solar collector, the upper channel spacing (distance between the two covers) is fixed at 2 cm.

The solar intensities versus time of the day for all days of experiment are shown in Figs. 4.29(a-c) and 4.30(a-c). For each day the mean solar intensity is also calculated. The average solar intensities for all days of experiment for the single pass solar air heater with normal glass cover for different bed heights (i.e., 3cm, 5.5cm and 8cm) were 722.4 W/m^2 and 731.3 W/m^2 and 710.3 W/m^2, respectively. For double pass solar air heater with normal glass cover and different bed heights of 3cm, 5.5cm and 8cm, the average solar intensities for all days of experiment were 725 W/m^2 and 747 W/m^2 and 727.1 W/m^2, respectively. The mean values of solar intensities during all days of experiment for the single pass collector with quarter perforated cover at bed heights of 3cm, 5.5cm and 8cm were 745.5 W/m^2 and 738.1 W/m^2 and 719.8 W/m^2, respectively and for double pass collector with the same cover and bed heights were 732.9 W/m^2 and 736.5 W/m^2 and 719.7 W/m^2, respectively. For the collector with half perforated cover and bed heights of 3 cm, 5.5 cm and 8 cm, the average solar intensity were calculated as 700.8 W/m^2 and 731.3 W/m^2 and 750.7 W/m^2 for single pass air collector and 673.5 W/m^2 and 761.2 W/m^2 and 743.9 W/m^2 for double pass collector, respectively. In general at each day of the tests solar intensity increased from morning and reached to its maximum amount at noon and then decreased afterward.

For the days that the single and double pass solar air heaters with various bed heights are examined, the inlet temperatures, T_{in}, versus time of the day are shown in Figs. 4.31(a-c) and 4.32(a-c). It can be seen from the figures that the inlet ambient temperatures are within a close range during all days.

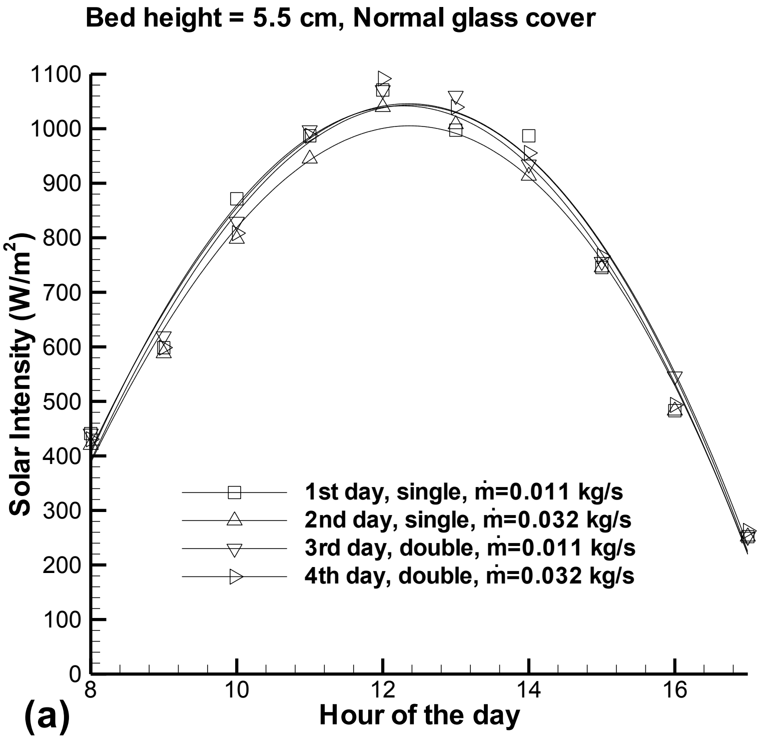


Figure 4.29(a): Solar intensity versus time of the day for single and double pass solar air collectors with normal glass cover and bed height of 5.5 cm

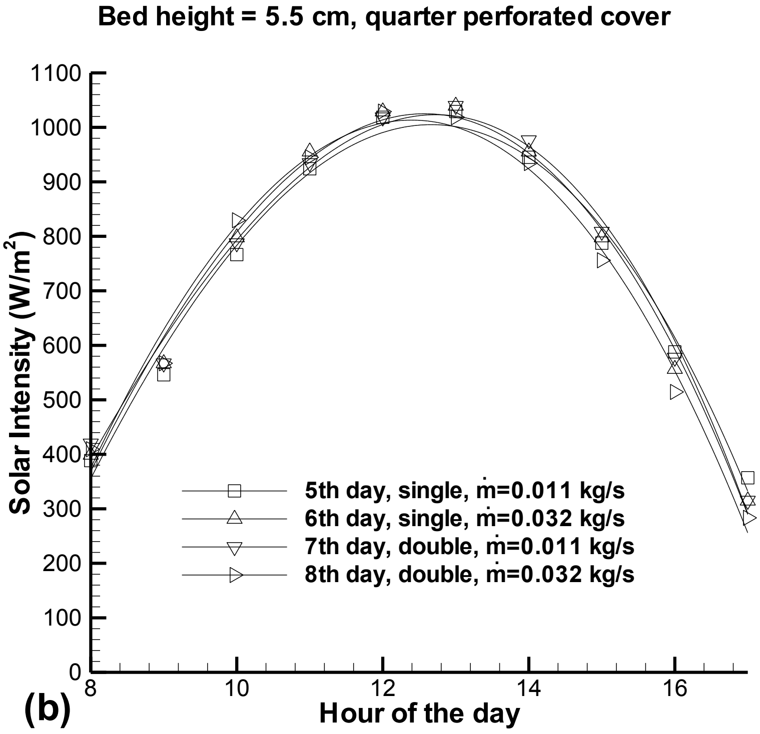


Figure 4.29(b): Solar intensity versus time of the day for single and double pass solar air collectors with quarter perforated cover and bed height of 5.5 cm

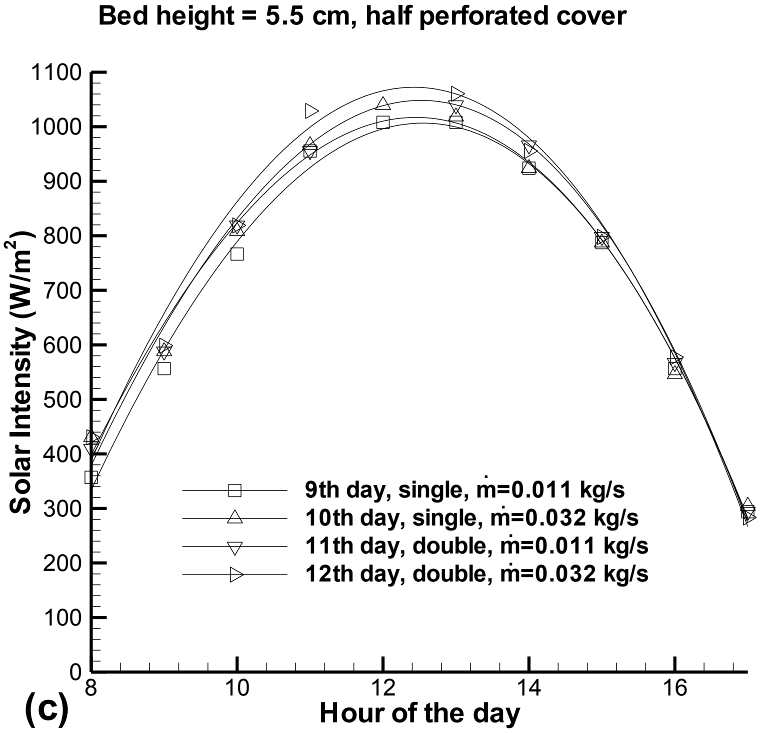


Figure 4.29(c): Solar intensity versus time of the day for single and double pass solar air collectors with half perforated cover and bed height of 5.5 cm

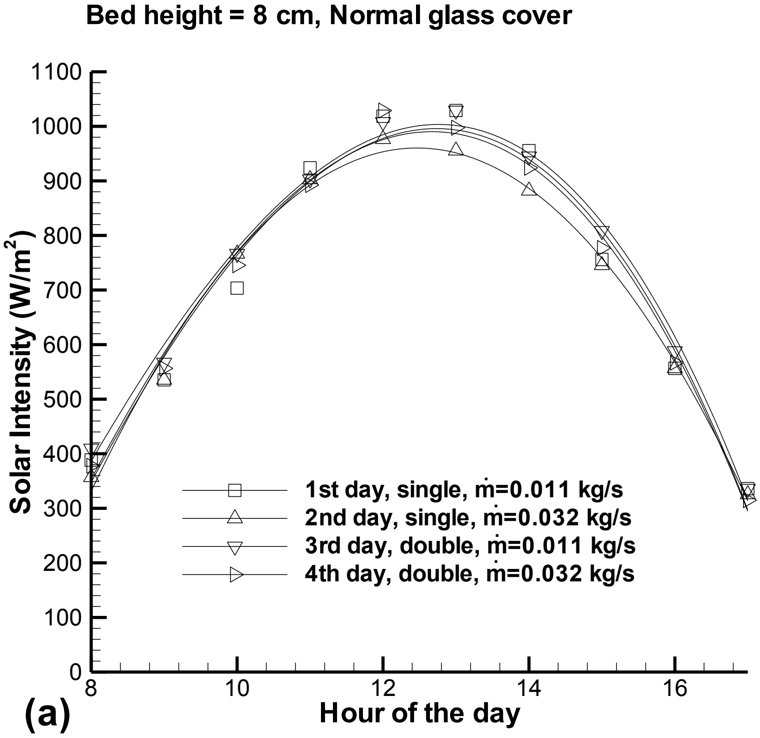


Figure 4.30(a): Solar intensity versus time of the day for single and double pass solar air collectors with normal glass cover and bed height of 8 cm

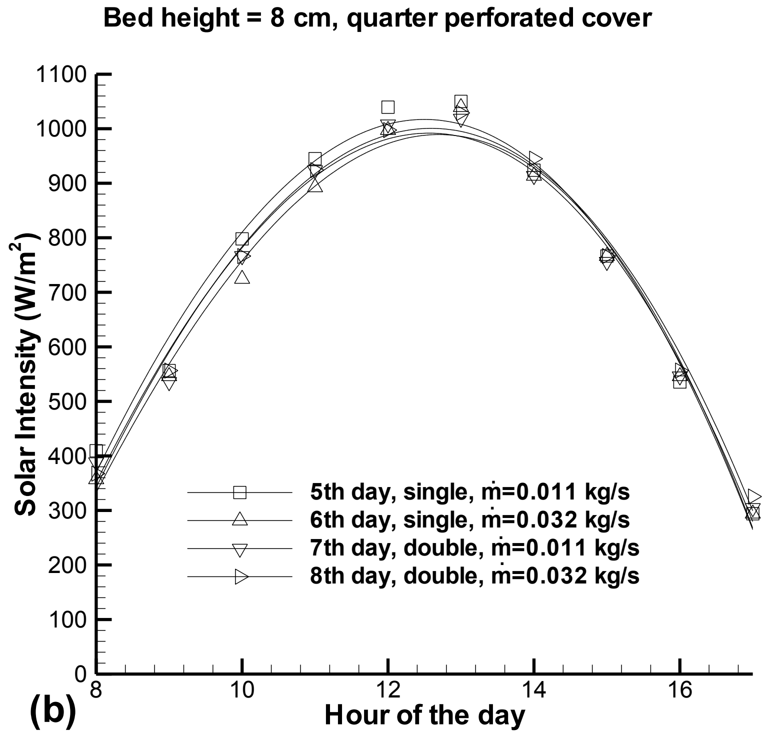


Figure 4.30(b): Solar intensity versus time of the day for single and double pass solar air collectors with quarter perforated cover and bed height of 8 cm

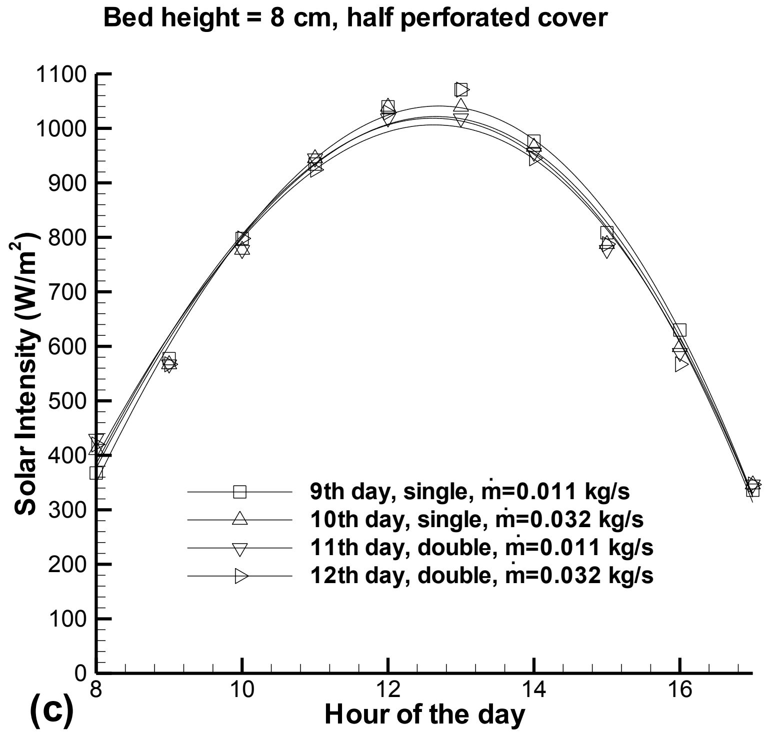


Figure 4.30(c): Solar intensity versus time of the day for single and double pass solar air collectors with half perforated cover and bed height of 8 cm

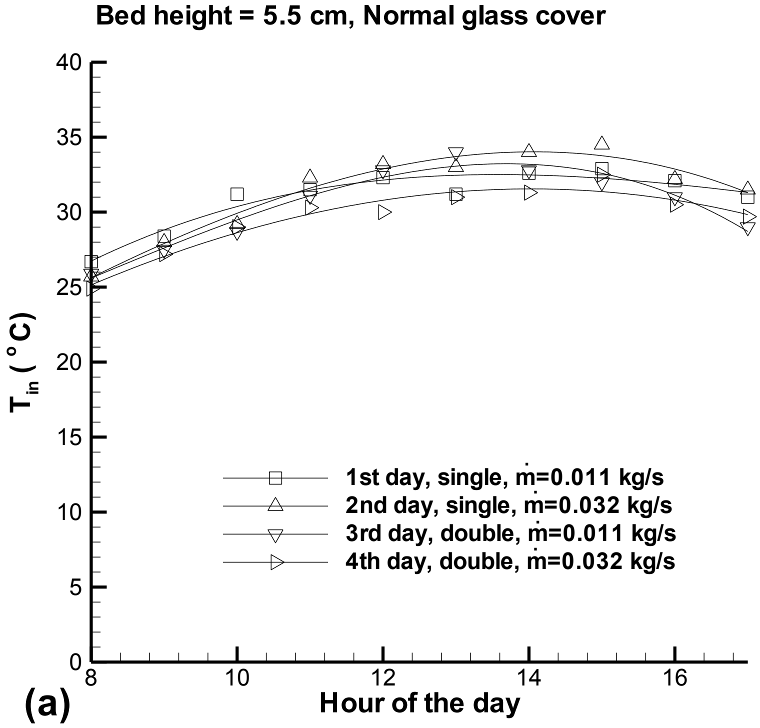


Figure 4.31(a): Inlet temperature versus time of the day for single and double pass solar air collectors with normal glass cover and bed height of 5.5 cm

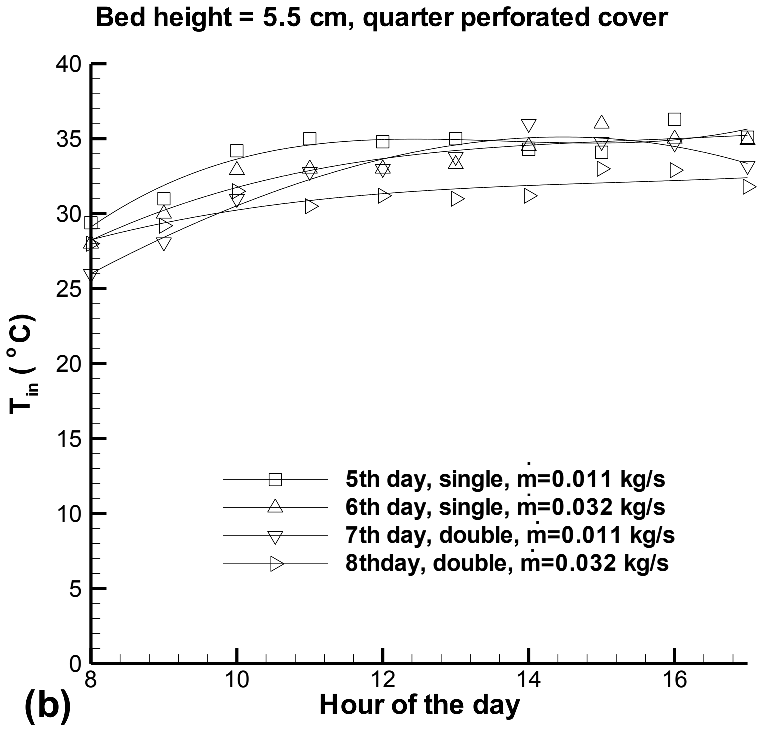


Figure 4.31(b): Inlet temperature versus time of the day for single and double pass solar air collectors with quarter perforated cover and bed height of 5.5 cm

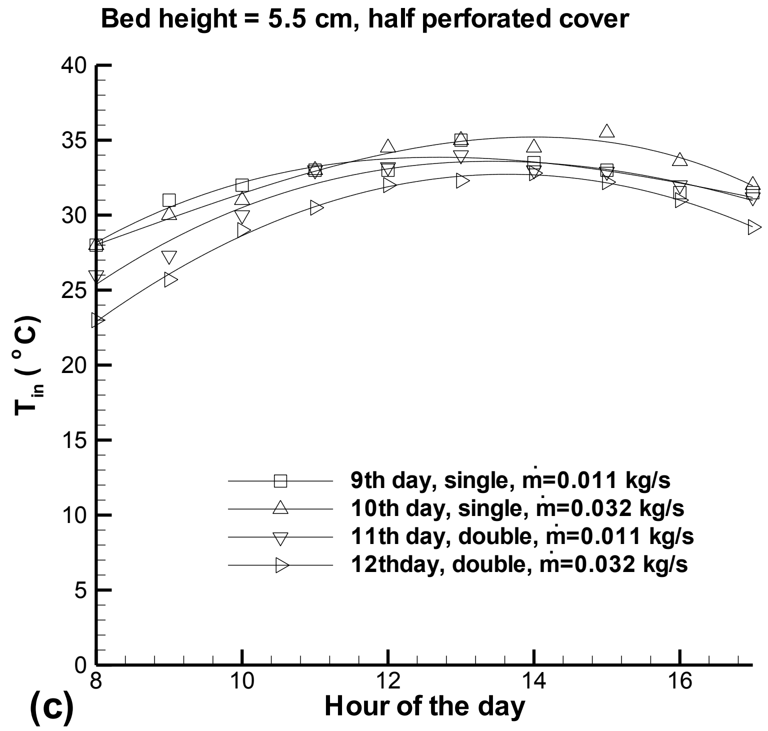


Figure 4.31(c): Inlet temperature versus time of the day for single and double pass solar air collectors with half perforated cover and bed height of 5.5 cm

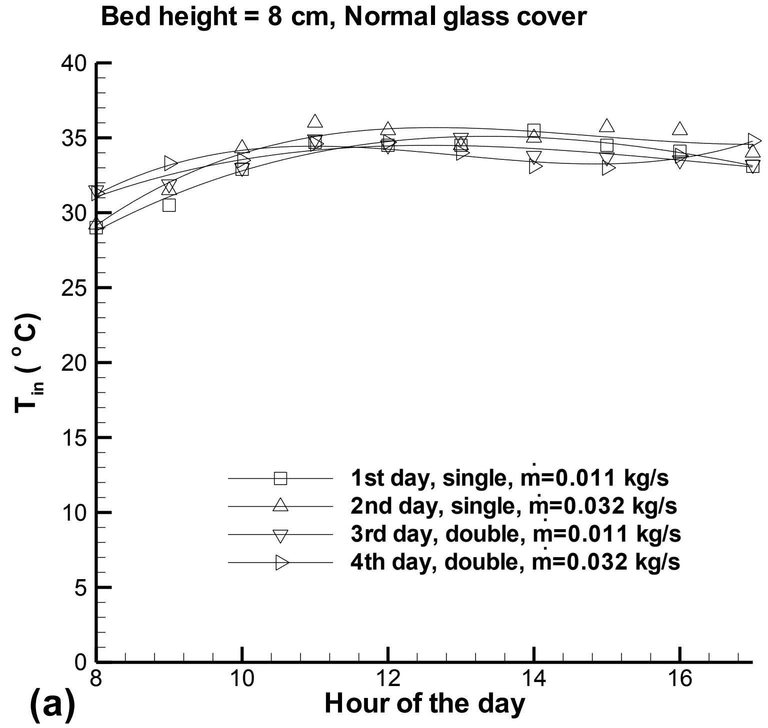


Figure 4.32(a): Inlet temperature versus time of the day for single and double pass solar air collectors with normal glass cover and bed height of 8 cm

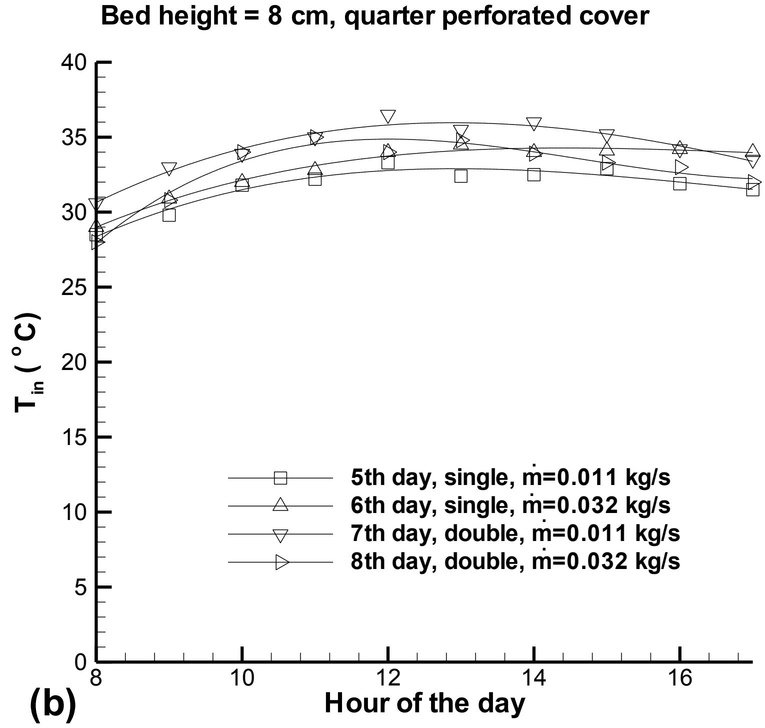


Figure 4.32(b): Inlet temperature versus time of the day for single and double pass solar air collectors with quarter perforated cover and bed height of 8 cm

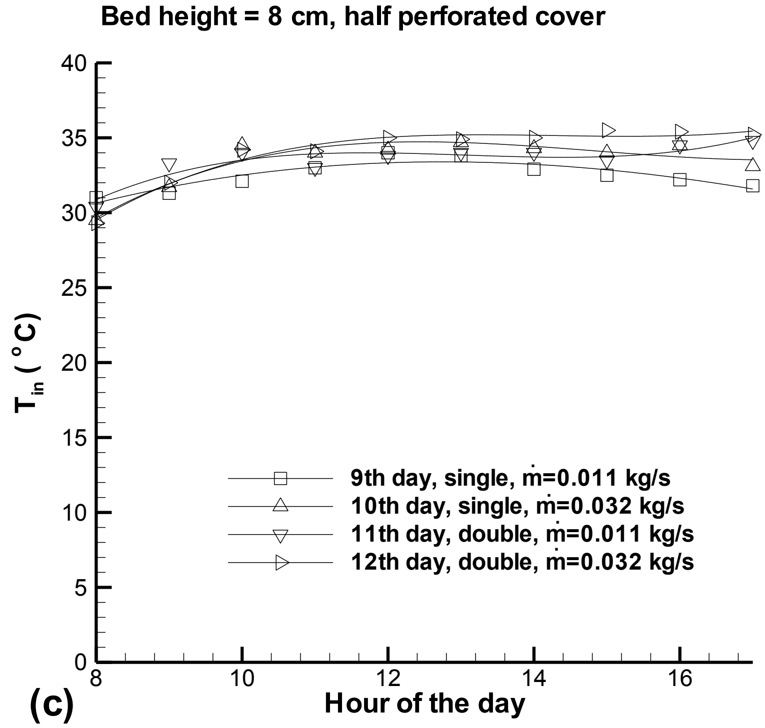


Figure 4.32(c): Inlet temperature versus time of the day for single and double pass solar air collectors with half perforated cover and bed height of 8 cm

The thermal efficiency versus time of the day for the single and double pass air heaters with different bed heights of 3 cm, 5.5 cm and 8 cm and various covers are shown in Figs. 4.33 - 4.38. The solar collector with various configurations is tested at two mass flow rates of 0.011 kg/s and 0.032 kg/s. As it is stated in the earlier results, in all the tests as the air mass flow rate increases the thermal efficiency also increases.

The average efficiency of single pass solar air heater with normal glass cover and bed height of 3, 5.5 and 8 cm are, 49.36%, 41.07% and 37.99%, respectively and, these values for the double pass solar air heater with same cover and bed heights are 51.70%, 48.53% and 46.28%, respectively at mass flow rate of 0.032 kg/s . At the same mass flow rate, the mean thermal efficiency of solar air heater with quarter perforated cover and bed height of 3, 5.5 and 8 cm are, 46.40%, 49.49% and 46.78%, respectively for the single pass and 54.76%, 51.33% and 49.23%, respectively for the double pass collector. For the single pass collector with half perforated cover and different bed heights of 3, 5.5 and 8 cm, the average thermal efficiency at $\dot{m}$=0.032 kg/s are 46.72%, 48.59% and 44.36%, respectively and the ones for double pass solar collector with the same cover and at the same $\dot{m}$ are 51.17%, 48.71% and 50%, at duct height of 3, 5.5 and 8 cm, respectively.

In general, the heat transfer coefficient decreases as the duct height increases. At the same mass flow rate, the velocity of air inside the duct increases by decreasing the cross sectional area of the duct, and as a result, heat transfer coefficient between the air and absorber increases. Therefore, the duct height has considerable effect on the performance of the solar air heater. Some researchers (Sopian, K. et al. (1999) and

Sopian, K. et al. (2009)) examined the effect of changes in the channel depth on the efficiency of the solar air heaters. According to their results, the optimum values for the upper and lower channels are 3.5 cm and 7 cm, respectively. However, according to El-sebaii et al. (2007), the upper and lower air channels should have equal heights to achieve higher temperature output.

The solar collector with bed height of 5.5 cm is tested with normal glass cover, quarter and half perforated covers at two different mass flow rates (0.011 kg/s and 0.032 kg/s). The thermal performances of these solar air collectors during the day are compared with each other and are presented in Fig. 4.39(a and b). The results show that in general the efficiency of the solar air heater with perforated covers is higher compared with the one with normal glass cover at the same mass flow rates. The temperature difference between the inlet and outlet air (ΔT) versus time of the day for the single and double pass solar air heaters with bed height of 5.5 cm and various covers are shown in Fig. 4.41(a and b). The highest ΔTs are obtained from the solar collectors with perforated covers especially for the single pass ones.

Figures 4.40 (a and b) present the thermal efficiency versus time of the day for the solar air collector with bed height of 8 cm and various covers. The obtained results show that most of the time the solar air heater with either quarter or half perforated cover has higher thermal performance than with normal glass cover especially at the highest mass flow rate (0.032 kg/s). Similar results are obtained from ΔT curves (see Fig. 4.42 (a and b)). The maximum temperature difference between the inlet and outlet air for the single pass solar air heater with bed height of 8 cm and quarter, half and normal glass cover are 36.95°C at 13:00h, 37.2°C at 13:00h and 29.25°C at

13:00h, at ṁ of 0.011 kg/s, respectively. These values for double pass solar air collector with the same duct height and quarter, half and normal glass cover are 39.8°C at 13:00h, 43.35 °C at 12:00h and 41.25°C at 13:00h, respectively at same mass flow rate.

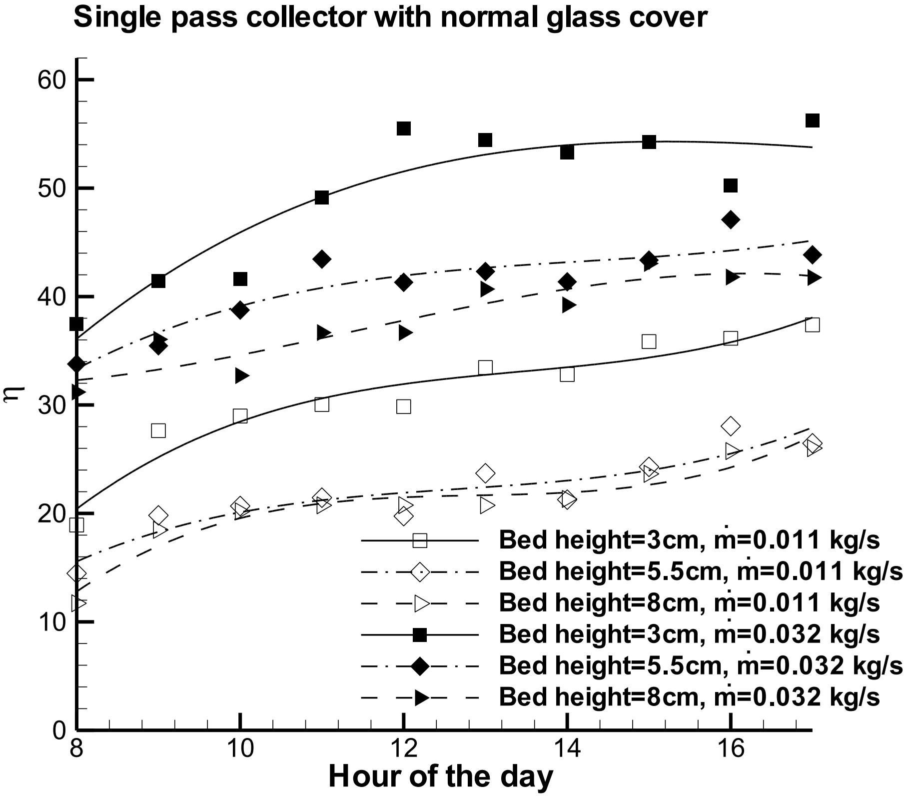


Figure 4.33: Efficiency versus time of the day for single pass solar air collector with different bed heights and normal glass cover

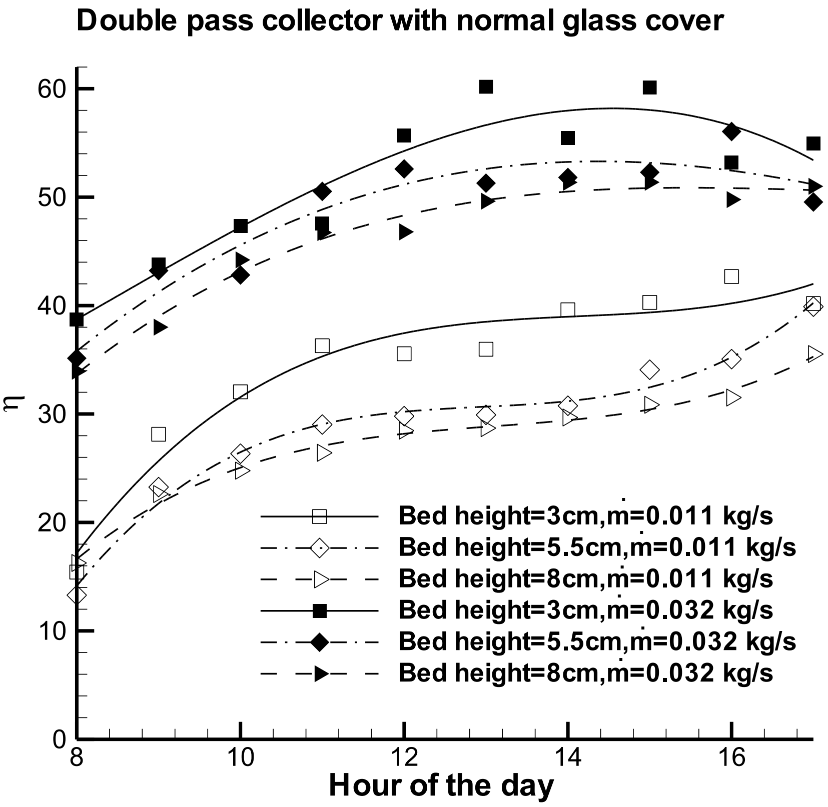


Figure 4.34: Efficiency versus time of the day for double pass solar air collector with different bed heights and normal glass cover

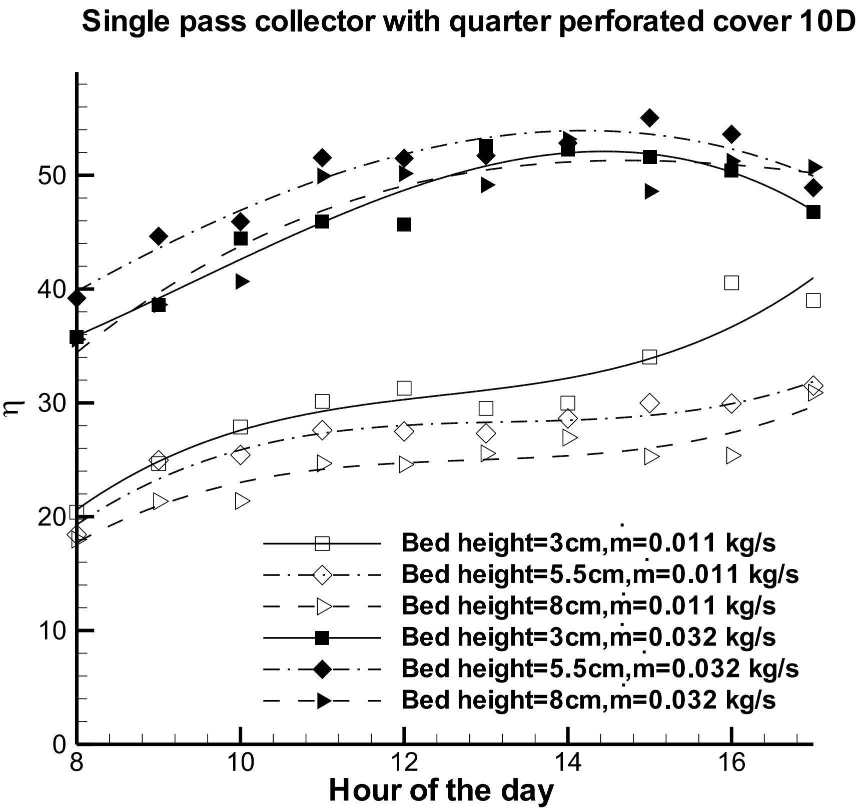


Figure 4.35: Efficiency versus time of the day for single pass solar air collector with different bed heights and quarter perforated cover 10D

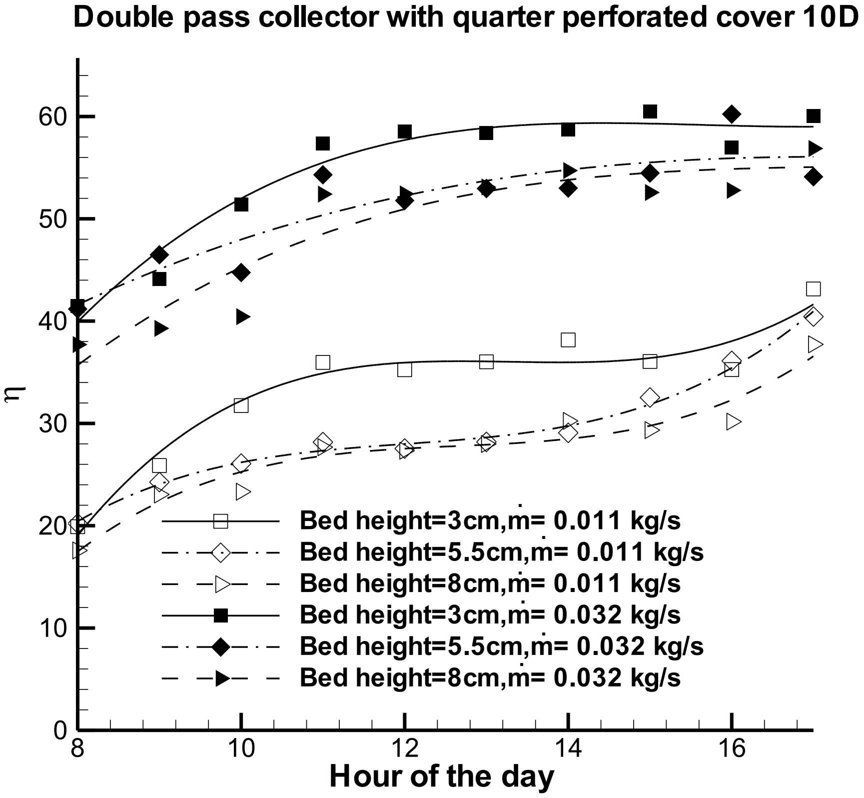


Figure 4.36: Efficiency versus time of the day for double pass solar air collector with different bed heights and quarter perforated cover 10D

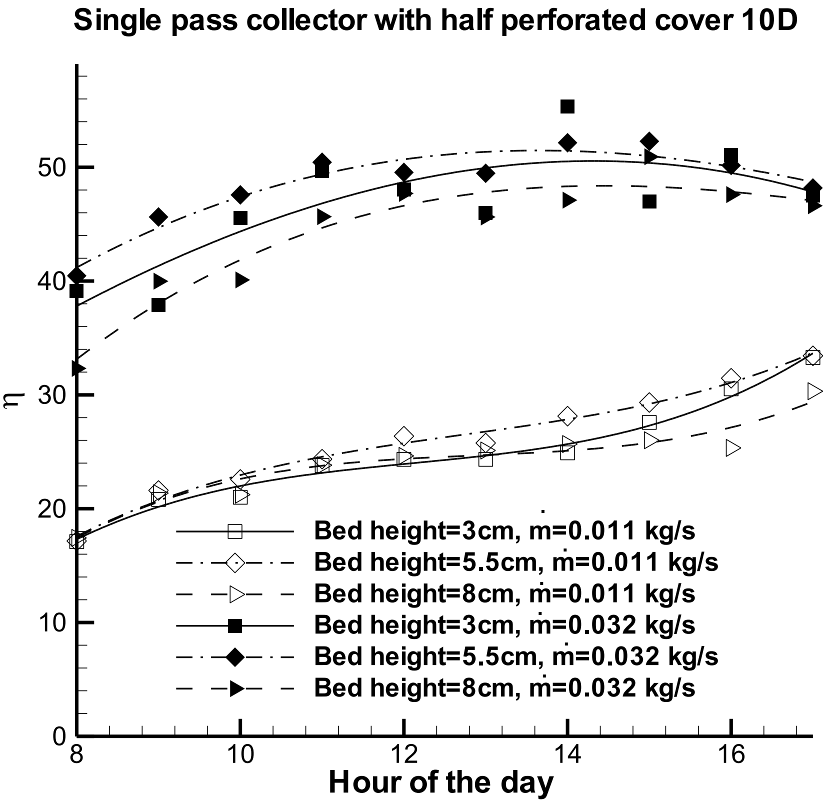


Figure 4.37: Efficiency versus time of the day for single pass solar air collector with different bed heights and half perforated cover 10D

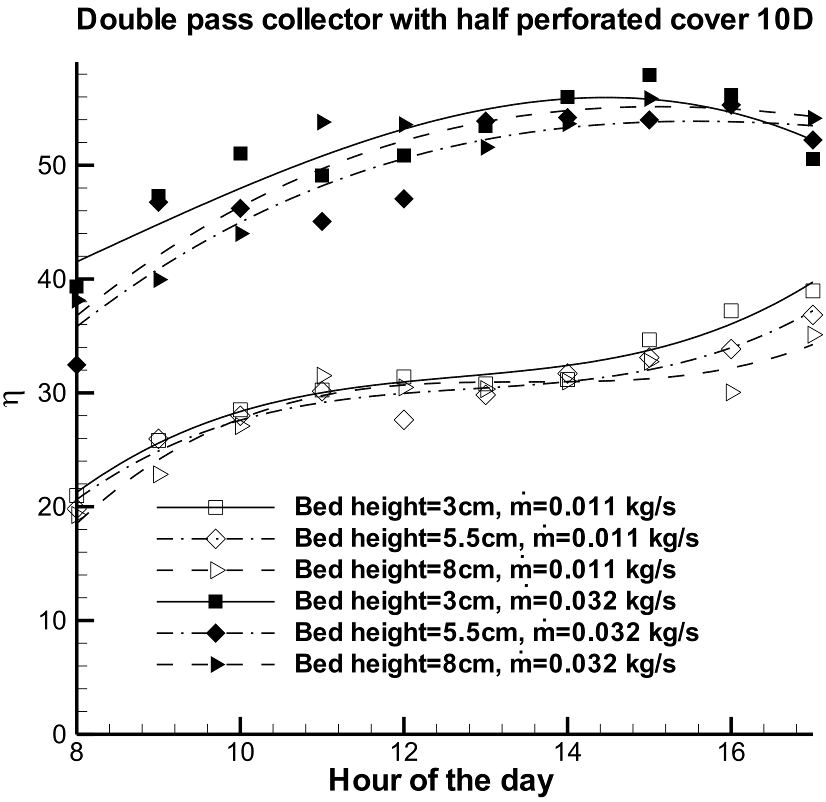


Figure 4.38: Efficiency versus time of the day for double pass solar air collector with different bed heights and half perforated cover 10D

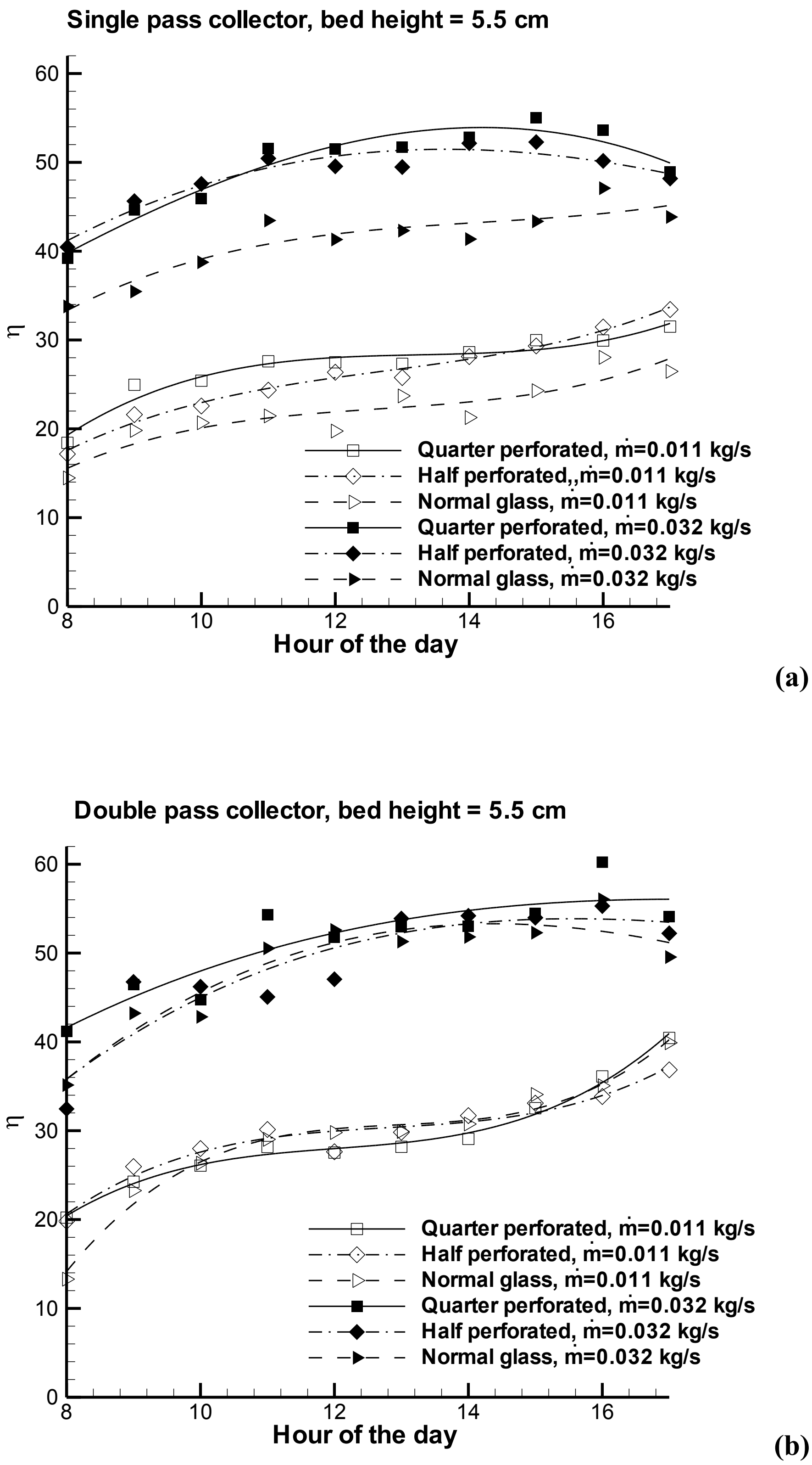
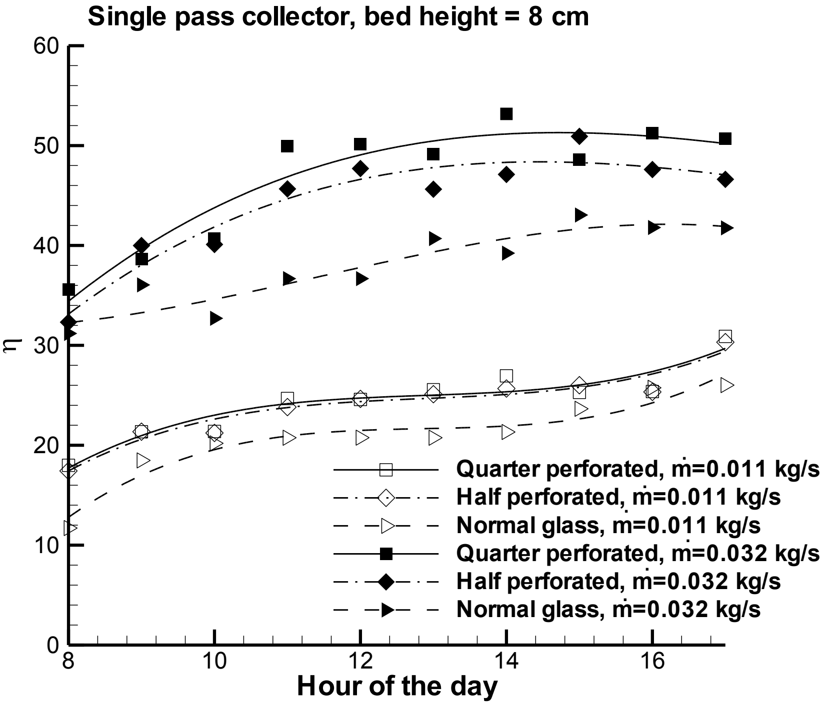
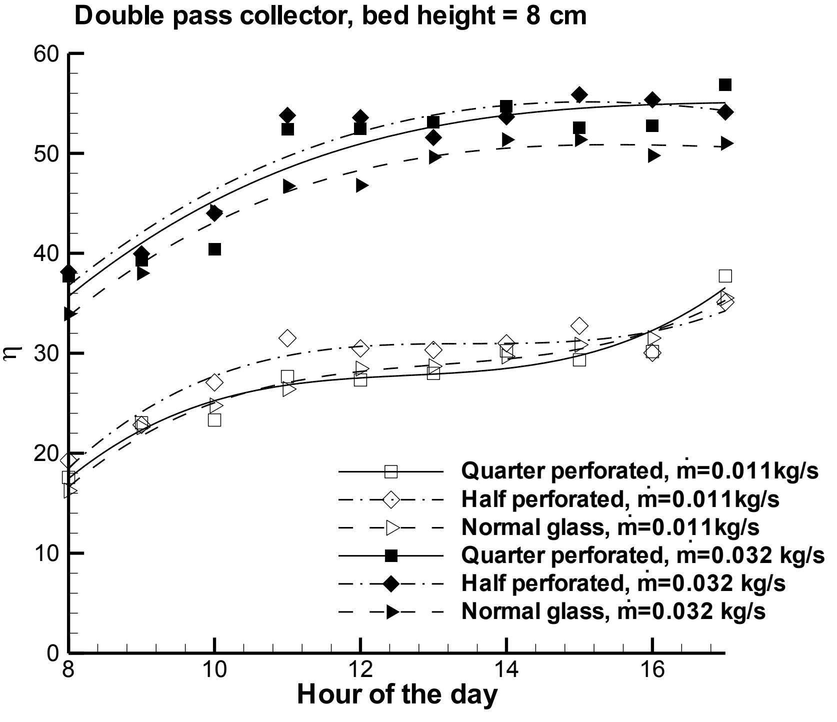


Figure 4.39: Efficiency versus time of the day for, (a) Single pass (b) Double pass solar air collector with various covers and bed height of 5.5 cm



(a)



(b)

Figure 4.40: Efficiency versus time of the day for, (a) Single pass (b) Double pass solar air collector with various covers and bed height of 8 cm

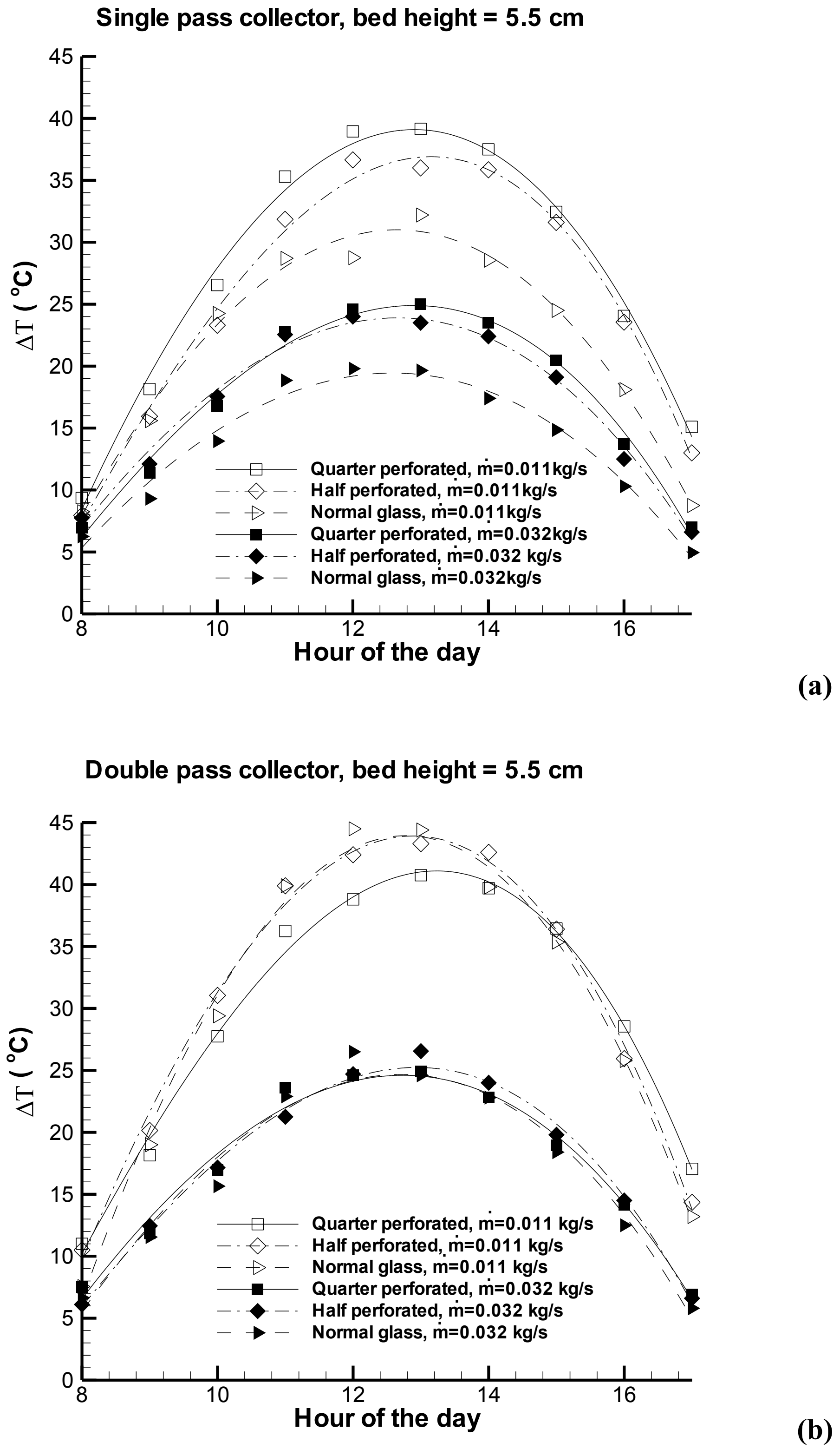
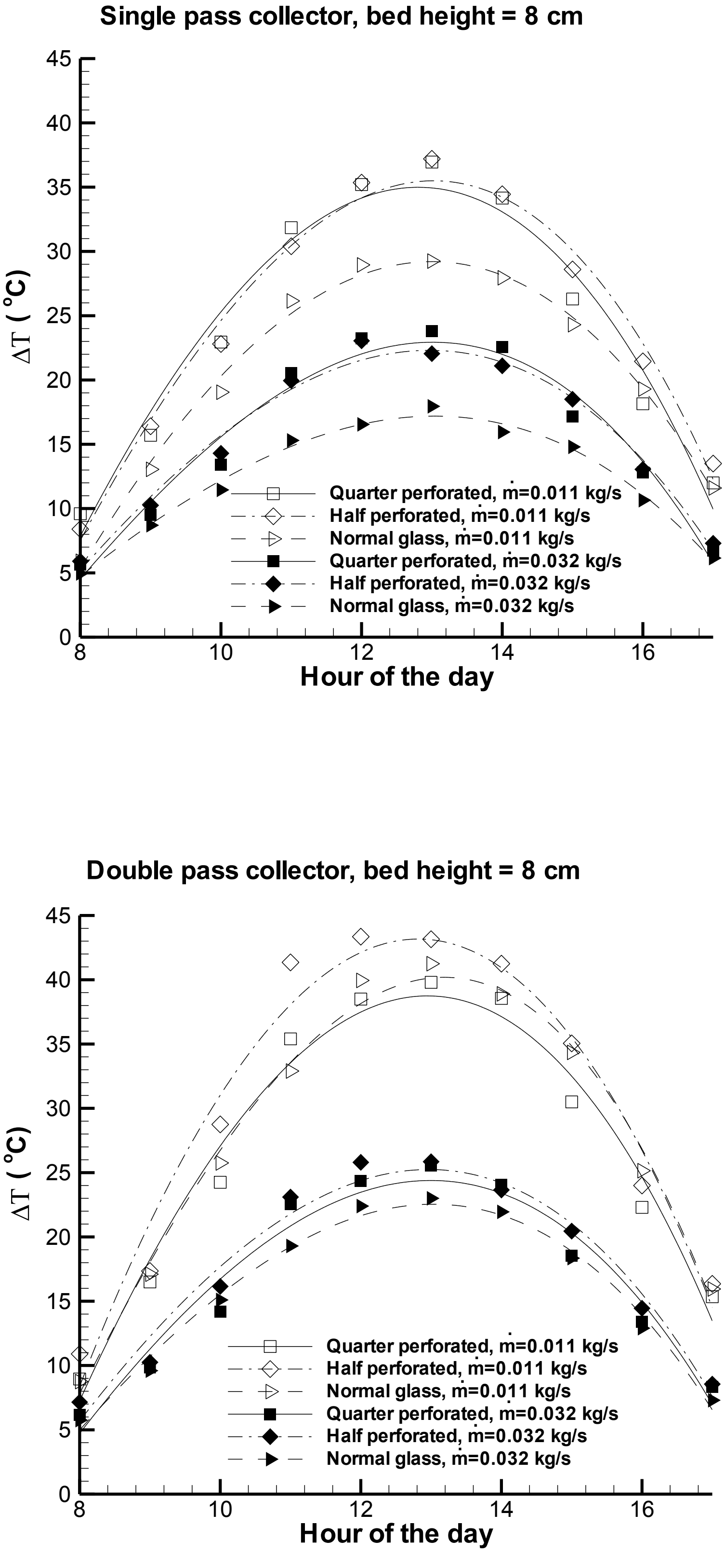


Figure 4.41: Temperature difference versus time of the day for, (a) Single pass (b) Double pass solar air collector with various covers and bed height of 5.5 cm



(a)

(b)

Figure 4.42: Temperature difference versus time of the day for, (a) Single pass (b) Double pass solar air collector with various covers and bed height of 8 cm.

The computed values of pressure drop for the single and double pass solar air heaters with different covers and bed heights (3, 5.5 and 8 cm) plotted against different mass flow rates are shown in Fig. 4.43 (a-c). It is found that increasing the mass flow rate results in higher efficiency but also the pressure drop is increased. In addition, at fixed mass flow rate, decreasing the bed height of the solar air heater results in increasing the system efficiency at the same time the pressure drop increased. Similar results are obtained by Bashria A.A. and Adam N. (2008) and Omojaro, A.P. and Aldabbagh, L.B.Y. (2010).

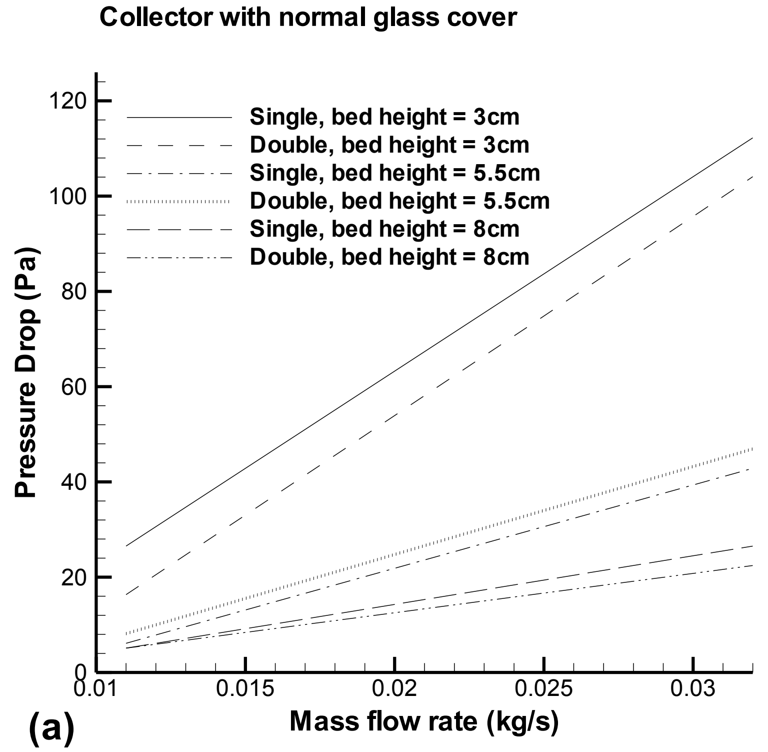


Figure 4.43(a): Pressure drop versus mass flow rate for single and double pass solar air collectors with normal glass cover at various bed heights

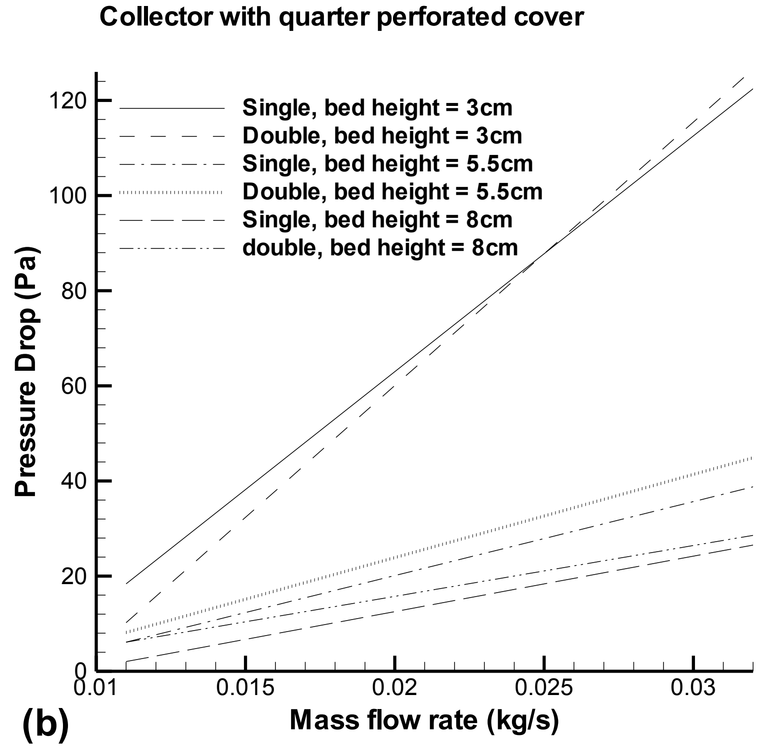


Figure 4.43(b): Pressure drop versus mass flow rate for single and double pass solar air collectors with quarter perforated cover at various bed heights.

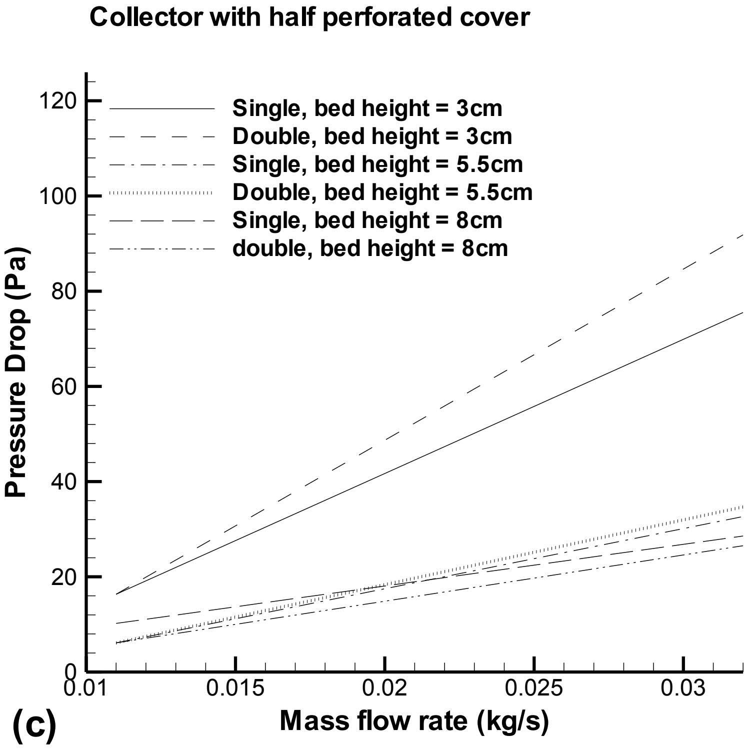


Figure 4.43(c): Pressure drop versus mass flow rate for single and double pass solar air collectors with half perforated cover at various bed heights.

4.4 Discussion of Results

Several configurations of solar air heater were tested. The aim of the study is to reduce the heat losses from the cover of collector to increase the operating temperature and therefore collector efficiency. Porous media was employed to increase area for heat transfer from the absorber to the airstream.

It is found that placing steel wire mesh layers in the solar air heater with small bed height (3 cm) instead of an absorber plate increased the thermal performance of the solar collector compared with other studies available in the literature. In the present study the single pass solar air heater with fourteen mesh layers, normal glass cover and bed height of 3 cm shows 51.08% maximum efficiency at $\dot{m} = 0.024$ kg/s while in an experimental work on a single pass solar air heater with fins, seven mesh layers and bed height of 7cm (Omojaro *et. al.*, 2010), the maximum efficiency obtained was 46% at $\dot{m} = 0.025$ kg/s.

The idea of using perforation on absorber plate in unglazed transpired solar air heaters was to minimize radiation and convective losses from the absorber plate. It was believed that the perforation on the cover reduces the heat losses through it. The temperatures of 10D and 20D perforated covers are compared with each other and the results are shown in Figs. 4.11 – 4.14. Obtained results showed that 10D perforated cover has lower temperature than 20D perforated cover during the experiments. Lower temperature means less heat losses to the environment and higher thermal performance of the solar air heater.

It is found that the solar air heater with quarter perforated cover has higher thermal efficiency compared with half perforated cover in most of the experiments. The reason is the mixing of the air flows entering to the solar air heater through the holes with various positions on the cover. In case of half perforated covers, air enters to the collector through the upper holes and absorbs heat from the mesh layers as it propagates inside the collector. At the time the hot air reaches to the holes close to the middle of the collector, the ambient air with lower temperature enters to the collector through the middle holes on the cover and mixes with the hot air which comes from the top side of bed. As a result of mixing, the air temperature decreases and therefore the thermal performance decreases.

Mean values of efficiency for the solar air heater with different normal and perforated covers and various bed heights are presented in Table 4.4. Obtained results showed that the solar collector with 8 cm bed height has always lower performance than the collector with 3 cm bed height. Generally increasing the bed height decreases the thermal efficiency of collector. A similar result was found by Omojaro *et. al*. (2010). At the same mass flow rate, the velocity of air inside the duct increases by decreasing the cross sectional area of the duct, as a result, heat transfer coefficient between the air and absorber increases.

In Fig. 4.44 the average thermal efficiency obtained from single pass solar air heater with 10D quarter perforated cover and bed height of 3 cm is compared with the results from other research studies which used; fins on wire mesh layers (Omojaro and Aldabbagh, 2010), cross-corrugated absorber plate (Wenxian *et al.,* 2006) and compound parabolic concentrator solar air heater (Tchinda Rene, 2008). Comparison of the results show that the average efficiency of the proposed solar air heater with perforated cover is higher compared with the solar collectors with fins and baffles.

Table 4.4: Average thermal efficiency of solar air heater at mass flow rate of 0.032 kg/s with different covers and bed heights

	Bed height (cm)			
		3	**5.5**	**8**
Single pass solar air heater	**Normal glass cover**	49.36%	41.07%	37.99%
	Quarter Perforated cover	46.40%	49.49%	46.78%
	Half Perforated cover	46.72%	48.59%	44.36%
Double pass solar air heater				
	Normal glass cover	51.70%	48.53%	46.28%
	Quarter Perforated cover	54.76%	51.33%	49.23%
	Half Perforated cover	51.17%	48.71%	50%

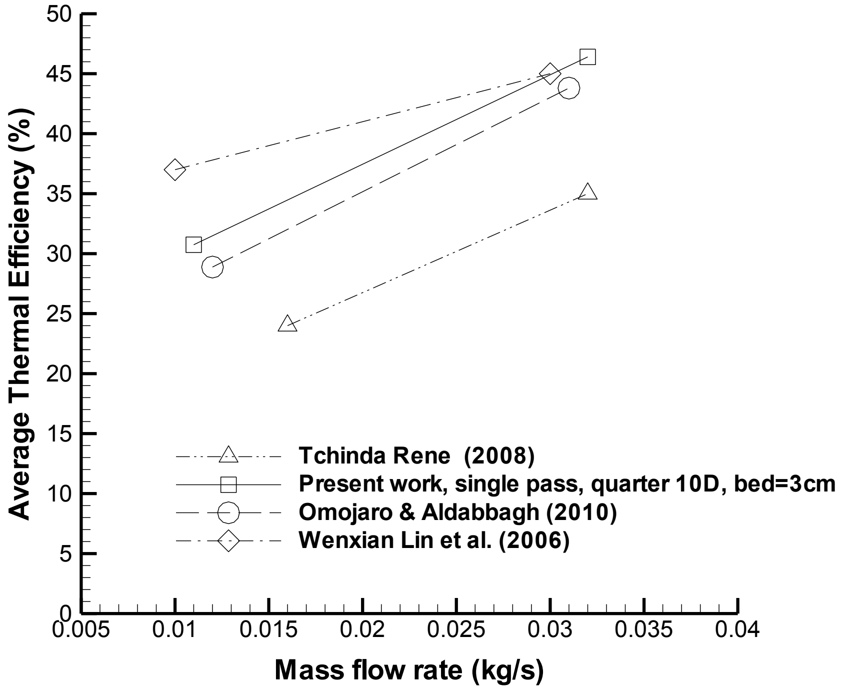


Figure 4.44: Average thermal efficiency versus mass flow rate, comparison between the present study and other published works

Chapter 5

CONCLUSION

The performances of four different configurations of the solar air heater are experimentally investigated in the city of Famagusta in North Cyprus. Two configurations include testing the single and double pass solar air heaters with the packed bed and normal glass and Plexiglas covers. The other two set-ups of the system include testing the single and double pass solar air heaters with the packed bed and partly perforated covers. The distance between the hole centers is selected to be 10D (3cm) and 20D (6cm), where D is the hole diameter (D = 0.3cm). Since the absorber plate is replaced by wire mesh layers, the cost of the solar air heater is reduced significantly. The collector is also tested with various bed heights of 3, 5.5 and 8 cm.

The results show that with increasing air mass flow rate, temperature difference between inlet and outlet air decreases but thermal efficiency increases. At the minimum mass flow rate of 0.011 kg/s, the maximum temperature differences obtained from single and double pass air heater with normal glass cover were 45.8°C and 53°C, respectively. The temperature differences of single and double pass solar collectors with either quarter or half perforated covers at low mass flow rate ($\dot{m}$=0.011 kg/s) are higher than the ones with normal Plexiglas cover. The maximum temperature difference was 52.5°C for the double pass collector with quarter perforated cover 10D at ṁ = 0.011 kg/s. For the same mass flow rate the maximum ΔT obtained for the counter flow collector with normal Plexiglas cover was 34.8°C.

It is found that increasing the mass flow rate results in higher efficiency but also the pressure drop increases. In addition, at fixed mass flow rate, decreasing the bed height of the solar air heater results in increasing the system efficiency at the same time the pressure drop increases.

The average efficiency for the single and double pass solar air heaters with different normal and perforated covers at mass flow rate of 0.032 kg/s are presented in Table 5.1. According to the results, double solar air heater with 10D quarter perforated cover has the highest performance compared with the other set-ups. The solar collector with quarter or half perforated cover has better performance compared with the one with normal Plexiglas cover due to the perforations on the covers which reduce the heat losses from the cover to the environment.

Comparison of the results obtained from solar air heater with different bed heights of 3, 5.5 and 8cm show that the thermal efficiency of solar collector with bed height of 3 cm is higher compared with the one with bed height of 8 cm. The thermal performances of solar air heater with bed heights of 5.5 and 8 cm are close to each other. It should be noted that for this study having uncertainty of 2.7% in efficiency values and due to the close range between the obtained results from solar air heater with bed heights of 5.5 and 8 cm, the improvement in efficiency is not certain.

Comparison of the results obtained from solar air heater with different normal and perforated covers show that the highest average efficiency (54.76% at ṁ = 0.032

kg/s) was obtained from double pass solar collector with 10D quarter perforated cover. The mean efficiencies of the double pass solar air heater with 10D and 20D half perforated covers are less than the one with 10D and 20D quarter perforated covers. The average efficiencies obtained from single pass solar air heater with 10D and 20D quarter perforated covers at mass flow rate of 0.032 kg/s are very close to each other and due to the uncertainty of 2.7% in efficiency values the improvements in collector efficiency are not certain. For single pass collector with 10D and 20D half perforated covers the mean efficiencies are also close to each other and very similar to the efficiency values obtained from single pass collector with normal Plexiglas cover.

The present experimental work suggests that the performance of a conventional solar air heater can be improved with packed mesh instead of an absorber sheet, perforated cover and small bed height (3cm). To best of our knowledge, the proposed model for the solar air heater is tested for the very first time and it is found that it performs with a higher efficiency compared with other studies available in the literature.

For future studies, it is suggested to perform some experiments on a solar air heater with covers that have various hole numbers on them. The number, arrangement and diameter of the holes can be changed to see their effect on the collector efficiency. Also, different material with various geometries can be used instead of an absorber plate.

Table 5.1: Average thermal efficiency of solar air heater with different covers and bed height of 3 cm

Solar air heater	Mass flow rate (kg/s)	Average efficiency (%)	Cover
Single pass	0.032 kg/s	47.67	Normal Plexiglas
Double pass	0.032 kg/s	50.92	Normal Plexiglas
Single pass	0.032 kg/s	46.54	Quarter perforated 20D
Single pass	0.032 kg/s	46.40	Quarter perforated 10D
Double pass	0.032 kg/s	54.76	Quarter perforated 10D
Double pass	0.032 kg/s	51.38	Quarter perforated 20D
Single pass	0.032 kg/s	47.86	Half perforated 20D
Single pass	0.032 kg/s	46.72	Half perforated 10D
Double pass	0.032 kg/s	48.21	Half perforated 20D
Double pass	0.032 kg/s	51.17	Half perforated 10D
Single pass	0.032 kg/s	49.36	Normal glass
Double pass	0.032 kg/s	51.70	Normal glass

REFERENCES

Aldabbagh, L.B.Y., Egelioglu, F., Ilkan, M. (2010). Single and double pass solar air heaters with wire mesh as packing bed. Energy 35, 3783-3787.

Bashria, A. A. Yousef, Adam, N. Mariah. (2008). Performance analysis of single and double passes flat plate collector with and without porous media. Strojn´icky Casopis 58, 275-290.

Bansal, N.K., Uhlemann R., Boettcher A. (1983). Plastic Solar Air Heaters of Novel Design, In: The internal report of Research Centre, 52425 Juelich, Germany.

Donggen Peng, Xiaosong Zhang, Hua Dong, Kun Lv. (2010). Performance study of a novel solar air collector. Applied Thermal Engineering 30, 2594-260.

Duffie, John A., Beckman, William A. (2013). Solar engineering of thermal processes, fourth edition. John Wiley & Sons, Inc. Hoboken, New Jersey.

Ekechukwua, O.V., Norton, B. (1999). Review of solar-energy drying systems III: low temperature air-heating solar collectors for crop drying applications. Energy Conversion & Management 40, 657-667.

El-khawajah, M.F., Aldabbagh, L.B.Y., Egelioglu, F. (2011). The effect of using transverse fins on a double pass flow solar air heater using wire mesh as an absorber. Solar Energy 85, 1479-1487.

El-Sebaii, A.A., Aboul-Enein, S., Ramadan, M.R.I., El-Bialy, E. (2007). Year round performance of double pass solar air heater with packed bed. Energy Conversion and Management 48, 990-1003.

Esen, H. (2008). Experimental energy and exergy analysis of a double-flow solar air heater having different obstacles on absorber plates. Building and Environment 43, 1046-1054.

Ho-Ming Yeh, Chii-Dong Ho, Chi-Yen Lin (2000). Effect of collector aspect ratio on the collector efficiency of upward type baffled solar air heater. Energy Conversion & Management 41, 971-981.

Holman, J.P. (1989). Experimental methods for engineers, seventh edition. McGraw-Hill, New York.

Karmare, S.V., Tikekar, A.N. (2009). Experimental investigation of optimum thermohydraulic performance of solar air heaters with metal rib grits roughness. Solar Energy 83,6-13.

Kolb, A., Winter, E.R.F., Viskanta, R. (1999). Experimental studies on a solar air collector with metal matrix absorber. Solar Energy 65, 91–98.

Martin, S.R.L., Fjeld, G.J. (1975). Experimental performance of three solar collectors. Energy 7, 345-349.

Mittal, M.K., Varshney, L. (2006). Optimal thermohydraulic performance of a wire mesh packed solar air heater. Solar Energy 80, 1112–1120.

Mohamad, A.A. (1997). High efficiency solar air heater. Solar Energy 60, 71-76.

Omojaro, A.P., Aldabbagh, L.B.Y. (2010). Experimental performance of single and double pas solar air heater with fins and steel wire mesh as absorber. Applied Energy 87, 3759-3765.

Ozgen, F., Esen, M., Esen, H. (2009). Experimental investigation of thermal performance of a double-flow solar air heater having aluminium cans. Renewable Energy 34, 2391-2398.

Paisarn, N. (2005). Effect of porous media on the performance of the double-pass flat plate solar air heater. International Communications in Heat and Mass Transfer 32, 140-150.

Paisarn, N. (2005). On the performance and entropy generation of the double-pass solar air heater with longitudinal fins. Renewable Energy 30, 1345-1357.

Prasad, S.B., Saini, J.S., Singh, K.M. (2009). Investigation of heat transfer and friction characteristics of packed bed solar air heater using wire mesh as packing material. Solar Energy 83, 773-783.

Qenawy, A.M., Mohamad, A.A. (2007). Analysis of high efficiency solar air heater for cold climates. 2nd Canadian Solar Buildings Conference, Calgary, Canada, June 10-14.

Ramadan, M.R.I., EL-Sebaii, A.A., Aboul-Enein, S., El-Bialy, E. (2007). Thermal performance of a packed bed double-pass solar air heater. Energy 32, 1524-1535.

Rjendra Karwa, Maheshwari, B.K., Nitin Karwa. (2005). Experimental study of heat transfer enhancement in an asymmetrically heated rectangular duct with perforated baffles. International Communications in Heat and mass Transfer 32, 275-284.

Tchinda Rene. (2008) Thermal behaviour of solar air heater with compund parabolic concentrator. Energy conversion and Management. 49, 529-540.

Sebastien Cordeau, Suzelle Barrington (2011). Performance of unglazed solar ventilation air pre-heaters for boiler barns. Solar Energy 85, 1418-1429.

Sopian, K., Supranto, W.R.W., Daud, M.Y., Othman, B.Y. (1999). Thermal performance of the double-pass solar collector with and without porous media. Renewable Energy 18, 557-564.

Sopian, K., Alghoul, M.A., Alfegi Ebrahim, M., Sulaiman, M.Y., Musa, E.A. (2009). Evaluation of thermal efficiency of double-pass solar collector with porous-nonporous media. Renewable Energy 34, 640-645.

Tian, J., Kim, T., Lu, T.J., Hodson, H.P., Queheillalt, D.T., Sypeck, D.J., et al. (2004). The effects of topology upon fluid flow and heat transfer within cellular copper structures. International Journal of Heat and Mass Transfer 47, 3171-3186.

T.R.N.C. (Turkish Republic of Northern Cyprus), ministry of public works and transport, department of meteorology. http://kktcmeteor.org/.

Tyagia, V.V., Panwarb, N.L., Rahima, N.A., Richa Kothari (2012). Review on solar air heating system with and without thermal energy storage system. Renewable and Sustainable Energy Reviews 16, 2289– 2303.

Wenxian Lin, Wenfeng Gao, Tao Liu (2006). A parametric study on the thermal performance of cross-corrugated solar air collectors. Applied Thermal Engineering 26, 1043–1053.

Yeh, H.M., Ho, C.D., Hou, J.Z. (2002). Collector efficiency of double-flow solar air heaters with fins attached. Energy 27, 715-727.