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***Yazar(lar) (Author(s))**: Ataollah KHANLARI[1], İlker AY[2]*

ORCID[1]: 0000-0001-9691-9799

ORCID[2]: 0000-0002-3077-5355

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A Numerical Study on Determination of the Optimal Hole Diameter and Pitch Value for the Unglazed Transpired Solar Collectors

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Araştırma Makalesi / Research Article

Ataollah KHANLARI[1*], İlker AY[2]

[1]Department of Clean Energy, Institute of Science, Hacettepe University, Ankara, Turkey
[2]Hacettepe Ankara Chamber of Industry 1st Organized Industrial Zone Vocational School, Sincan, Ankara, Turkey

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ABSTRACT

This investigation is concerned with the unglazed transpired solar collector (solar wall) type. With this purpose, the optimum hole arrangement has been determined by investigating the effect of hole diameter and pitch on the thermal efficiency of the system for different environmental condition. A thermodynamic model is used to simulate the heating process within the system. As a result, for extremely small hole diameters or extremely large hole pitches, the system works as a Trombe wall (glazed thermal storage wall) rather than an unglazed transpired solar collector because of the fact that there is not enough air flow through the absorber.

Keywords: Unglazed solar collectors, solar wall, hole diameter, pitch, efficiency.

1. INTRODUCTION

The unglazed transpired collector (UTC) is a subsystem which is used to heating the building. Unlike the Trombe walls, it has provided continuously fresh air. A Trombe wall absorb heat from the sun during the day and transfer it into the interior space of building during the night and no fresh air provided. The UTC system is providing preheating by heating the fresh air which is passing through the system. Thus, the load of the building heating system is decreased generating energy saving and it provides comfortable living environment with getting fresh air into the building.

The solar wall acts as a barrier between the surrounding air and outer wall surface of the building. It causes minimization of the heat loss from building walls due to heat transmission. Solar wall systems minimize the heat loss from building walls due to heat transmission by providing a barrier between the surrounding air and outer wall surface of the building. In addition to ventilating and air-conditioning systems, this system is also used for drying of agricultural products and preventing the overheating of photovoltaic cells [1].

The first application of the UTC was reported in 1981 by a company in Germany named Wieneke for providing preheated air for ventilating and air-conditioning of the building. Later, it was used for drying of agricultural products by another Germany company Schulz in 1988 [2]. These systems have spread slowly around the world [1].

Economic and technical characteristics of system such as solar wall structure, usage areas, increasing efficiency have been studied by many researchers [3-14]. For example; Hollick summarized working principle of UTC, examples of applications, monitoring results, and the potential use of this technology [3, 4]. Shukla et al. reviewed the transpired solar collector. Various types of TSCs introduced and working principle explained. Authors indicate that most critical factors affecting TSC efficiency are wind velocity, flow rate, porosity, absorptivity and porosity [5]. Augustus Leon and Kumar developed a mathematical model to analyze the thermal performance of the unglazed transpired solar collectors. The results have been used to develop nomograms, that could be a valuable tool for designers. Also, observations show that absorptivity, collector pitch, and airflow rate have the strongest effect on collector efficiency [7]. Summers proposed thermal simulation and economic assessment of unglazed transpired collector systems. A simple energy balance model used to simulate the UTC system. The author indicated that the UTC systems are economically feasible for large buildings and they should be considered for new buildings [8]. Barker and Kiatreungwattana investigated pressure drop as a function of air flow rate for transpired solar collectors with different porosities experimentally. They collected pressure drop, air flow rate, air temperature, and air relative humidity data during the tests. The data were fit to a model that can be used to predict pressure drop across the absorber. Using these models can help designers in ensuring that transpired collector systems are designed for optimal thermal efficiency [13]. Fleck et al. studied the wind effects on the performance of an unglazed transpired solar collector experimentally. They observed that peak efficiencies did not occur at the lowest wind speeds [14].

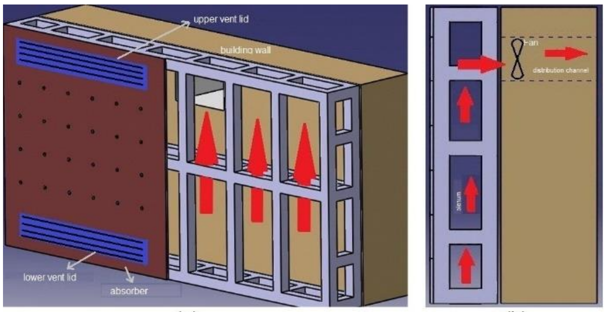
**Sorumlu Yazar (Corresponding Author)*
e-posta : ata_khanlari@yahoo.com

2. SYSTEM PROPERTIES

A Schematic drawing of a solar wall is shown as Figure 1. UTC system has a transpired absorber plate. It is fixed on a steel construction as parallel to the building surface which supplies the air flow in vertical direction pointing upwards and it has air vents which are located at the up and down-sides of the collector for using air ventilating in summer. The UTC system has a plenum between the outer wall surface of the building and the collector. The system has also a heated air distribution channels and a fan system.

The parameters that affectsystem efficiency can be grouped in 5 categories; such as, climatic conditions, location limitations, surface coating, fan power, hole diameter and pitch.

Climatic conditions: The most important factors are the amount of solar radiation and wind speed. Efficiency increases with increasing the amount of solar radiation until a certain amount of solar radiation which leads to a fixed efficiency. A further increase in solar radiation, would increase the heat losses by radiation, that's why efficiency is decreased [7].



(a) (b)

Figure 1. Mounting an unglazed transpired solar collector on building facade a. perspective, b. right view

The incoming velocity is depended on the wind speed so, the increasing wind speed causes to increase incoming velocity. In this case experimental studies shows that the efficiency is increased with increasing incoming velocity until the incoming velocity reaches the 0,05 m/s and then the efficiency increase is fixed. If the incoming velocity is further increased, the cooling effect of the wind will be observed on the collector and it causing a decrease of the system efficiency [11].

Location limitations: To get the best efficiency of the system in the northern hemisphere the collector should be mounted on the south facing facade of the building; and in southern hemisphere mounted on north facing facade of the building. It is important to avoid any shading on these surfaces.

Surface coating: Surface coatings can be divided into two groups. The first method is the paint coating: For this method, the surface is coated with a black matte paint. Black matte paint has a high absorption rate (90-98%); but its emissivity is high (85-92%), consequently heat losses increases. To eliminate this problem, selective surface coating is used as the second method of the surface coating. In this method, the selective surface is used to completely absorb short wavelength radiation and minimize long wavelength radiation emission. So, irradiation decreases at high temperatures and efficiency increases [15, 16]. Generally, in the UTC paint coating are used, due to comparable low cost and easy manufacturability.

Fan power: Fan power affects the air flow rate proportionally but the efficiency is inversely proportional with the air flow rate. This means, the increase in flow rate causes a decrease in efficiency and vice versa. When high temperature is needed in the building, the fan speed should be reduced whereas, when low temperatures are needed in the building, fan speed should be increased. Changing the fan power, affects the air flow rate in the plenum in addition to changing the achievable efficiency. That's why to adjust the air flow rate in the plenum, the hole diameter and pitch on the collector must be determined.

Hole diameter and pitch: Thermal efficiency reduces, when the hole diameter is enlarged. If the hole diameter is constant, then the thermal efficiency decreases, if the hole pitch increased. That's why an optimum value for hole diameter and pitch should be determined. Wind speed and fan power are important factors for determining these values. Moreover, the geographical condition must be considered while choosing the hole diameter of the system. The hole diameter designation process is limited by conditions which mention above. Because particles such as, sand, sawdust and dust, which are found around the systems, can clog the holes of system. So, the smallest hole diameter should be chosen firstly and then proper hole pitch is determined.

3. HEAT TRANSFER MECHANISMS OF THE UTC

The heat transfer model of the UTC is shown in Figure 2. This type of modeling has been investigated by many researchers [5-12].

For the investigation of the heat transfer model of the UTC, some assumptions for the calculations have been done;

- Air moves only in the upward direction in the plenum
- Plenum temperature and room input temperature are equal (T_p=T_{in})
- Plenum air temperature (T_p) and collector temperature (T_c) are distributed uniformly.

The energy balance equation for the collector and the outer wall surface can be written as [10]:

$$q_{in} + q_{rad,w-c} = q_{conv,c-p} + q_{conv,loss} + q_{rad,loss} \quad (1)$$

$$q_{cond,w} = q_{conv,w-p} + q_{rad,w-c} \quad (2)$$

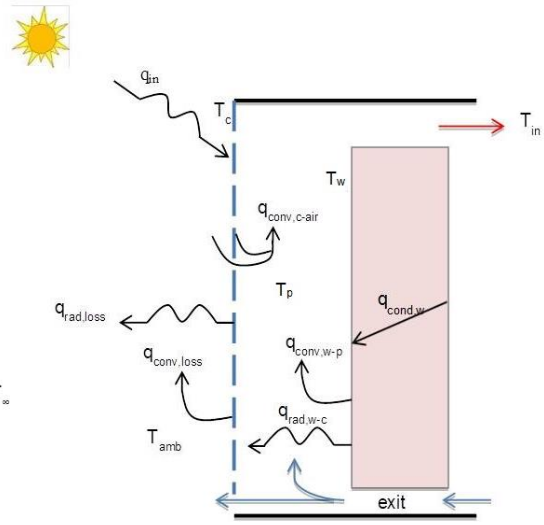


Figure 2. Heat transfer model for UTC

Where q_{in}, is the absorbed energy by the collector; $q_{rad,w-c}$, is the radiation from the outer wall surface to the collector; $q_{conv,c-p}$, is the convective heat transfer when the air flowing through the collector into the plenum; $q_{conv,loss}$, is the convective heat losses from the collector to the surrounding air; $q_{rad,loss}$, is the radiation heat losses from the collector to the surrounding air; $q_{cond,w}$, is the conduction heat transfer from the inside room to the outside surface of the wall; $q_{conv,w-p}$, is the convective heat transfer from outer wall surface to the plenum air.

$$k_{i,d}A(T_{in}-T_w)=\frac{kNu_Y}{Y}A\left(T_w-\left(T_{amb}+\left[(T_c-T_{amb})\left(1-exp\left(-\frac{kNu_D(1-\sigma)}{D\rho V_s C_p}\right)\right)\right]\right)\right)+\frac{\sigma_{sb}A(T_w^4-T_c^4)}{\frac{1}{\varepsilon_w}+\frac{1}{\varepsilon_c}-1} \quad (4)$$

There are two unknowns in Eqs. 3 and Eqs. 4, outer wall temperature of the surface of the building (T_w) and the collector temperature (T_c). The thermophysical properties of air in these equations are calculated from using a polynomial curve, which is given as $f(T) = AT_{amb}^4 + BT_{amb}^3 + CT_{amb}^2 + DT_{amb} + E$ and the constants are given in Table 1. Also, the air density can be obtained from $\rho=360.7782T_{amb}^{-1.00336}$ (kg/m^3) [10]. After the thermophysical properties of air calculated the Newton's methods are used to calculate two unknowns [18]. Then the results are inserted into the thermal efficiency expression resulting in the following expression for thermal efficiency [7,10].

$$\eta=\frac{\dot{m}_c C_p}{I_T A}(T_c-T_{amb})\left[1-exp\left(-\frac{kNu_D(1-\sigma)}{D\rho V_s C_p}\right)\right] \quad (5)$$

Table 1. Properties of air

f(T)	A	B	C	D	E
C_p (J/kg.K)	1.933E-10	-7.999E-07	1.141E-03	-4.489E-01	1.058E+03
υ (m^2/s)	0	-1.156E-14	9.573E-11	3.760E-08	-3.448E-06
k (W/m.K)	0	1.521E-11	-4.857E-08	1.018E-04	-3.933E-04
α (m^2/s)	0	0	9.102E-11	8.820E-08	-1.065E-05

Table 2. UTC parameters and their values used in the study

Adjustable Parameter	Value	Unadjustable Parameter	Value
Collector Height	2(m)	Ambient Temperature (T_{amb})	10°C
Collector Length	3(m)	Indoor Temperature (T_{in})	22°C
Hole Diameter (D)	Variable	Approach Velocity (V_s)	0,02 m/s
Hole Pitch (P)	Variable	Outdoor Air Flow Rate (V_∞)	1,2 m/s
Absorptivity of Collector (α_c)	0,9	Solar Radiation (I_T)	400 W/m^2
Emissivity of Collector (ε_s)	0,9	Overall Heat Transfer Coefficient ($k_{i,d}$)	1,2 W/m^2.K
Corrugation Factor (C_f)	1		
Wall Emissivity(%)	90		

4. NUMERICAL ANALYSIS OF UTC MECHANISM

If the terms in Eqs. 1 and Eqs. 2 are substituted by terms previously defined in literature [7,10] and some arrangements are made, then the final equations are found:

$$\alpha_c I_T A_c+\frac{\sigma_{sb}A(T_w^4-T_c^4)}{\frac{1}{\varepsilon_w}+\frac{1}{\varepsilon_c}-1}=\dot{m}_c C_p\left[1-exp\left(-\frac{kNu_D(1-\sigma)}{D\rho V_s C_p}\right)\right](T_c-T_{amb})+\varepsilon_c\sigma_{sb}A_c(T_c^4-T_\infty^4)+\frac{Nu_{loss}k}{Y}A(T_c-T_{amb}) \quad (3)$$

There are many variables in Eqs. 3, Eqs. 4 and Eqs. 5, but some of these variables such as ambient temperature, wind speed and solar radiation depend on climatic conditions, the others such as collector size, hole diameter and pitch, collector absorption and collector emission constants are adjustable and completely depend on the design conditions.

In this study the numerical calculations using the Eqs.3, Eqs. 4 and Eqs. 5, are carried out by employing the values of the parameters provided in Table 2.

All adjustable parameters affect the thermal efficiency, but hole diameter and pitch are the most important adjustable parameters. Both parameters depend on each other. However, the first hole diameter must be designated, because it determines the air flow rates and the amount of air which is transferred to the building.

5. RESULTS AND DISCUSSION

Figure 3 indicates the dependence of the thermal efficiency on variation of the hole diameters for a fixed hole pitch. An asymptotic behavior is seen in the thermal efficiency variation in Figure 3. In the left part of the curve, because of the quite small hole diameter, sufficient fresh air can't be provided to the building. Therefore, the system works as a Trombe wall.

Looking the right side of the asymptote in Figure 3, the system works as an UTC and shows the dependence of the thermal efficiency on variation of the hole diameter. There is minimum hole diameter (D_{min})which leads to a minimum in thermal efficiency. When slight incrementing the hole diameter starting from this point (D_{min}), thermal efficiency is rapidly increase and reaching its maximum (D_{max}). However, if the hole diameter increases continuously then the increment in thermal efficiency will be down slowly. If the increase of hole diameter reaches large value then thermal efficiency will start to decrease.

The same behavior is observed for different hole pitches as shown in Figure 4. As shown in Figure 4, the point Dmin is reaching even smaller values with decreasing the hole pitch. In addition, hole diameter values for each hole pitch value are inserted, where the maximum thermal efficiency is obtained. These hole diameter values (D_{max})are increasing with the hole pitch proportionally. However, the particles such as, sand, sawdust and dust which are located around the systems can clog the holes of system, that's why the hole diameter value can't be choose so small.

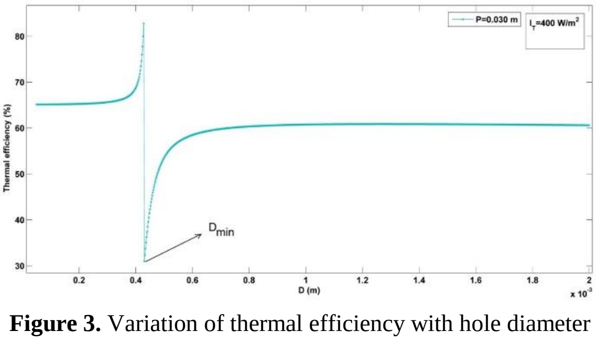


Figure 3. Variation of thermal efficiency with hole diameter

The right side of the asymptotic peaks in Figure 4 are identified as D_{min} and D_{max} point for each hole pitch. If the hole's diameter is smaller than the D_{min} point for choosing hole pitch, the system will not work properly, in this case sufficient fresh air can't be provided.

Accordingly, while $D<D_{min}$ the system works as a Trombe wall, for $D>D_{min}$ the system works as an UTC for a fix hole pitch. Also, when the hole diameter is equal to the D_{min} point, the efficiency can be written as:

$$\eta = \lim_{D\to D_{min}^{-}} \frac{\dot{m}_c C_p}{I_T A}(T_c - T_{amb})\left[1 - \exp\left(-\frac{kNu_D(1-\sigma)}{D\rho V_s C_p}\right)\right] = +\infty \quad (6)$$

$$\eta = \lim_{D\to D_{min}^{+}} \frac{\dot{m}_c C_p}{I_T A}(T_c - T_{amb})\left[1 - \exp\left(-\frac{kNu_D(1-\sigma)}{D\rho V_s C_p}\right)\right] = -\infty \quad (7)$$

Figure 5 indicates the variation of the thermal efficiency with hole pitch for different hole diameters. As shown in figure 5 for small hole diameter (D<0,25mm), the thermal efficiency does not change and the collector works as a Trombe wall. Whereas, for a hole diameter larger than 0,25 mm (D≥0,25mm), with slight increase the hole pitch, thermal efficiency increases. But, for larger values of the hole pitch thermal efficiency decrease. When the thermal efficiency reaches the minimum value for a fixed hole diameter, the hole pitch value is called critical hole pitch (P_c).

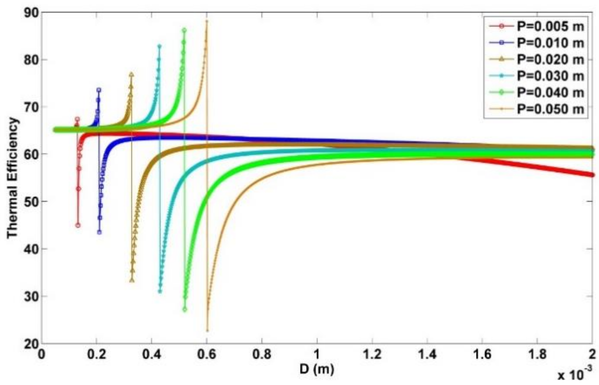


Figure 4. Variation of thermal efficiency with hole diameter for different pitches

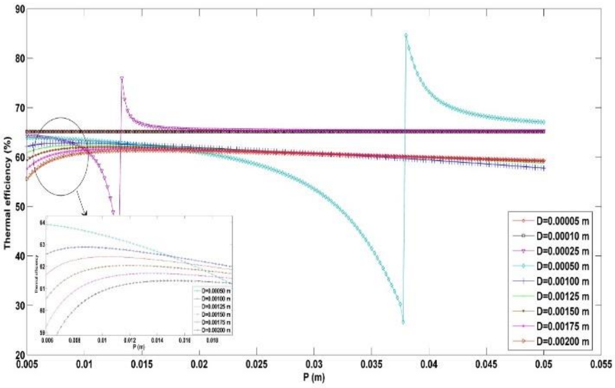


Figure 5. Variation of thermal efficiency with hole pitch for different hole diameters

In the left side of the asymptote that is shown in Figure 5, the system works as a UTC. Because of the distance between the holes is too large in the right side of the asymptote , the system works as a Trombe wall and the thermal efficiency fixed. In this case the amount of fresh air which is supplied to the building, is limited.

While $P<P_c$, the system works as UTC, for $P>P_c$ the system works like a Trombe wall for a fixed hole diameter. When the hole pitch is equal to the critical hole pitch value (P_c), the efficiency can be written as:

$$\eta = \lim_{P \to P_c^-} \frac{\dot{m}_c C_p}{I_T A} (T_c - T_{amb}) \left[1 - \exp\left(-\frac{kNu_D(1-\sigma)}{D\rho V_s C_p}\right)\right] = -\infty \quad (8)$$

$$\eta = \lim_{P \to P_c^+} \frac{\dot{m}_c C_p}{I_T A} (T_c - T_{amb}) \left[1 - \exp\left(-\frac{kNu_D(1-\sigma)}{D\rho V_s C_p}\right)\right] = +\infty \quad (9)$$

Analysis Figure 4 and 5, it is obvious, that hole pitch and hole diameter cannot be studied independently from each other. To find the optimum values of D and P Figure 4 and Figure 5 should be combined and a 3D graphic with boundaries of $D>D_{min}$ and $P<P_c$ should be drawn. Before drawing the graphic, the boundaries must be identified. As mentioned above, the thermal efficiency is at its maximum for hole diameter of 0,25 mm; this value, however, is so small, that particles around the system can clog the holes of system easily. Therefore, sufficient air cannot be provided and the system works as a Trombe wall. Therefore, for choosing the hole diameter, the geographical condition must be considered carefully. In this study minimum hole diameter of the system is found to be 0,8 mm (D_{min}=0,8mm). The Pc value can be extracted from the Figure 5. Using these boundaries, Figure 6 gives a 3D view on the variation of thermal efficiency with the hole diameter and the hole pitch. A maximum thermal efficiency of 63.26% is obtained for D=0,8 mm, P=7 mm using the values in Table 2. Similar results were obtained by Augustus Leon and Kumar (2007) and Motahar and Alemrajabi (2010). Also, it has been indicated that optimum hole diameter and hole pitch should be determined simultaneously [7,10].

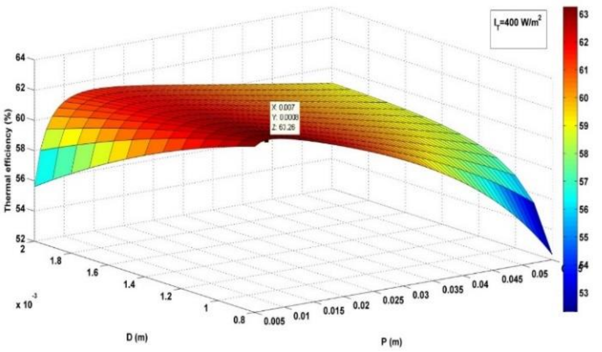


Figure 6. Variation of thermal efficiency with hole diameter and pitch

6. CONCLUSIONS

Solar wall systems are used in buildings that need continuous ventilation. This system is suitable for places which have long winter season with sunny days. In winter, the tilt angle of the sunrays is come more tilted. Therefore, high efficiency can be obtained in winter using solar wall system.

To obtain high efficiency from solar wall system; climate conditions of location such as temperature, wind speed and solar radiation must be determined firstly. Secondly, the collector dimensions determined using building dimensions and the minimum hole diameter is chosen considering the geographical condition. Then finally, the variation of the thermal efficiency with the hole pitch for Dmin value has been plotted. Thus, the proper hole pitch for choosing the minimum hole diameter considering the geographical condition can be determined. Consequently, we can find out the optimum hole diameter and pitch for obtaining maximum efficiency.

The optimum hole diameter and pitch values were achieved as D=0,8 mm and P=7 mm with maximum thermal efficiency of 63.26%.

Using such systems, the energy resources can be used more efficiently. Also, these systems can be helpful to reduces the amount of CO_2 emissions and helps for protecting the environment.

REFERENCES

[1] www.solarwall.com.

[2] Kutscher C.F., "An investigation of heat transfer for air flow through low porosity perforated plates", Ph.D. Thesis, University of Colorado, Department of Mechanical Engineering, Colorado, USA, (1992).

[3] Hollick J.C. "Unglazed solar wall air heaters", ***Renewable Energy***, 5, 415-421, (1994).

[4] Hollick J.C. "Solar cogeneration panels", ***Renewable Energy***, 15, 195-200, (1998).

[5] Shukla A., Nkwetta D.N., Cho Y.J., Stevenson V. and Jones P., "A state of art review on the performance of transpired solar collector", ***Renewable and Sustainable Energy Reviews***, 16, 3975-3985, (2012).

[6] Kutscher C.F. "Heat exchange effectiveness and pressure drop for air flow through perforated plates with and without crosswind", ***Journal of Heat Transfer***, 116, 391-399, (1994).

[7] Augustus Leon M. and Kumar S., "Mathematical modeling and thermal performance analysis of unglazed transpired solar collectors", ***Solar Energy***, 81, 62-75, (2007).

[8] Summers D.N. "Thermal Simulation and Economic Assessment of Unglazed Transpired Collector Systems", M.Sc. Thesis, University of Wisconsin-Madison, USA, (1995).

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

[10] Motahar S., and Alemrajabi A.A., "An Analysis of Unglazed Transpired Solar Collectors Based on Exergetic Performance Criteria", ***International Journal of Thermodynamics***, 13, 153-160, (2010).

[11] Kutscher C.F., Christensen C., and Barker G., "Unglazed transpired solar collectors: heat loss theory", ***Journal of Solar Engineering***, 115, 182-188, (1993).

[12] Moaveni S., Tebbe P.A., Schwartzkopf L., Dobmeier J., Gehrke J., and Simones M.A., "numerical model for

thermal performance of an unglazed transpired solar collector," ***ASME 5th International Conference on Energy Sustainability***, 1-5, (2011).

[13] Gunnewıek L.H., Brundrett E., and Hollands K.G.T., "Flow distribution in unglazed transpıred plate solar aır heaters of large area", ***Solar Energy***, 58, 221-237, (1996).

[14] Fleck B.A., Meier R.M., and Matovic M.D., "A field study of the wind effects on the performance of an unglazed transpired solar collector," ***Solar Energy***, 73, 209-216, (2002).

[15] Tırıs Ç., and Söhmen H.M., "Türkiye'de üretilen güneş enerjili su ısıtma sistemlerinde kullanılan güneş kollektörleri," ***Güneş günü sempozisyomu***, 99, 1999, 25-27, (1999).

[16] Goswami D.Y., Kreith F., and Kreider J.F., "***Principles of Solar Engineering***", Second Edition. Taylor &Farncis Publishing Company, (2000).

[17] Incropera F.P., DeWitt D.P., Bergman T.L., and Lavine AS., "***Fundamentals of Heat and Mass Transfer***", 6th Edition. John Wiley&SonsPublishing Company, (2007).

[18] Balagurusamy E., "***Numerical Methods***", 25th Reprint. Tata McGraw-Hill Publishing Company, (2008).

NOMENCLATURE

α_c	Collector absorptivity
A	Total frontal collector area (m^2)
A_c	Collector surface area (m^2)
C_p	Specific heat capacity (J/kg.K)
D	Hole Diameter (m)
D_{max}	Max. Hole Diameter (m)
D_{min}	Min. Hole Diameter (m)
ε_c	Collector Emissivity
ε_w	Wall Emissivity
η	Thermal efficiency (%)
I_T	Solar radiation (W/m^2)
k	Thermal conductivity (W/m.K)
$k_{i,d}$	Overall heat transfer coefficient (W/m^2.K)
$\dot{m}_c$	Mass air flow rate through the collector into the plenum (kg/s)
Nu_D	Nusselt number of hole
Nu_{loss}	Loss Nusselt number
Nu_y	Nusselt number depends on the height of the collector
P	Hole pitch (m)
P_c	Critical hole pitch (m)
$q_{cond,w}$	Conduction heat transfer from the inside room to the outside surface of the wall (W)
$q_{conv,c-p}$	Convective heat transfer from the collector to the air when the air flowing through the plenum (W)
$q_{conv,loss}$	Convective heat losses from the collector to the surrounding air (W)
$q_{conv,w-p}$	The convective heat transfer from outer wall to plenum air (W)
q_{in}	Absorbed energy by the collector (W)
$q_{rad,loss}$	Radiation heat losses from the collector to the surrounding air (W)
$q_{rad,w-c}$	Radiation from the outer wall surface to the collector (W)
ρ	Density of air (kg/m^3)
υ	Kinematic viscosity of air (m^2/s)
σ	Porosity
σ_{sb}	Stefan-Boltzmann constant
T	Temperature (K)
T_∞	Surrounding temperature (K)
T_{amb}	Ambient temperature (K)
T_c	Collector surface temperature (K)
T_{in}	Room input temperature (K)
T_w	Outer wall surface of the building temperature (K)
V_s	Approach velocity (m/s)
Y	Collector height (m)