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THEORETICAL AND EXPERIMENTAL INVESTIGATION OF PERFORATED SOLAR AIR COLLECTOR COUPLED TO A CAPILLARY RADIANT HEATING SYSTEM

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ABSTRACT

The unglazed transpired solar collector uses the solar energy to preheat ventilation air for buildings and agricultural applications. The thermal performance of transpired collector is depending on solar radiation significantly. This study reports on the influence of capillary heating system which is using as a supplemantary heating system for non solar radiaton conditions. A theoretical and experimental analysis were carried out regarding perforated solar air collectors which is coupled to a capillary heating system. Heat transfer effectiveness between capillary tubes and solar collector is investigated for different conditions such as mass flow rates, inlet temperatures.

INTRODUCTION

Perforated Solar Air Heating collectors are the most widely used collectors which supply tempered ventilation air to reduce the total heating load for building ventilation and heating. Perforated air collector coupled to a capillary radiant heating system is a new type of solar air collector which provides continuously hot air by using a supplementary heat source.

John Hollick first developed transpired collector that was used for heating outside air directly [1]. Research and investigation into using perforated solar air collector for solar heating systems first appears in 1990. The basic heat loss theory for perforated solar air collector was presented by Kutscher and Christensen [2]. Kutscher used the derived equations to develop a predictive model for thermal performance [3]. Van Decker investigated heat exchange effectiveness more thoroughly for three dimensional flow [4]. Van Decker and Hollands and Van Decker extended the correlation for the effectiveness to no-wind conditions circular holes on a square or triangular pitch [5,6]. Gunnewiek extended their previous study to include the effects of wind on flow inside the plenum [7]. Leon and Kumar developed a model used for drying [8]. Eryener has designed a new perforated solar air collector coupled to capillary radiant heat exchanger which is used for heating and cooling [9].

The objective of the present study is to investigate heat transfer characteristic and thermal behavior between solar air collector and capillary heating system.

NOMENCLATURE

A	[m^2]	collector area
C_p	[J/kgK]	specific heat capacity
D	[m]	diameter
h	[W/m^{2}K]	convective heat transfer coefficient
I_T	[W/m^2]	solar radiation incident on the collector
m	[kg/s]	mass flux
N		the number of the tube
N_T		the number of capillary tube rows that are parallel to the air flow direction
Re_D		Reynolds number
Q	[W]	heat transfer
S_T	[m]	the distance between two capillary tubes' center lines
T	[K]	temperature
ΔT_{lm}	[K]	the logarithmic mean temperature difference
u	[m/s]	the velocity

Special characters

α		solar absorptance of the collector surface
ε_{HX}		heat exchange effectiveness
γ	[m^2/s]	the kinematic viscosity
ρ	[kg/m^3]	density

Subscripts

abp	absorber plate
$air\ inlet$	inlet property of the air
bp	back plate
$conv.abp\sim pa$	the convective heat transfer from absorber plate to plenum air
$conv.bp\sim sur$	the convective heat transfer from back plate to the surrounding
$conv.CT\sim pa$	the convective heat transfer from capillary tube to plenum air
$conv.pa\sim bp$	the convective heat transfer from plenum air to back plate
inlet	inlet
max	maximum
out	outlet
pa	the plenum air
plen, outlet	outlet property of plenum
rad. abp~bp	the radiation heat transfer from absorber plate to back plate
$rad.abp\sim amb$	the radiation heat transfer from absorber plate to the ambient
$rad.bp\sim sur$	the radiation heat transfer from back plate to the surrounding
$rad.CT\sim abp$	the radiation heat transfer from capillary tube to absorber plate
$rad.CT\sim bp$	the radiation heat transfer from capillary tube to back plate
w	water
∞	the property of the fluid

Capillary heating system is a conventional method for room radiant heating, however there is less information regarding heat transfer characteristic and thermal behavior of capillary heating system in the relevant literature. In this regard this study gives some additional information for heat transfer mechanism of capillary tubes.

The first published papers describing capillary tube research appeared in the 1940's. Two key papers published in that time period were those written by R. H. Swart and L. A. Staebler [10, 11]. Swart was the first to describe the thermodynamic behavior of refrigerants in a capillary tube. Steabler discussed the effects of different combination of capillary tube lengths and diameters on refrigerant flow and formulated a table for selecting capillary tube geometries for various operating conditions. Hopkins describes two models which can be used to determine optimum sizes for capillary tube [12]. Whitesel proposes a model that assumes adiabatic flow and saturated inlet conditions [13]. Cooper described two phase flow visualization [14]. Mikol performed significant work in the areas of flow visualization and friction factor determination [15]. Erth created two computer codes for sizing capillary tubes [16]. Goldstein published a model which can accommodate saturated or sub cooled inlet conditions, and adiabatic or non-adiabatic operation [17]. Sweedyk used profilometer measurements to show the variability in wall roughness inherent in capillary tubes [18]. Pate presents a model similar to that of Goldstein [19].

In this study, theoretical and experimental analyses were carried out regarding perforated solar air collectors which is coupled to a capillary heating system. The capillary heating system is designed as a supplementary heating system for the conditions of non solar radiaton. The required heating energy of the capillary system could be obtained by any conventional heating system such as boiler, heat pump, solar water heating etc. In the cases of a lack of solar radiation, the perforated collector heats to air insufficiently, thus the conventional heating system supplies hot water to heat cold outside air which enters in the plenum of the perforated collector. The main advantage of using a capillary heating system is that supplementary heating system requiries a low water temperature, because of the larger heat transfer area in the plenum, and the heat exchange effectiveness would be higher in comparison to use a classical heat exchanger as a supplementary heating system.

Heat transfer mechanism between capillary tubes and solar collector air flow is investigated for different conditions such as the air flow of collector and mass flux of capillary tube system, inlet temperatures.

Additionally, theoretical analysis based on heat balance equations is testified to agree well with experimental results; theoretical analysis is carried out by using a FEA Software. Experiments show that there is a high effectiveness between capillary tubes and solar air heating which depends on mass flux and inlet temperatures. It is found that it is possible to heat air for low hot water temperatures and mass flux. Additionally, experimental results are used for developing heat transfer correlations between tubes and air flow by using regression analysis.

CONFIGURATION OF TRANSPIRED SOLAR COLLECTOR COUPLED TO CAPILLARY RADIANT HEATING SYSTEM

The perforated solar air collector has a perforated plate which has low emissivity and high absorption. The plate is made of special aluminum alloy. There are 2500 holes which are 0.8 mm diameter on the absorber plate per square meter. The absorber plate is mounted on the wall with a distance of 10 cm- 30 cm (This distance is 10 cm in this study). The capillary tube system is a heating system for integration into construction elements such as flooring, walls or ceiling. The tube diameters of a capillary heating system are significantly small compared to the conventional tube heating systems such as 3-5 mm. Therefore it is called as the capillary tube system or the capillary mats in the relevant literature. The word "capillary" is a misnomer since surface tension is not important in heating application of capillary tubes.

In this study, the capillary tube heat exchanger is mounted on the collector's back plate in the internal volume of the collector. The capillary tubes that are used in this study are made of polypropylene material and the diameters of the capillary tubes are 3 mm. The heat transfer occurs between hot water which is in the capillary tubes and the plenum air. When the fan which is mounted on the top of the back plate runs, the vacuum occurs in the plenum. With the effect of negative pressure the ambient air passes through the plenum air via the holes on the absorber plate. The heat of the absorber plate is transferred to the air while the ambient air passed through the plenum. The heated air moves towards the top of the plenum and then sends to the ventilation duct. Compared to other solar air collectors, one of the most important advantages of the perforated solar air collector coupled to capillary tube heat exchanger is decreasing heat losses during the absorption process. Therefore, to reduce optical losses there is no need for any coating. To effectively utilize solar radiation collector installed on the south wall of the building.

Configuration of solar collector which will be analyzed is given in Figure 1. The collector which is mounted vertical, consists of capillary tube heat exchanger, perforated absorber plate and pack plate. The plenum separates absorber plate from capillary tubes and back plate. While the collector runs, a fan which is mounted on the upper side of back plate, provides the necessary vacuum.

The heat transfer theory of perforated solar air collector is obtained by calculating the total energy balance between the components of perforated collector. Equations are used to calculate the heat transfer via convection and radiation between the collector components.

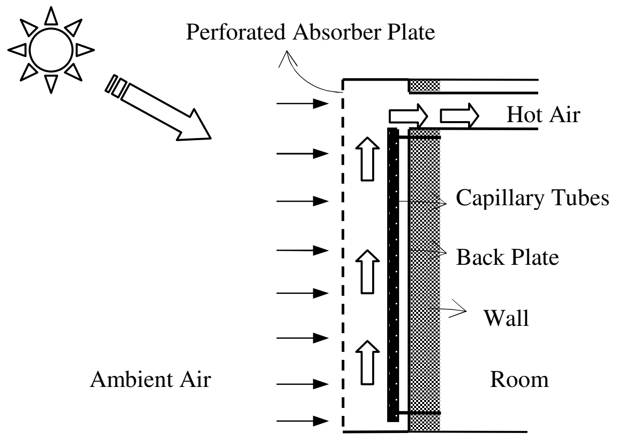


Figure 1 Schematic of the perforated solar air collector

BASIC EQUATIONS OF CAPILLARY TRANSPIRED AIR COLLECTOR

In the analysis, the energy balance equations for four components (absorber panels, capillary tube heat exchanger, air and back plate) was written by calculating the mass flux and heat transfer.

Heat transfer in the collector shown in Figure 2. Energy input to the system is the solar radiation and the heat transfer done by the capillary tube heat exchanger. The net losses in the system are caused by convection and radiation from the absorber plate and back plate.

Absorber plate

$$m_{abp} \times C_{p,abp} \times \left(dT_{abp}/dt\right) = \left(\propto_{abp} \times I_T \times A_{abp}\right) + Q_{rad.CT\sim abp} - \left(Q_{conv.abp\sim pa} + Q_{rad.abp\sim bp} + Q_{rad.abp\sim amb}\right) \tag{1}$$

$Q_{conv.abp\sim pa}$ is the heat gain from the absorber plate to the plenum air . The term of $Q_{rad.abp\sim bp}$ refers to the radiative heat transfer from the absorber plate to the back plate. $Q_{rad.abp\sim amb}$ is the radiative heat loss from the back plate to ambient. $Q_{rad.CT\sim abp}$ is the radiative heat transfer from capillary tube to the absorber plate.

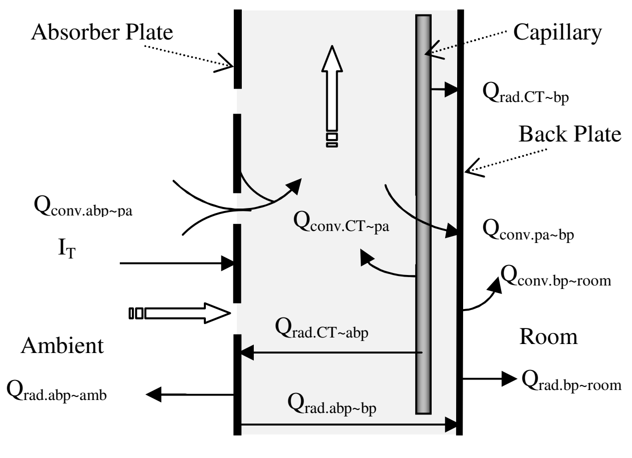


Figure 2 Heat transfer in the perforated solar air collector

Plenum Air

$$\left(m_{pa.out} \times dt\right) \times C_{p,pa} \times \left(dT_{pa.out}/dt\right) = \left(Q_{conv.abp\sim pa} + Q_{conv.CT\sim pa} - Q_{conv.pa\sim bp}\right) \tag{2}$$

$Q_{conv.abp\sim pa}$ gives the convective heat exchange between the back plate and the air flowing through the collector. $Q_{conv.cap\sim pa}$ is the convective heat transfer from the capillary tube to the plenum air. $Q_{conv.pa\sim bp}$ is the convective heat transfer between the plenum air and the back plate.

Capillary Tube

$$\left(m_w \times dt\right) \times C_{p,w} \times \left(dT_w/dt\right) = \left(-Q_{conv.CT\sim pa} - Q_{rad.CT\sim bp} - Q_{rad.CT\sim abp}\right) \tag{3}$$

In Equation 3, $Q_{conv.CT\sim pa}$ gives the convection heat transfer from the capillary tube to the plenum air. $Q_{rad.CT\sim bp}$ is the radiative heat transfer between capillary tube and the back plate. $Q_{rad.CT\sim abp}$ gives the radiative heat transfer from capillary tube to back plate.

Back Plate

$$m_{bp} \times C_{p,bp} \times \left(dT_{bp}/dt\right) = \left(Q_{conv.pa\sim bp} + Q_{rad.abp\sim bp} + Q_{rad.CT\sim bp} - Q_{conv.bp\sim room} - Q_{rad.bp\sim room}\right) \tag{4}$$

$Q_{conv.bp\sim room}$ is the convective heat transfer losses from back plate to the surrounding. $Q_{rad.bp\sim room}$ gives the radiative heat losses from back plate to the surrounding. While the radiation heat transfer losses from the back plate to the ambient is calculated, the ambient temperature is determined from the sky temperature and the ground temperature.

Heat Transfer Equations of Capillary Tubes

In figure 3, the counter-current flow scheme between the water in the vertical capillary tube and plenum air is shown.

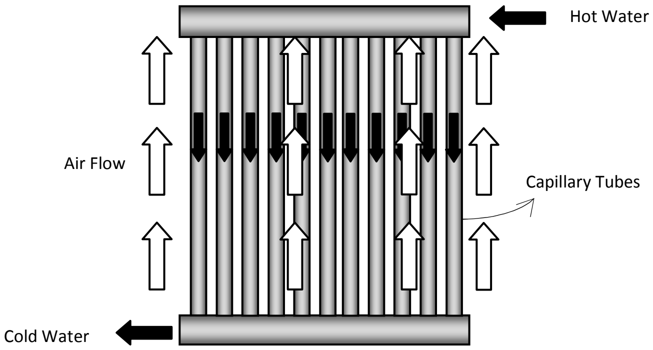


Figure 3 The counter-current flow scheme between the water in the vertical capillary tube and plenum air

The forced convection heat transfer occurs between the capillary tubes and the plenum air. Calculation of heat transfer is performed using the following equations.

The factor affecting the heat transfer coefficient is depends on the air flow conditions. The heat transfer coefficient of capillary tube system is approximately equal to the heat transfer coefficient of a single tube. The average convective heat transfer coefficient is usually used in engineering applications. However, the Reynolds number which is used in the calculation of correlations is defined by the fluid velocity at the maximum value.

$$Re_{D_{max}} = \frac{u_{max} D}{\gamma} \tag{5}$$

For the regular order capillary tubes, the maximum velocity consists in the section that is between the two capillary tubes. According to continuity equation,

$$u_{\infty} S_T = u_{max}(S_T - D) \tag{6}$$

The maximum velocity can be expressed as given below:

$$u_{max} = u_{\infty} \frac{S_T}{S_T - D} \tag{7}$$

Determination of the average convective heat transfer coefficient at the capillary tube is not enough to find the total heat transfer. Because the temperature difference between the capillary tube surface temperature and the water temperature varies along the capillary tubes. Thus ΔT is not constant, the logarithmic mean temperature difference is used in the Newton's cooling law. The logarithmic mean temperature difference is performed the following equations.

$$\Delta T_{lm} = \frac{(T_S - T_{w,inlet}) - (T_S - T_{w,outlet})}{\ln\left(\frac{T_S - T_{w,inlet}}{T_S - T_{w,outlet}}\right)} \tag{8}$$

Where $T_{w,inlet}$ is the water inlet temperature, $T_{w,outlet}$ is the outlet temperature of the capillary tube system and N is the number of the tube. The total heat transfer per length of capillary tube is calculated by the following equation.

$$Q = N\, \bar{h}\, \pi\, D\, \Delta T_{lm} \tag{9}$$

The heat transfer from the capillary tube to the plenum air will be equal to the energy that is supplied to the plenum air. Therefore, also the following equation can be written.

$$Q = m_w c_p (T_{w,outlet} - T_{w,inlet}) \tag{10}$$

N_T is the number of rows that are parallel to the air flow direction. The mass flux is expressed as follows

$$\dot{m} = \rho u_{\infty} N_T S_T \tag{11}$$

The heat transfer from the capillary tube to the plenum air can be expressed as,

$$Q = \rho u_{\infty} \dot{N}_T S_T c_p (T_{w,outlet} - T_{w,inlet}) \tag{12}$$

If the expression 10 and 12 are set equal to each other, the relation which follows is obtained.

$$\frac{T_S - T_{w,outlet}}{T_S - T_{w,inlet}} = exp\left(-\frac{\pi D N \bar{h}}{\rho u_{\infty} N_T S_T c_p}\right) \tag{13}$$

This expression can be used to find the temperature of the water exit temperature of the capillary tube system.

Heat Exchange Effectiveness

The heat exchange effectiveness of the perforated solar air collector coupled to a capillary radiant heating system can be defined as

$$\varepsilon_{HX} = \frac{T_{plen,outlet} - T_{air\ inlet}}{T_{w,inlet} - T_{air\ inlet}} \tag{14}$$

In this study, the temperature of the absorber plate is not taken into account for the heat exchange effectiveness, because of this study highlights the heat exchange for the non-solar radiation conditions, hence it is assumed that there is no solar energy effect on the absorber plate.

EXPERIMENTAL RESULTS

Figure 4 presents exit air temperature-air flow rate relationship for different inlet temperatures of capillary mass flux. Results show exit temperatures for an ambient temperature of 10 °C and capillary tubes mass flux 11.45 kg/h. In general, decreasing the air flow increases exit air temperature. For a constant air flow, increasing the capillary inlet temperature, increases exit air temperature significantly.

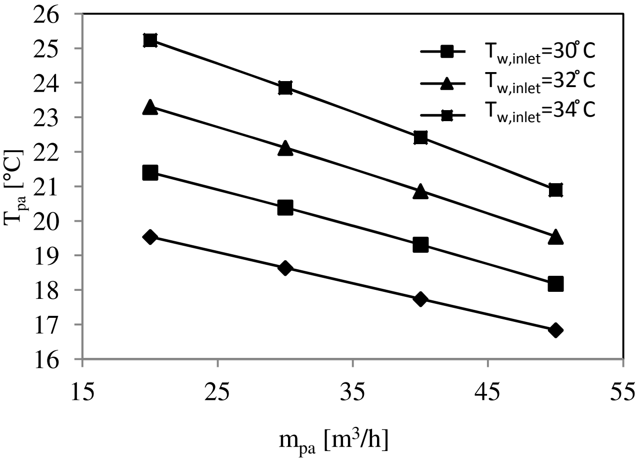


Figure 4 The exit air temperature-air flow rate relationship for different inlet temperatures of capillary mass flux

Figure 5 shows the heat exchange effectiveness between capillary tubes and air flow of transpired collector for an ambient temperature of 10 °C and capillary tubes mass flow 11.45 kg/h. Heat exchange effectiveness is effected by air flow and capillary tubes inlet temperature significantly. Larger water inlet temperatures and lower air flows result higher effectiveness, because of increased heat transfer coefficient which is a result of the higher temperature difference between capillary heating system and plenum airflow.

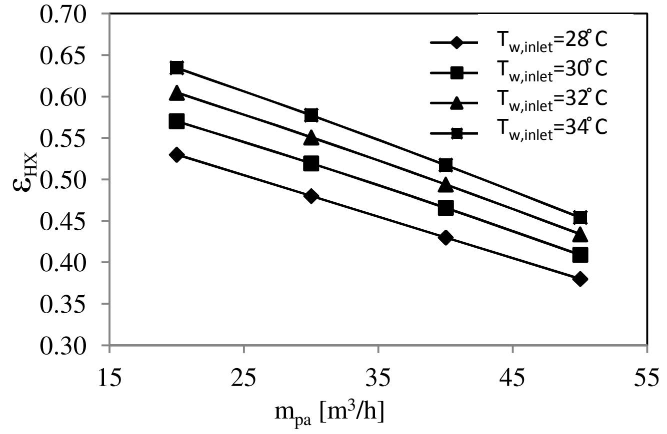


Figure 5 The heat exchange effectiveness between capillary tubes and air flow of transpired collector for different mass flux of capillary tube

Figure 6 presents the effect of various mass flux of capillary tubes on exit air temperatures for an ambient temperature of 10 °C and mass flux inlet temperature 28 °C. Larger mass flux increase exit air temperature significantly. For an air flow of 15 m^3/h, the temperature rise of cold air is obtained as 14.7 °C.

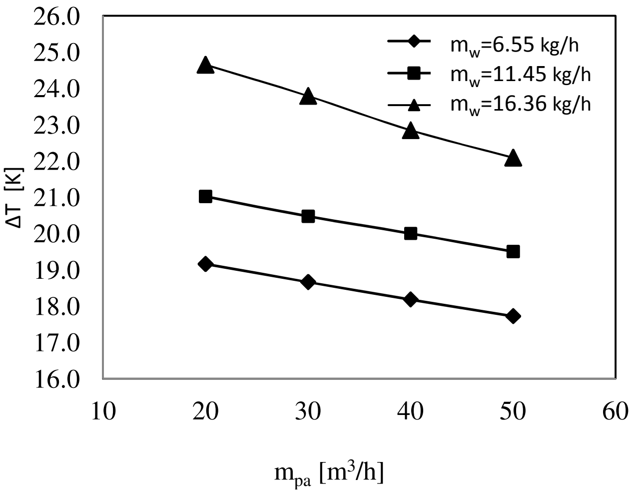


Figure 6 The effect of various mass flux of capillary tubes on exit air temperatures

Figure 7 shows the effect of different mass flux on heat exchange effectiveness between capillary tubes and air flow of transpired collector for an ambient temperature of 10 °C and capillary tubes mass flux 11.45 kg/h. Heat exchange effectiveness increase with decreasing air flow and increasing mass flux. The effect of mass flux on effectiveness is greater than effect of air flow. In general, it is possible to obtain high heat effectiveness for lower air flows and larger mass flux . Figure 8 shows the heat transfer coefficients between the capillary tubes and air flow of transpired collector for different mean temperature differences. Results are compared with heat transfer coefficient which is obtained by Glück for typical room heating applications.

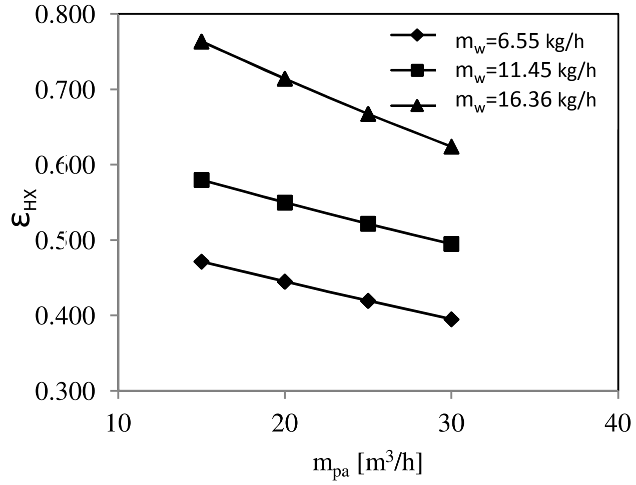


Figure 7 The effect of different mass flux on heat exchange effectiveness between capillary tubes and air flow of transpired collector

As seen from Figure 8, heat transfer coefficient are larger than heat transfer coefficients of typical room heating. It is obvious that multipoint air flow of transpired collector and forced convection result higher heat transfer rates in comparison to classical room heating of capillary heating systems. On the other hand, wall configurations for capillary heating system decrease heat transfer coefficient in general. Heat transfer coefficient is effected by air flow and capillary tubes inlet temperature significantly. Larger inlet temperatures and air flows result higher heat transfer rates.

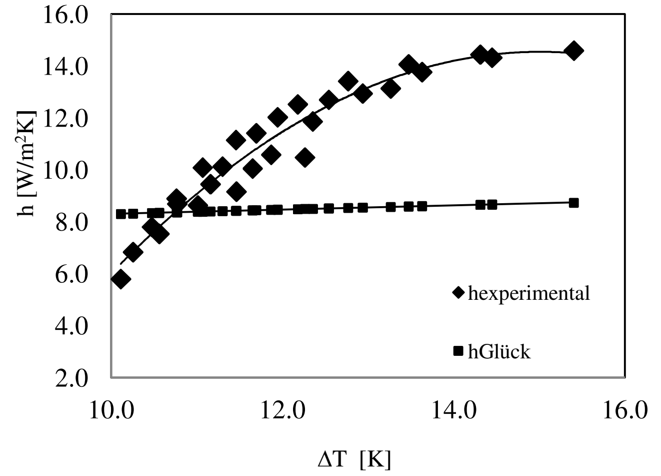
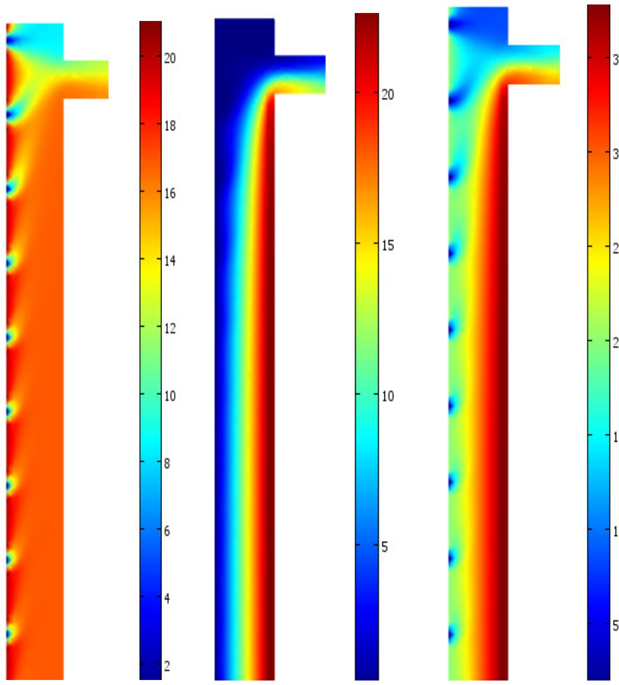


Figure 8 The heat transfer coefficients between the capillary tubes and air flow of transpired collector for different mean temperature differences

The effect of capillary heating tubes on transpired collector is validated numerically with the use of the commercially available computational package, Comsol Multiphysics. A comparison of the temperature distributions obtained for different cases from the Comsol Multiphysics simulation results and that of the two-dimensional model and simulations results are shown in Figure 9. It is found that temperature and effectiveness values are comparable with experimental results. It is obvious that capillary tubes provide a very good temperature rise for the case of non-solar radiation. Figure 9 also shows that lower inlet temperatures of capillary heating system provide a very good temperature rise for lower solar radiation on transpired collectors and it helps as a supplementary system for continuous heating of outside air.



(a) (b) (c)

(a) No Capillary Heating T_{amb}=0 °C, T_{abp}=20°C,

(b) Capillary Heating T_{amb}=0 °C, T_{abp}=0°C, T_{CT}=25°C

(c) Capillary Heating T_{amb}=0 °C, T_{abp}=20°C, T_{CT}=40°C

Figure 9 The effect of capillary heating system with numerical Comsol Multiphysics results for the two-dimensional model

CONCLUSION

Experimental results indicate that the capillary heating system provide higher heat exchange effectiveness for transpired solar air collectors. Heat exchange effectiveness is effected by air flow and capillary tubes inlet temperature significantly. Larger inlet temperatures and lower air flows result higher effectiveness. Experimental results show that heat transfer coefficients are higher than classical capillary heating applications. The heat transfer mechanism of capillary heating tubes on transpired collector is validated numerically with the use of the commercially available computational package. It is obvious that capillary heating system is a supplementary system for non or lower solar radiation conditions.

REFERENCES

[1] Hollick J.C.,Unglazed Solar Wall Air Heaters, Conserval Engineering Inc., 200 Wildcat Rd. Downsview, Ontario M3J 2N5, Canada, Available online 2 July 2003

[2] Kutscher, C.F., Christensen, C., Barker, G.,. Unglazed transpiredsolar collectors: an analytic model and test results. In: Proceedings of ISES Solar World Congress 1991, Elsevier Science, vol. 2:1. pp. 1245–1250, 1991

[3] Kutscher, C.F., Christensen, C., Barker, G., Unglazed transpired solar collectors: heat loss theory. ASME Journal of Solar Engineering, vol.115 (3), pp.182–188, 1993

[4] Van Decker, G.W.E., Hollands, K.G.T., Brunger, A.P., Heat exchange effectiveness of unglazed transpired-plate solar collector in 3D flow. In: Goietzburger, A., Luther, J. (Eds.), Proceedings of EuroSun 96, Freiburg, Germany. DGS–Sonnen energie Verlags GmbH, Munchen, Germany, pp. 130–846, 1996

[5] Van Decker, G.W.E., Hollands, K.G.T., An empirical heat transfer equation for the transpired solar collectors, including no-wind conditions. In: Proceedings of the ISES 99 Solar World Congress, Australia, 1999

[6] Van Decker, G.W.E., Hollands, K.G.T., Brunger, A.P., Heat exchange relations for unglazed transpired solar collectors with circular holes on a square or triangular pitch, Solar Energy, vol. 71 (1), pp.33–45, 2001

[7] Gunnewiek, L.H.; Brundrett, E.; Gunnewiek, L.H., Flow distribution in unglazed transpired plate solar air heaters of large area ., Solar Energy, vol.57, Iss.4, pp.227, (0038-092X) 10/1/1996.

[8] Leon, M. Augustus; Kumar, S.; Leon, M. Augustus., Mathematical modeling and thermal performance analysis of unglazed transpired solar collectors. Solar Energy Volume 81,Iss.1;p.62-75, (0038-092X)1/1/2007.

[9] Eryener D., Metal Cladding System with a Heat Exchanger System , Turkish Patent Institute, 2009

[10] Swart, R. H.,-, Capillary Tube Heat Exchangers, Refrigerating Engineering (September), pp.221-224, 248-249, 1946

[11] Staebler, L. A, Theory and Use of a Capillary Tube for Liquid Refrigerant Control, Refrigerating Engineering (January), pp.55-59, 1948

[12] Hopkins, N. E, Rating the Restrictor Tube: Method of Determining Flow Capacities For Freon-12 and Freon-22, Journal of the ASRE – Refrigerating Engineering (November), pp.1087-1094, 1950

[13] Whitesel, H. A, Capillary Two-Phase Flow, Part II, Refrigerating Engineering, pp.35-40, 1957

[14] Cooper, L., C. K. Chu, and W.R. Brishken, Simple Selection Method for Capillaries Derived from Physical Flow Conditions, Refrigerating Engineering, pp. 37-41, 1957.

[15] Mikol, E. P., Adiabatic Single and Two-Phase Flow in Small Bore Tubes, ASHRAE Journal (November), pp.75-86, 1963

[16] Erth, R. A., Two-Phase Flow in Refrigeration Capillary Tubes: Analysis and Predi~tion, Ph.D. Thesis, Purdue University, 1970

[17] Goldstein, S. D., P.E, A Computer Simulation Method For Describing TwoPhase Flashing Flow in Small Diameter Tubes, ASHRAE Transactions, pp.51-60, 1981

[18] Sweedyk, J. M., Capillary Tubes – Their Standardization and Use, ASHRAE Transactions, pp.1069- 1076, 1981

[19] Pate, M. B., A Theoretical and Experimental Analysis of Capillary TubeSuction Line Heat Exchangers, Ph.D. Thesis, Purdue University, 1982