Budapest University of Technology and Economics
Faculty of Mechanical Engineering
Department of Building Service and Process Engineering

Pattantyús-Ábrahám Géza Doctoral School of Mechanical Engineering
Subprogram of building service and process engineering

COMPLEX EVALUATION OF TRANSPIRED SOLAR COLLECTOR SYSTEMS

Thesis booklet by:
Balázs Bokor
graduate engineer in building services

Supervisor:
Dr. habil László Kajtár
associate professor

Budapest
2018

1. INTRODUCTION

Climate change urges developed countries to reduce their energy consumption, as well as to increase the share of renewable energies in what they use. As the building sector is responsible for 40 % of the total energy consumption in the European Union, every feasible investment reducing the primary energy consumption of a building sector is favourable.

Solar air heating is a cost effective way of providing a building with renewable solar energy. Transpired solar collectors (TSC), which are common in North America and are getting more and more widespread in Europe too, represent a remarkable segment of the solar air heating market. The potential of the transpired solar collector lays in its simple construction, almost maintenance-free operation and thus low payback periods. A dark, perforated absorber plate is mounted in 15-20 cm distance onto the building's original façade, creating an air gap, which is closed from its sides. Air handling units are supplied with fresh air from the gap, which air can enter only through the perforations of the absorber plate. The transpiration of the absorber ensures the transfer of the solar heat into the fresh airstream.

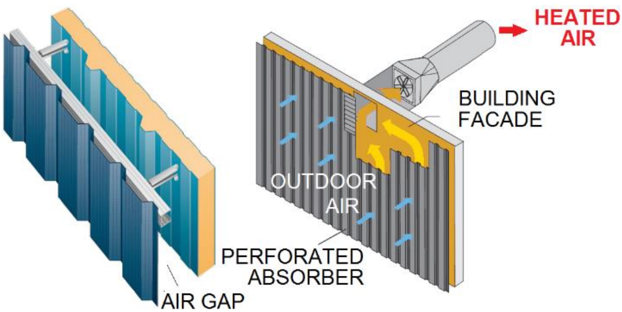

Figure 1: TSC construction and operational principle [1]

One has to be aware of the summertime operation of every solar thermal system, because they should never negatively influence the energy household of the building. Research focuses primarily on the summer operation of the roof-mounted TSC system, underlining that it not only does not increase, but reduces cooling load, in every hour of the day.

During night-time, a roof-mounted TSC cools down below ambient temperature as its collector plate radiates heat towards the cold sky. If air is drawn through the perforated plate, it can be cooled down in a passive manner. Literature mentions the nocturnal cooling down of the sky-facing collector plate [2], and at the same time calls for research on this phenomenon, as no adequate information is available to describe the passive cooling operation of the TSC.

Over the day, the roof-mounted TSC is independent from the ventilation system, as the air handling units are supplied over a by-pass duct, directly from the ambience. As the solar radiation heats up the collector plate of the TSC, a natural airflow comes to be in the air gap and thermally decouples the collector plate and the roof. Thus, a building can benefit from the transpired solar air heater all year, as it not only turns solar energy into air heating but also contributes in the summer cooing load reduction, twofold.

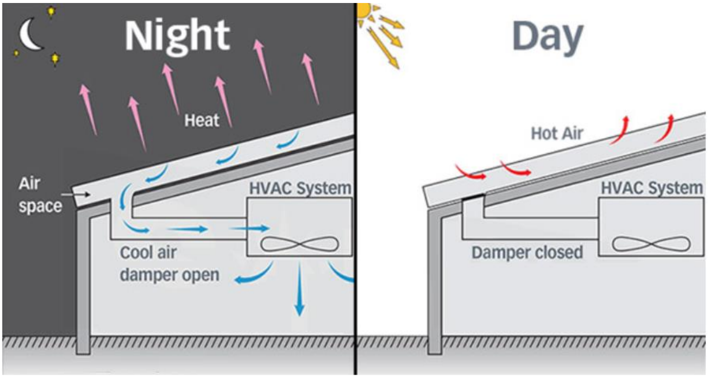

Figure 2: Nocturnal passive air cooling and roof ventilation by transpired solar collectors [3]

The literature of the transpired solar collector lacks the information about the climate dependency of the thermal performance in solar air heating operation. Investigating this marks the third main direction of research. A reference industrial building has been created with characteristic architecture and quality parameters of the building envelope. It is equipped with a TSC system, the energy production of which is to be evaluated for four locations with different climate, using RET Screen 4 software.

2. TARGETS OF RESEARCH

The focus of the dissertation is to investigate the cooling load reduction of the transpired solar collector, as well as the climate dependency of its solar air heating performance. The research can be divided into three major parts.

First, the night-time passive air cooling operation of the roof-mounted TSC has been described by creating a mathematical model for the heat transfer mechanisms between the parts of the TSC and the cooled airflow. Main targets of the nocturnal passive cooling research are:

- creating a physical and mathematical model to describe the heat transfer mechanisms between the TSC parts and the cooled airflow. The model aims to be suitable for the evaluation of the cooling potential,
- validation of the mathematical model based on measurements,
- proving that the energy analysis of nocturnal air cooling with a small scale TSC (5 m^2) can be successfully carried out by using global energy balance equations with concentrated parameters, expressing the first law of thermodynamics,
- determination of a new Nusselt-correlation for the calculation of the convective heat transfer between the collector plate and the plenum air,
- elaboration of a method to determine the most suitable equivalent clear sky temperature model to be used for the performance evaluation of the nocturnal air cooling operation with TSC.

The second main target of research is to underline that the roof-mounted TSC significantly reduces the cooling load, which reaches the building through the roof. Research objectives of the daytime cooling load reduction are the following:

- creating a physical and mathematical model to describe the heat transfer mechanisms between the TSC parts for the daytime case without suction. The model aims to be suitable for the evaluation of the cooling load reduction potential,
- creating a correlation to describe the cooling load reduction between the collector plate and the back plate (symbolising the building roof),
- proving that the roof mounted TSC reduces the cooling load reaching the building interior through the roof.

The third goal of research is related to the solar air heating operation, namely to determine the climate dependency of the TSC performance. Detailed targets are as follows:

- determination of the energy consumption of the reference building when located in four Turkish cities with different climate. For each location, the energy consumption is to be determined in a monthly time step for four cases:

collector azimuth of 0° (south-facing), 45° (southwest or southeast facing) and 90° (west or east facing), and without TSC,

- determination of the solar fraction's dependency on heating degree days and the intensity of solar radiation.

3. LITERATURE REVIEW

Due to its build-up, the heat producing mechanism of the transpired solar collector is different from conventional flat plate or vacuum-tube collectors. In order to determine the nocturnal passive cooling performance or the daytime cooling load reduction of the TSC, it is inevitable to understand the heat transfer mechanism of solar air heating with it.

The mathematical model of the heat production has been developed by several researchers based on equations of heat transfer between TSC elements (collector plate, air gap and back plate). [4–7] Performance evaluation of solar air heating by TSC can be carried out by available models. These models rely on some fundamental simplifications, the applicability of which have been also backed up in several studies.

Temperature distribution of the collector plate has been investigated by many. [5,7–9] As a result of the high thermal conductivity of the aluminium or steel collector plate, its temperature distribution can be considered as homogenous. This allows us to characterise the collector plate temperature by one single value. This statement is also one of the assumptions of the current research, as the temperature of the collector plate was measured in one point in the geometrical centre of the collector.

Besides the collector material, several studies have reported on the effect of different collector geometries. This direction of research is particularly important, as the commercially available TSC – which is also objective of the current investigation – is not flat, but a trapezoidal plate. CFD simulations have been carried out using collector plates with sinusoidal [10] as well as trapezoidal corrugations [11] in order to give an overview of flow structure and convective heat losses resulted by wind. Flat and trapezoidal collector plates were compared in these regards using numerical simulation and laboratory measurements. [12] Various perforation geometries were investigated with the visualisation of the flow patterns in order to determine the most advantageous shape for enhanced heat transfer between the collector plate and the airflow. [13] In the current research a measurement setup was used consisting of a trapezoidal collector plate with slit-like perforations, as this is the commercially available TSC plate.

Hall and Blower [14] recommend the use of selective coating, in order to minimise radiative losses from the collector plate to the surroundings. Absorption and emission coefficients are highly important in the current research of nocturnal passive cooling, as they significantly influence the radiant heat flow to the sky, and the heat gains of the collector plate from the surroundings. Different optical parameters would be ideal for the daytime solar air heating and the night-time radiant air cooling operation. However, this was not objective of the current research, as it aims to investigate the air cooling performance and cooling load reduction capacity of the commercially available TSC.

Based on the review of the literature of the transpired solar collector, it can be stated that remarkable information is available about the solar air heating operation. Studies have been conducted in order to acquire information about the mechanism of heat production as well as the maximisation of performance by various constructional developments. However, no scientific results can be found regarding the summertime operation of the building integrated TSC, when the necessity of solar air heating restricts to certain process applications and buildings generally have to be provided with cooling.

Free cooling systems are gaining increased attention as air conditioners are responsible for a remarkable amount of the electric peak load in summer. Several studies have shown that night ventilation of buildings reduces peak loads of the following day. Whenever the outdoor temperature is cold enough to cool down a building's structure over the night, it is led to the interior either on a natural or a mechanical way, creating a colder thermal mass for the next day. In whole Northern Europe, including the British Isles, the potential of night time ventilation is very significant in building cooling. In Central, Eastern and in even some regions of Southern Europe the climatic potential remains still significant. However, in regions such as southern Spain, Italy and Greece, where the highest cooling loads come to be, the potential is limited. [15–20] A way to increase the cooling performance of nocturnal ventilation is the introduction of a radiator which cools down below ambient temperature under nocturnal longwave radiation to the sky. Systems based on long-wave radiation to the sky have been widely investigated by scientists, yet they are considered to be a novel technology in today's building service engineering praxis. [21,22] Parker [23,24] carried out an evaluation to see the potential of a nocturnal radiant cooling system for residential buildings in North-America. Hollick [2] investigated the cooling down and the air cooling potential of a corrugated, perforated metal plate which is commonly used as absorber of the transpired solar collector TSC. He concludes that "tests have shown that night radiation cooling has the ability to cool air and thus buildings but the design tools to predict and evaluate the amount of cooling are severely lacking."

The roof of a building can heat up to high temperatures, increasing significant cooling load for interior spaces in summer. One of the methods of reducing the effect of solar radiation is to prevent it from reaching building surfaces by employing double layer techniques either on the wall or on the roof. Several studies have examined the energy saving potential of double roofs, underlining their beneficial effects. [25–31] The effects of cavity ventilation, roof slope, solar radiation intensity, cavity size, and shape and panel profiles have been investigated on the airflow in a ventilated roof. [32–34] It has also been proven that steeper roof slopes result in lower cavity temperatures. [35] Chan et. al. [36] presented a review of passive solar heating and cooling technologies, in which it is underlined that the main benefit of a ventilated roof can be realised in summer when the building is protected from solar gains. The study also reports on the air heating function of the transpired solar collector.

The aim of the current research is to supplement the scientific literature of transpired solar collectors with the complex energy evaluation of the TSC. This incorporates the performance evaluation of the nocturnal air cooling based on radiation towards the clear sky, the daytime cooling load reduction by natural ventilation of the air cavity, as well as the climate dependency of the solar air heating performance.

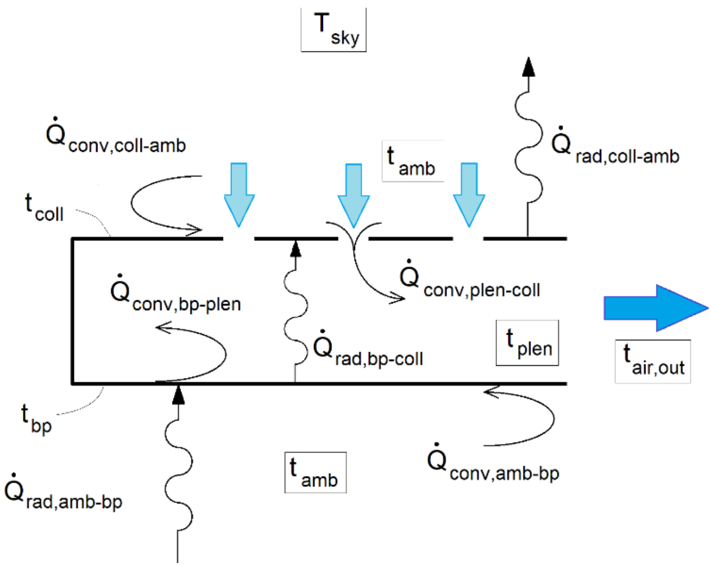

Figure 3: Heat transfer mechanisms between TSC components during nocturnal air cooling

I have developed a mathematical model for the energy evaluation of the nocturnal passive air cooling by TSC. The roof-mounted TSC consists of a collector plate, back plate and an air gap between them. The air gap is sealed from all directions, so air can enter only through the perforations. A fan is connected to the air gap, which makes the air transpire the collector plate. Heat transfer between the TSC components can be seen in Figure 3, based on which the mathematical model has been set up.

Similarly I have elaborated a mathematical model for the daytime cooling load reduction. In this case natural ventilation comes to be in the air gap, which thermally decouples the back plate from the collector plate. The physical model can be seen in Figure 4.

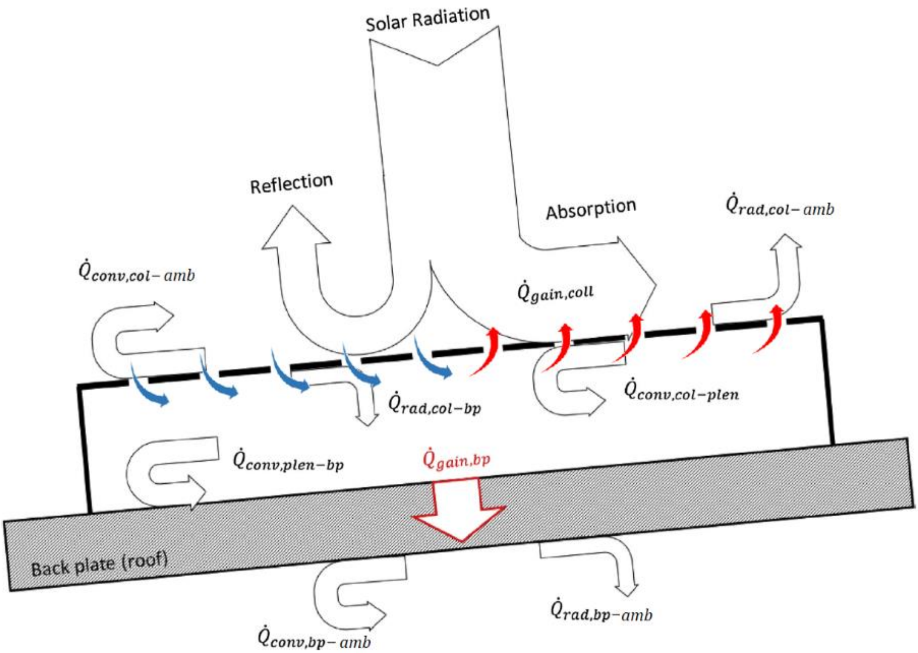

Figure 4: Heat transfer mechanisms between TSC components during daytime roof ventilation

Figure 5: TSC measurement setup used for the complex energy evaluation

For the validation of the mathematical models I used the TSC measurement setup, which can be seen in Figure 5. It was installed on the Engineering Faculty Campus of Trakya University, Edirne, Turkey.

4. MAIN RESULTS

TSC Nocturnal Radiant Cooling Operation Mathematical Model

A mathematical model has been elaborated for the determination of the passive cooling performance of the transpired solar collector. The model contains simplifications and assumptions which have been previously used in the TSC solar air heating research. These are:

- the temperature of the collector plate can be characterised by one single value,
- the temperature of the back plate can be characterised by one single value,
- the temperature of the plenum air can be characterised by one single value,
- the effect of the edges can be neglected.

The model has been validated with measurements for typical roof tilts (0°, 20°, 30°, 40°).

A new Nusselt-correlation has been developed for the calculation of the convective heat transfer between the cold collector plate and the airstream which transpires it. Measurement points fit the recommended correlation by $R^2 = 0.99$. The application boundaries of the Nusselt-correlation equal the general operational boundaries of transpired solar collectors with transpiration range of 28.63-76.36 [$m^3/(hm^2)$] and wind velocities 0.53-3.08 [m/s].

For the calculation of the radiative heat transfer between the collector plate and the sky, a correlation is necessary to estimate the equivalent temperature of the sky. This is a fictional temperature, using which one can simplify the surface-to-volume radiation to a much simpler surface-to-surface phenomenon. For the determination of the equivalent sky temperature several models are available in the literature. Finding the most suitable one is critical for the performance evaluation of the nocturnal radiant cooling, because the entire process is powered by the radiant heat flow from the collector plate to the sky. I have developed an algorithm for choosing the model that delivers the most accurate cooling performance. The procedure is summarised in Main Result 3.

Main Result 1

In the energy evaluation of nocturnal radiant cooling with a small-scale (5 m^2 or bigger) transpired solar collector, the description of the heat transfer and airflow phenomena with multi-dimensional, simultaneous energy balance equations can be neglected. The cooling performance can be determined by a system of global energy balance equations of concentrated parameters, given for each component of the transpired solar collector based on the first law of thermodynamics. The resultant of these approximates the actual cooling performance with -3.1 W absolute and 1.8 % relative error.

Publications: [P1]-[P4]

Main Result 2

For the calculation of the convective heat transfer between a perforated, trapezoidal plate and warmer airflow transpiring the plate, the following Nusselt correlation is to be utilised:

$$Nu_D = 1{,}05 \cdot Re_D^{0{,}82}.$$

The equation determines the correlation between the Reynolds and the Nusselt number with R^2 = 0.99.

Ranges of application:

- **tilt of plate: 0°-40° from the horizontal**
- **wind velocity: $w_{wind} = 0.53 - 3.08\ m/s$**
- **plate transpiration: $\dot{V}_0 = 28.63 - 76.36\ m^3/(h \cdot m^2)$**

Main Result 3

The most suitable equivalent sky temperature model for the air cooling performance evaluation of transpired solar collectors can be determined using the following method. TSC cooling performance can be either determined by direct measurement or given as the resultant of the energy balance equations given for its components. The latter results in different performance values for each sky temperature model used. Chosen is to be the model which delivers the resultant performance fitting the measured one with the most favourable results of statistical analysis.

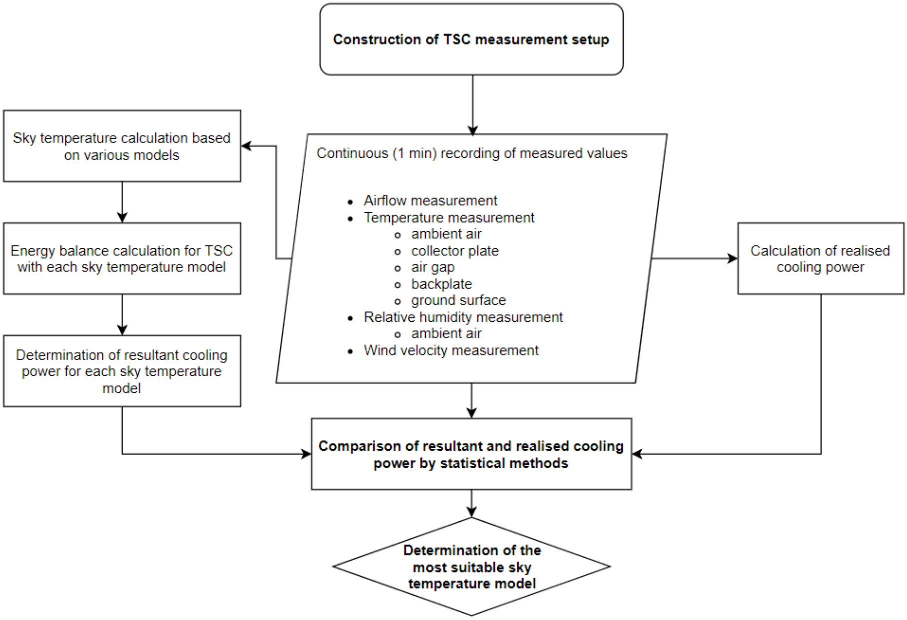

Figure 6: Flowchart of the most suitable equivalent sky temperature model determination

Publications: [P1]-[P2]

Daytime Cooling Load Reduction with Roof-Mounted TSC

I developed mathematical model for the evaluation of the roof cooling load reduction by a naturally ventilated double-roof constructed by mounting a transpired solar collector onto the original roof. The model has been validated with measurements for typical roof tilts (10°, 20°, 30°, 40°). Thermal images and measurements verify that the natural airflow comes to be in the air gap and the perforated plate is being transpired. The target of the model is the determination of the cooling load reduction between the collector plate and the back plate, which comes to be due to the shading of the roof by the TSC as well as the natural airflow. The roof cooling load reduction is advantageous not only from the energy point of view, but also the indoor thermal comfort is improved as the radiant heat flow striking the occupants from the ceiling can be significantly reduced.

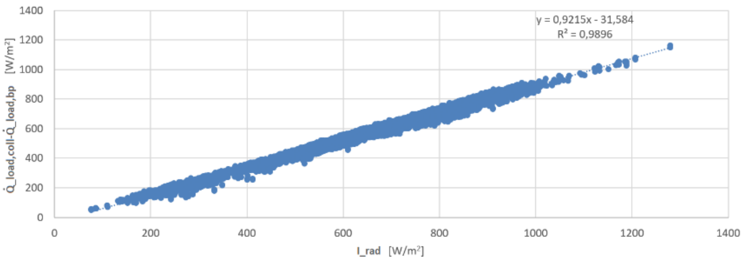

Figure 7: Heat load reduction between the collector and the back plate as a function of the solar radiation intensity measured in the collector plane

<u>Main Result 4</u>

A roof-mounted transpired solar collector with no suction applied, reduces a building's cooling load through the roof. The reduction is directly proportional to the intensity of the solar radiation measured in the collector plane. As a result of this the roof heat gain stays independent from the intensity of the solar radiation. This can be expressed as:

$$\dot{q}_{gain,coll} - \dot{q}_{gain,bp} = 0.92 \cdot I_{rad} - 31.6$$

with $\dot{q}_{gain,coll}$ the heat gain of the collector plate [W/m^2], $\dot{q}_{gain,bp}$ the heat gain of the back plate [W/m^2] and I_{rad} the intensity of solar radiation measured in the collector plane [W/m^2]. The equation describes the correlation between the cooling load reduction and the solar radiation intensity with $R^2 = 0.99$.

Publications: [P5], [P6]

Effect of Different Climates on the Solar Fraction

Energy consumption analysis of a reference industrial building has been executed using RETScreen 4 software in order to obtain the differences for four Turkish locations with significantly different climate. The cities chosen represent extrema regarding the solar radiation intensity and heating degree days in Turkey, a country with so diverse climatic conditions, that the cities can also represent the edges of the HDD and SR scales in Central and Southern Europe. The energy consumption of the reference building has been determined for all for locations, for every month of a reference year for cases with and without TSC. The correlation between the solar fraction, the heating degree days and the intensity of solar radiation is summarised in Main Result 5. The correlation is visualised by Figure 8, based on which it can be stated that the solar fraction has a minimum on the heating degree day scale. This means that when the TSC operates in a cold location, a high proportion of the solar heat is utilised, whereas in warm climates the solar heat takes out a high proportion of the generally low heating demand. HDD in Budapest is 3061 day°C/a, whereas the yearly sum of global solar radiation is 1260 kWh/m^{2}a, meaning that Figure 8 delivers locally applicable information for Hungary.

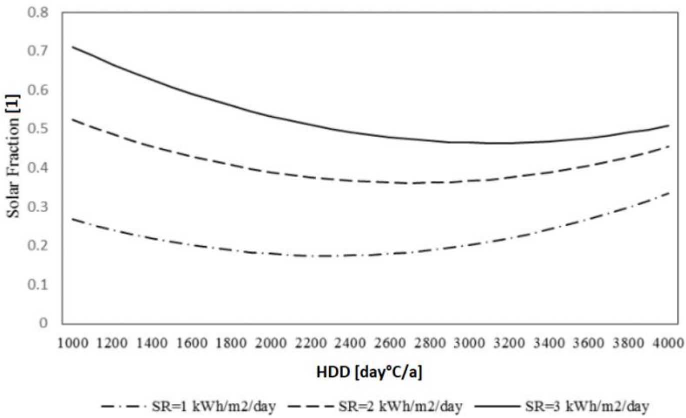

Figure 8: Solar fraction as a function of heating degree days and solar radiation

Main Result 5

For a TSC-heated industrial building of typical architectural features and building envelope quality the solar fraction can be expressed as a function of the heating degree days and the intensity of the solar radiation with the following equation:

$$SF = a_1 + a_2 \cdot SR + a_3 \cdot HDD + a_4 \cdot SR^2 + a_5 \cdot HDD^2 + a_6 \cdot SR \cdot HDD$$

in which SF is the solar fraction [1], SR is the solar energy reaching one m^2 of surface in a year [kWh/(m^{2}a)] and HDD represents the heating degree days [day°C/month].

Constants of the equation:

a_1	**0.1016**	**[1]**
a_2	**0.3995**	**[(m^{2}day)/kWh]**
a_3	**- 2.1016 E-4**	**[month/day°C]**
a_4	**-3.3203 E-2**	**[m^{4}day^2/kWh^2]**
a_5	**5.5499 E-8**	**[month^2/(day°C)^2]**
a_6	**-4.5012 E-5**	**[(m^{2}month)/(kWh°C)]**

Publications: [P7]-[P11]

5. APPLICABILITY OF RESULTS

The main aim of the research was to acquire results which are not only useful for TSC researchers, but also applicable for building service engineers designing TSC systems.

The nocturnal passive air cooling operation, as well as the daytime roof ventilation by transpired solar collectors have been up until now an unknown area. This means that the results open up new ways to utilise a simple solar air heater which can be installed on low first costs and operated in an almost maintenance-free manner.

The evaluation of the model for nocturnal air cooling with energy balance equations of concentrated parameters, and the validation of this method make it possible to carry out industrial trial measurements for the estimation of cooling performance before setting up a TSC system.

The developed Nusselt-correlation can be valuable first of all for transpired solar collector researchers. Using this the convective heat transfer between a complicated airstream (transpiration of a perforated trapezoidal plate by air) can be calculated.

Moreover, it can be used in all cases of heat transfer calculation with transpired trapezoidal plates with a warmer airflow, within the ranges of applicability.

The developed method for the determination of the most suitable sky temperature model is to be utilised every time the cooling performance evaluation of a TSC system is carried out, as differences in geographical location can result in various models turning out to be the most suitable one.

It is important to make it clear to engineers and architects that covering the façade or roof of a building with dark transpired solar collectors does not increase the cooling load in summer. In the contrary – as the current research has shown – it reduces the cooling load significantly. Results are scientific proof of this phenomenon, understanding which may help the TSC technology go more widespread.

The correlation between the solar fraction, the heating degree days and the intensity of solar radiation can help engineers to estimate the solar fraction provided by a proposed TSC system, once performance information from other systems, operating in different climates is available.

6. NOMENCLATURE

abbreviation	description	unit
HDD	heating degree day	[day°C/month]
I_{rad}	intensity of solar radiation	[W/m²]
Nu_D	Nusselt-number	[1]
$\dot{Q}_{\mathrm{conv,amb-coll}}$	convective heat transfer btw. ambiance and collector	[W]
$\dot{Q}_{\mathrm{conv,plen-coll}}$	convective heat transfer btw. plenum and collector	[W]
$\dot{Q}_{\mathrm{conv,bp-plen}}$	convective heat transfer btw. back plate and plenum	[W]
$\dot{Q}_{\mathrm{conv,amb-bp}}$	convective heat transfer btw. ambiance and plenum	[W]
$\dot{Q}_{\mathrm{rad,coll-amb}}$	radiative heat transfer btw. collector and ambiance	[W]
$\dot{Q}_{\mathrm{rad,bp-coll}}$	radiative heat transfer btw. back plate and collector	[W]
$\dot{Q}_{\mathrm{rad,amb-bp}}$	radiative heat transfer btw. ambience and back plate	[W]
$\dot{Q}_{\mathrm{gain,bp}}$	back plate heat gain	[W]

abbreviation	description	unit
$\dot{Q}_{gain,coll}$	collector plate heat gain	[W]
$\dot{Q}_{conv,coll-amb}$	convective heat transfer btw. collector and ambience	[W]
$\dot{Q}_{conv,coll-plen}$	convective heat transfer btw. collector and plenum	[W]
$\dot{Q}_{conv,plen-bp}$	convective heat transfer btw. plenum and back plate	[W]
$\dot{Q}_{conv,bp-amb}$	convective heat transfer btw. back plate and ambience	[W]
$\dot{Q}_{rad,coll-bp}$	radiative heat transfer btw. collector and back plate	[W]
$\dot{Q}_{rad,bp-amb}$	radiative heat transfer btw. back plate and ambiance	[W]
Re_D	Reynolds number	[1]
SF	solar fraction	[1]
SR	daily sum of solar energy on horizontal surface	[kWh/m^{2}d]
t_{bp}	back plate temperature	[°C]
t_{coll}	collector plate temperature	[°C]
t_{amb}	ambient temperature	[°C]
t_{plen}	plenum temperature	[°C]
$t_{air,out}$	leaving air temperature	[°C]
T_{sky}	equivalent sky temperature	[K]

7. PUBLICATIONS

[P1] Bokor B, Kajtár L, Eryener D: Nocturnal Radiation, New Opportunity in Building Cooling. Energy Procedia 112 (2017) pp. 118-125.

[P2] Bokor B, Kajtár L: Transpired Solar Collectors in Building Service Engineering: Combined System Operation and Special Applications. International Review of Applied Sciences and Engineering 9:(1) (2018) pp. 65-71.

[P3] Szabo J, Kajtar L, Nyers J, Bokor B: A new approach and results of Wall and Air Temperature Dynamic Analysis in Underground Spaces. Energy 106: pp. 520-527. (2016)

[P4] Bokor Balázs: Mérési összeállítás koncepciója levegős kollektorok teljesítményének meghatározására. Magyar Épületgépészet (HU ISSN 1215 9913) 2014/5. pp. 7-10.

[P5] Bokor B, Akhan H, Eryener D, Kajtár L: Theoretical and experimental analysis on the passive cooling effect of transpired solar collectors. Energy and Buildings 156: pp. 109-120. (2017)

Number of independent citations: 2

[P6] Kajtár L, Nyers J, Szabó J, Ketskeméty L, Herczeg L, Leitner A, Bokor B: Objective and subjective thermal comfort evaluation in Hungary. Thermal Science 21:(3) pp. 1409-1418. (2017).

Number of independent citations: 4

[P7] Bokor B, Akhan H, Eryener D, Kajtár L: The Potential of Solar Air Heating in the Turkish Industrial Sector. Periodica Politechnica, 8 oldal, közlésre elfogadva (2018. október)

[P8] Bokor Balázs, Kajtár László: Solar Air Heaters, New Opportunities in Solar thermal Energy Use. New Energy 2015: pp. 36-39. (2015)

Number of independent citations: 9

[P9] Bokor B: Levegős napkollektorok - napenergia hasznosítása épületek szellőztetésében: 2. rész: Perforált abszorberű, burkolat nélküli kollektorok és rendszermegoldások. Magyar Installateur 2014/6-7.: pp. 41-43. (2014)

[P10] Bokor B, Kajtár L: Luftkollektoren: Nutzung der Sonnenenergie in der Gebäudelüftung. Proceedings of International conference E-Nova 2014. Graz Leykam, 2014. pp. 305-310. (ISBN: 978-3-7011-0316-4)

Number of independent citations: 1

[P11] Bokor Balázs, Hacer Akhan, Dogan Eryener, Kajtár László: Ventilation Air Heating with Transpired Solar Collectors. Magyar Épületgépészet 67:11 pp. 15-18. (2018)

8. REFERENCES

[1] Bokor B., Vörös K., Kajtár L.: *Fűtőművek energetikai korszerűsítése szolárfal rendszerrel*, Magy. Épületgépészet. 67. évfoly (2018) 1–6.

[2] Hollick John: *Nocturnal radiation cooling tests*, Energy Procedia. 30 (2012) 930–936. doi:10.1016/j.egypro.2012.11.105.

[3] Conserval Engineering Inc.: *SolarWall, Solar Air Heating System*, (n.d.). http://solarwall.com/en/home.php (accessed October 13, 2018).

[4] Kutscher C.F., Christensen C.B., Barker G.M.: *Unglazed Transpired Solar Collectors: Heat Loss Theory*, J. Sol. Energy Eng. 115 (1993) 182. doi:10.1115/1.2930047.

[5] Kutscher C.F.: *Heat Exchange Effectiveness and Pressure Drop for Air Flow Through Perforated Plates With and Without Crosswind*, J. Heat Transfer. 116 (1994) 391. doi:10.1115/1.2911411.

[6] Van Decker G.W.E., Hollands K.G.T., Brunger A.P.: *Heat-exchange relations for unglazed transpirred solar collectors with circular holes on a square or triangular pitch*, Sol. Energy. 71 (2001) 33–46. doi:10.1016/S0038-092X(01)00014-7.

[7] Leon M. Augustus, Kumar S.: *Mathematical modeling and thermal performance analysis of unglazed transpired solar collectors*, Sol. Energy. 81 (2007) 62–75. doi:10.1016/j.solener.2006.06.017.

[8] Kutscher C.F.: An Investigation of Heat Transfer for Air Flow through Low Porosity Perforated Plates, University of Colorado, 1992.

[9] Gawlik Keith, Christensen Craig, Kutscher Charles: *A Numerical and Experimental Investigation of Low-conductivity Unglazed, Transpired Solar Air Heaters*, J. Sol. Energy Eng. 127 (2005) 153. doi:10.1115/1.1823494.

[10] Gawlik K.M., Kutscher C.F.: *Wind heat loss from corrugated, transpired solar collectors*, J. Sol. Energy Eng. Asme. 124 (2002) 256–261. doi:10.1115/1.1487886.

[11] Collins Michael R., Abulkhair Hani: *An evaluation of heat transfer and effectiveness for unglazed transpired solar air heaters*, Sol. Energy. 99 (2014) 231–245. doi:10.1016/j.solener.2013.11.012.

[12] Li Siwei, Karava Panagiota, Savory Eric, et al.: *Airflow and thermal analysis of flat and corrugated unglazed transpired solar collectors*, Sol. Energy. 91 (2013) 297–315. doi:10.1016/j.solener.2013.01.028.

[13] Croitoru Cristiana V., Nastase Ilinca, Bode Florin I., et al.: *Thermodynamic investigation on an innovative unglazed transpired solar collector*, Sol. Energy.

131 (2016) 21–29. doi:10.1016/j.solener.2016.02.029.

[14] Hall Richard, Blower John: *Low-emissivity Transpired Solar Collectors*, Energy Procedia. 91 (2016) 56–63. doi:10.1016/j.egypro.2016.06.171.

[15] Artmann N., Manz H., Heiselberg P.: *Parameter study on performance of building cooling by night-time ventilation*, Renew. Energy. 33 (2008) 2589–2598. doi:10.1016/j.renene.2008.02.025.

[16] Artmann N., Manz H., Heiselberg P.: *Climatic potential for passive cooling of buildings by night-time ventilation in Europe*, Appl. Energy. 84 (2007) 187–201. doi:10.1016/j.apenergy.2006.05.004.

[17] Kolokotroni M., Webb B.C., Hayes S.D.: *Summer cooling with night ventilation for office buildings in moderate climates*, Energy Build. 27 (1998) 231–237. doi:10.1016/S0378-7788(97)00048-0.

[18] Kolokotroni M., Aronis A.: *Cooling-energy reduction in air-conditioned offices by using night ventilation*, Appl. Energy. 63 (1999) 241–253. doi:10.1016/S0306-2619(99)00031-8.

[19] Kolokotroni M., Gowreesunker B.L., Giridharan R.: *Cool roof technology in London: An experimental and modelling study*, Energy Build. 67 (2013) 658–667. doi:10.1016/j.enbuild.2011.07.011.

[20] Blondeau P., Spérandio M., Allard F.: *Night ventilation for building cooling in summer*, Sol. Energy. 61 (1997) 327–335. doi:10.1016/S0038-092X(97)00076-5.

[21] Mihalakakou G., Ferrante A., Lewis J.O.: *The cooling potential of a metallic nocturnal radiator*, Energy Build. 28 (1998) 251–256. doi:10.1016/S0378-7788(98)00006-1.

[22] Bagiorgas H.S., Mihalakakou G.: *Experimental and theoretical investigation of a nocturnal radiator for space cooling*, Renew. Energy. 33 (2008) 1220–1227. doi:10.1016/j.renene.2007.04.015.

[23] Parker Danny S., Sherwin John R.: *Theoretical Evaluation of the NightCool Nocturnal Radiation Cooling Concept*, Cocoa, Florida, 2005.

[24] Parker Danny S., Sherwin John R.: *Experimental Evaluation of the NightCool Nocturnal Radiation Cooling Concept : Performance Assessment in Scale Test Buildings*, Cocoa, Florida, 2005.

[25] Shiraishi Yasuyuki, Murakami Shuzo, Kato Shinsuke: *Study on thermal shielding effect of double roofing with air passage by coupled simulation of convection and radiation S tudy on thermal shielding effect of double roofing with air passage by coupled simulation of c onvection and ra diation*, (2016) 19–22.

[26] Černe Boštjan, Medved Sašo: *Determination of transient two-dimensional heat transfer in ventilated lightweight low sloped roof using Fourier series*, Build. Environ. 42 (2007) 2279–2288. doi:10.1016/j.buildenv.2006.04.022.

[27] Ong K.S.: *Temperature reduction in attic and ceiling via insulation of several passive roof designs*, Energy Convers. Manag. 52 (2011) 2405–2411. doi:10.1016/j.enconman.2010.12.044.

[28] Gagliano A., Patania F., Nocera F., et al.: *Thermal performance of ventilated roofs during summer period*, Energy Build. 49 (2012) 611–618. doi:10.1016/j.enbuild.2012.03.007.

[29] Tong Shanshan, Li Hua: *An efficient model development and experimental study for the heat transfer in naturally ventilated inclined roofs*, Build. Environ. 81 (2014) 296–308. doi:10.1016/j.buildenv.2014.07.009.

[30] Oh Jeong Hee, Kopp Gregory A.: *An experimental study of pressure distributions within an air-permeable, double-layer roof system in regions of separated flow*, J. Wind Eng. Ind. Aerodyn. 138 (2015) 1–12. doi:10.1016/j.jweia.2014.12.006.

[31] Zingre Kishor T., Wan Man Pun, Wong Swee Khian, et al.: *Modelling of cool roof performance for double-skin roofs in tropical climate*, Energy. 82 (2015) 813–826. doi:10.1016/j.energy.2015.01.092.

[32] Biwole P.H., Woloszyn M., Pompeo C.: *Heat transfers in a double-skin roof ventilated by natural convection in summer time*, Energy Build. 40 (2008) 1487–1497. doi:10.1016/j.enbuild.2008.02.004.

[33] Lai Chi ming, Huang J.Y., Chiou J.S.: *Optimal spacing for double-skin roofs*, Build. Environ. 43 (2008) 1749–1754. doi:10.1016/j.buildenv.2007.11.008.

[34] Li Dong, Zheng Yumeng, Liu Changyu, et al.: *Numerical analysis on thermal performance of naturally ventilated roofs with different influencing parameters*, Sustain. Cities Soc. 22 (2016) 86–93. doi:10.1016/j.scs.2016.02.004.

[35] Lee Kyoung Ho, Lee Dong Won, Baek Nam Choon, et al.: *Preliminary determination of optimal size for renewable energy resources in buildings using RETScreen*, Energy. 47 (2012) 83–96. doi:10.1016/j.energy.2012.08.040.

[36] Chan Hoy Yen, Riffat Saffa B., Zhu Jie: *Review of passive solar heating and cooling technologies*, Renew. Sustain. Energy Rev. 14 (2010) 781–789. doi:10.1016/j.rser.2009.10.030.