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Preliminary Results of Testing a Solar Air Heater Equipped with Turbulators

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Abstract. The paper presents the thermal performance of a newly designed device for preheating ventilation air. This new type of a solar air collector is equipped with turbulators to increase heat exchange and eventually to obtain more energy from the Sun. Support elements of this type have not yet been implemented in such heat exchangers. The panel has the following dimensions: width – 0.97 m, length – 1.9 m, thickness – 0.1 m, the area where solar radiation enters the collector – 1.49 m^2. Air flow through the exchanger is forced by two radial high flow fans, typically used to cool down servers. The test stand beside the collectors is equipped with an inlet and outlet temperature data recorder and an anemometer to control the air flow rate through the collector. Meteorological data such as solar radiation, wind speed and ambient temperature is obtained from a weather station. The parameters of the working installation have been analysed through the monitoring of measurement variables collected on one-minute time intervals from April to September 2016. The measurement results have been used to determine the thermal performance of the air solar collector of this type. The results of the energy analysis have shown the validity of such an installation.

Keywords: solar air heater, turbulators, renewable energy sources, thermal performance.

Conference topic: Energy for buildings.

Introduction

The widespread use of solar air heaters (SAH) can contribute to the achievement of the "Climate and Energy Package" goals. The SAHs are becoming increasingly popular in agriculture, and particularly in the residential buildings sector. A general review of the construction of solar energy conversion devices is presented in (Saxena *et al.* 2015; Zukowski 2013) where both the advantages and disadvantages of glazed, unglazed, parallel-pass, double-pass and transpired solar air panels are characterized. It is generally believed that air is not the most effective working fluid when considering the optimization of heat exchangers. This negative feature is the direct result of the low value of thermal conductivity and specific heat. For this reason, various technical solutions can also be applied in order to improve the thermal performance of such equipment (Zukowski 2013).

Solar energy is the type of energy source that is both freely available and possible to be endlessly used. The solar air heater is one of the most popular thermal collection devices because it is easy to use and maintain. However, its energy saving parameters are quite low due to the low convective heat transfer coefficient for smooth surface or the flat plate of the solar air heater. They can be improved by the application of passive techniques in the form of artificial roughness on the absorber plate of the SAH. A fin, groove, baffle, rib, wing and winglet are often introduced to the design of the solar air heater in order to increase the convective heat transfer rate which leads to more compact heat exchangers and to increased thermal performance. A turbulent promoter (called 'vortex generator', VG) in the form of a wing-type vortex generator (WVG) is often used to help increase the heat transfer coefficient through fast fluid mixing between the core and the near-surface and to reduce thermal boundary layer in the absorber plate (Aris *et al.* 2011; Tamna *et al.* 2014; Skullong *et al.* 2016).

The use of artificial roughness or turbulence promoters, such as sand grains, ribs or wires, on a heated surface, is an effective technique to increase the heat transfer rate to a convective fluid (Webb *et al.* 1971; Han *et al.* 1978). In particular, rib-roughened channels with repeated rib turbulators along the main flow direction have been recommended for heat transfer augmentation in several engineering systems: gas-cooled nuclear reactors, electronic devices, compact heat exchangers, combustor walls, solar air heater ducts and internal passages gas turbine blades (Han *et al.* 2000; Tanda 2011). Protrusions, fins and other kinds of extended surface geometries mainly produce augmented heat transfer surfaces as compared to a flat surface, resulting in higher heat transfer rates. Examples of SAH ducts filled with fins are documented in (Hachemi 1995; Moummi *et al.* 2004): significant enhancement of the efficiency of the finned collector has been found despite the increase in the pressure losses generated by the addition of the fins. Investigations of the efficiency of SAHs with obstacles and double-flow passages have been performed in (Esen 2008; Ozgen *et al.* 2009), where various shapes of extended surfaces have been studied: triangular and rectangular fins deployed normal to the main flow in a staggered arrangement, and rows of circular cross-section channels (made of aluminum cans open at the top and the bottom) installed, staggered or in-line, on the absorber plate and oriented along the main flow. Both the double-flow passage and the presence of the fins or cans contribute to increased performance, as compared to a conventional, one-passage, flat solar air collector. The application of wires or ribs fixed on the absorber plate has been widely studied and recommended by several investigators (Prasad, Saini 1988; Gupta *et al.* 1993; Saini, R. P., Saini, J. S. 1997; Gupta *et al.* 1997; Karwa *et al.* 1999; Verma, Prasad 2000; Momin *et al.* 2002; Bhagoria *et al.* 2002; Sahu, Bhagoria 2005; Mittal *et al.* 2007; Layek *et al.* 2007; Kumar *et al.* 2009; Aharwal *et al.* 2009). The implementation of artificial roughness elements, like ribs, is useful to break the laminar sublayer and create local wall turbulence due to flow separation and reattachment between the ribs, thus greatly enhancing the cooling effect. However, this is typically accompanied by an increase in frictional losses which leads to the fan requiring more power. Thus, the design of the roughness elements should take into account both the convective heat transfer enhancement and the corresponding increase in friction losses (Tanda 2011). Some examples of applications of the entropy generation minimization criterion are provided in (Bejan 1987; Tagliafico, Tanda 1996; Zimparov 2001), with specific reference to heat exchanger design. As attention is focused on the SAH with roughness elements or fins on the absorber plates, the performance analysis should include the friction penalty along with the useful energy collection rate. Cortes and Piacentini (1990) define an effective efficiency of a SAH on the basis of net thermal energy gain obtained by subtracting the equivalent thermal energy, required to overcome the friction power, from the collector useful gain. The performance evaluation criterion based on the effective efficiency, ruled by the first law analysis, has been adopted by Gupta *et al.* (1997) and Mittal *et al.* (2007), to compare the performance of SAHs with different types of roughness elements on the absorber plate; the effects of roughness parameters, insolation and flowrate have been typically investigated. The second law analysis of a SAH, rarely encountered in literature, has been solved by Layek *et al.* (2007) and Esen (2008). Despite the transient nature of the SAH performance under real working conditions, these studies were conducted in the steady-state due to the complexity of the analysis and the large number of variables involved.

The environmental impact of different types of solar panels are presented by Aman *et al.* (2015). The authors have studied this issue taking into account the manufacturing and demolition phases. It is concluded that, due to the content of toxic materials in their components, solar air panels can pose environmental threat. On the other hand, passive and active solar systems provide significant environmental benefits during the operation phase. Negative and positive environmental implications associated with the use of solar energy techniques are reported by Tsoutsos *et al.* (2005). The reduction of greenhouse gases (GHG) emissions and the prevention of emission of toxic gases has been listed by Zukowski (2016) as the main environmental advantages.

Description of the solar air heater and the test apparatus

The solar air heater under the test, a prototype, was made of an aluminum casing of the following dimensions: height – 1900 mm (with fans chamber and inlet and outlet tubes), depth – 100 mm (without the channel connections), length – 850 mm (without handles). The top cover of the SAH was a solar glass with the thickness of 3.2 mm. Phenolic foam thermal insulation (thickness – 40mm, thermal conductivity λ = 0.021 W/m/K) was applied as a protection against heat loss. The most important part of the collector – the absorber – was made of aluminum sheet covered with a special coating to ensure high absorption of solar radiation (emissivity = 0.97). The SAH was equipped with turbulators, which were patented in 2016 (P31221PC00/ZA / PCT/IB2017/050617).

The solar panel was equipped with a system allowing to change the angle of inclination in the range of 0 to 90 degrees. The main dimensions of the solar heater were as follows:

- Gross area (calculated as the height multiplied by the length) – 1.84 m^2,
- Absorber area (calculated as the exposed area of the absorber plate) – 3.4 m^2,
- Aperture area (calculated as the area of the glazing exposed to the Sun's radiation) – 1.53 m^2.

As shown in Figure 1, the SAH was installed on the roof of the building of Faculty of Civil Engineering and Environmental Engineering – Bialystok University of Technology (Poland).

Fig. 1. SAH tested experimentally in normal operating conditions

The test stand is provided in Figure 2. The external air was sucked from the back shaded side of the collector by two centrifugal fans. The flow rate could be adjusted over a wide range from 50 m^3/h to 120 m^3/h. The air temperature at the SAH inlet and outlet was measured by four PT1000 resistance temperature sensors. A multi-channel data recorder was used to collect the results of the investigations with one-minute time intervals. Meteorological parameters monitoring was performed by an automatic weather station integrated with a wireless data logger that was located inside the building. The station allowed to measure such environmental parameters as outside air temperature, wind speed and direction, humidity and solar radiation. The sampling frequency of the weather conditions was set to one minute.

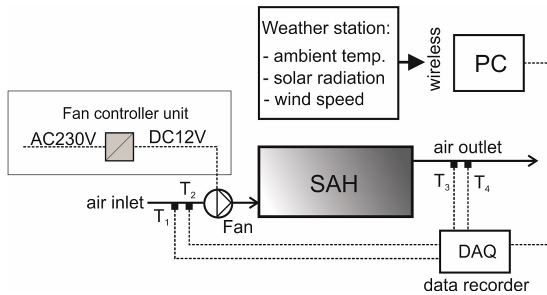

Fig. 2. Diagram showing the measurement stand

Results of the experiments and discussion

The main goal of this project was to determine the thermal characteristic of the new type of the air solar heater. As has been already mentioned, the project was conducted as two series of experiments with different air flow rates. In the first case (110 m^3/h) the study lasted from April 27 to May 5, 2016. After reducing the air flow rate to 80 m^3/h, the other series of measurements was carried out, from May 11 to 19, 2016.

The characteristics of the weather conditions that occurred during these two periods are shown in Figure 3 and Figure 4. The figures show that a wide range of variation of both irradiance and air temperature occurred during both experiment periods while wind speed remained light and moderate.

Selected results of the measurements are presented below. In the case of solar air heaters, an important parameter is the temperature rise ΔT_{SAH} (Eq. (1)) inside the device, i.e. the difference between the outlet T_{out} and inlet T_{in} temperature of the air. The increase in the temperature of air passing through the solar panel as the function of solar radiation flux is shown in Figure 5 (*Case I)* and Figure 6 (*Case II)*. In both cases, the sets of data have a linear correlation (dashed line). Thus, the results of the experiment were approximated with the use of the linear regression method. As can be observed, with lower air flow rate – 80 m^3/h, the maximum temperature rise exceeds 40 °C, which can be considered as a good result. As is well known, an increase in flow rate causes a decrease in ΔT_{SAH} value.

$$\Delta T_{SAH} = T_{out} - T_{in} . \quad (1)$$

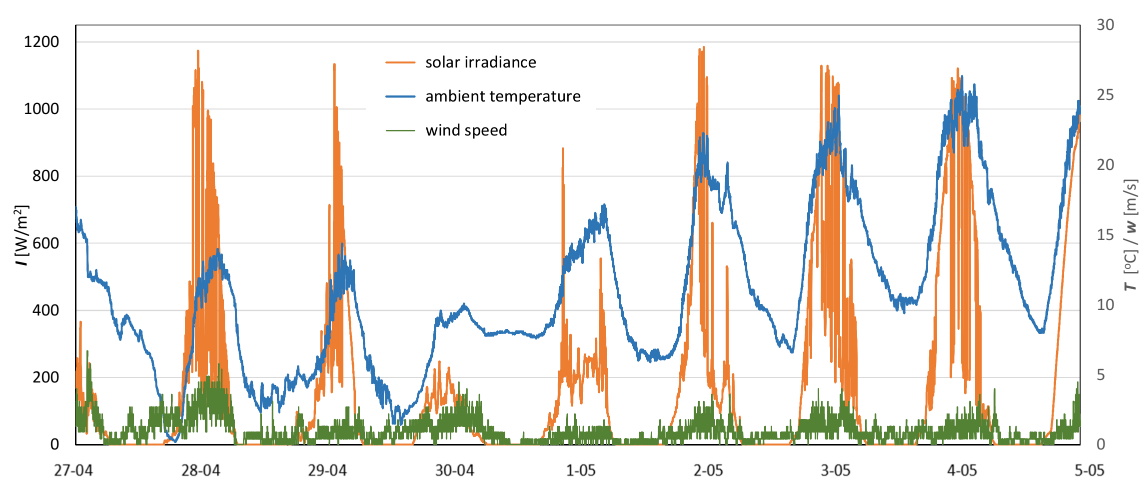

Fig. 3. Solar radiation intensity falling on the collector surface and ambient temperature during *Case I*

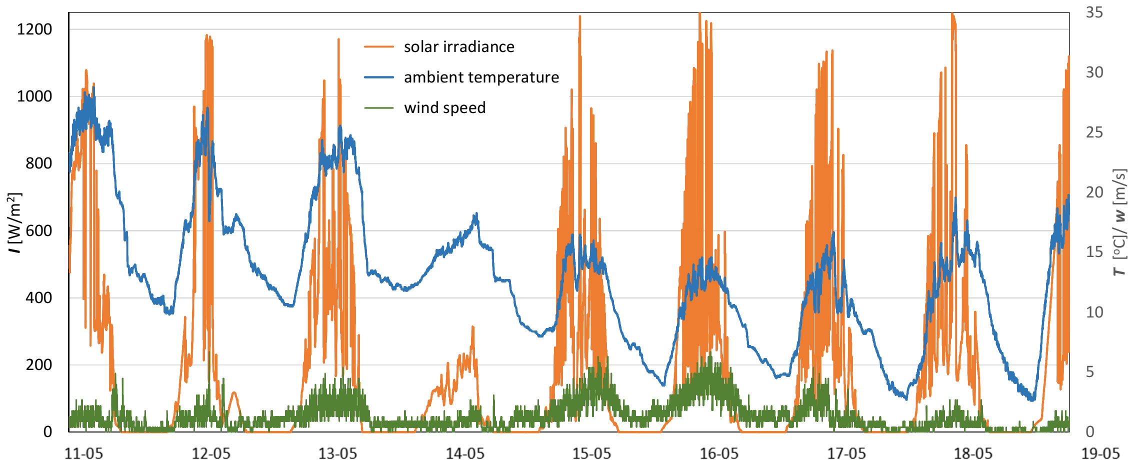

Fig. 4. Solar radiation intensity falling on the collector surface and ambient temperature during *Case II*

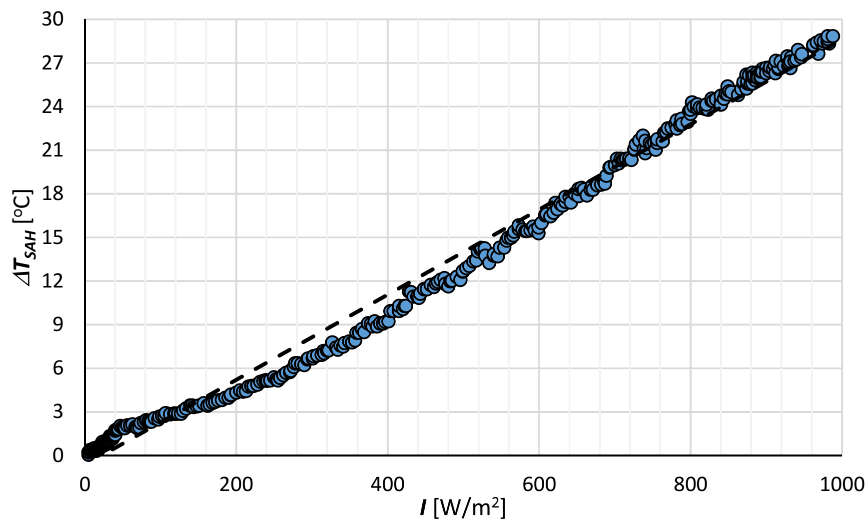

Fig. 5. Dependence between air temperature rise and solar radiation intensity for *Case I*

The relationship between ΔT_{SAH} and I can be defined using Eq. (2) (*Case I)* and Eq. (3) (*Case II)* with excellent linear reliability, because the value of the correlation coefficient *R*-squared is equal 0.9917 and 0.9928, respectively.

$$\Delta T_{SAH} = 0.0293 \cdot I - 0.6581 . \tag{2}$$

$$\Delta T_{SAH} = 0.0414 \cdot I - 1.2989 . \tag{3}$$

Knowing the value of air temperature increase resulting from the flow through the panel, we can estimate the power output of the solar collector q_{SAH} in W/m^2, based on the following relation:

$$q_{SAH} = \frac{V_a \cdot \rho_a \cdot c_p \cdot \Delta T_{SAH}}{A_A} , \tag{4}$$

where: V_a – volume air-flow rate [m^3/s], ρ_a – air density [kg/m^3], c_p – heat capacity of air [J/kg/K], A_A – aperture area [m^2].

Figure 7 shows the dependence of actual useful power extracted from 1 m^2 of the SAH on the intensity of solar radiation.

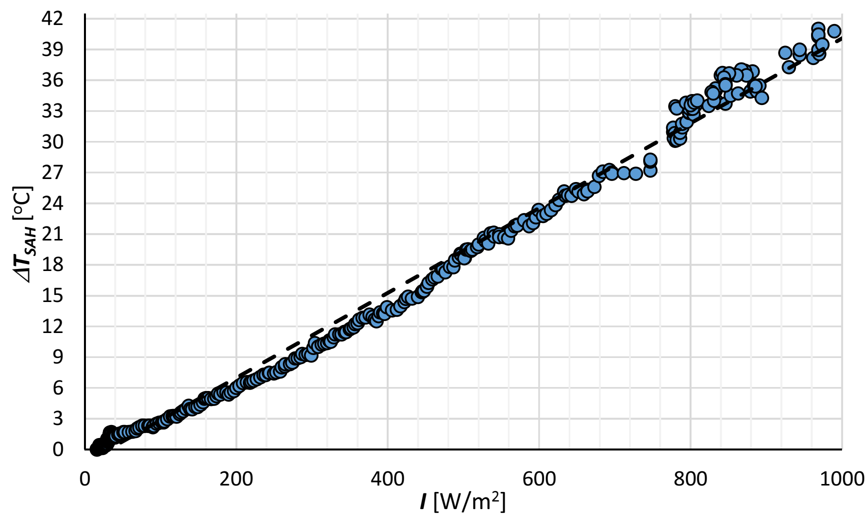

Fig. 6. Dependence between air temperature rise and solar radiation intensity for *Case II*

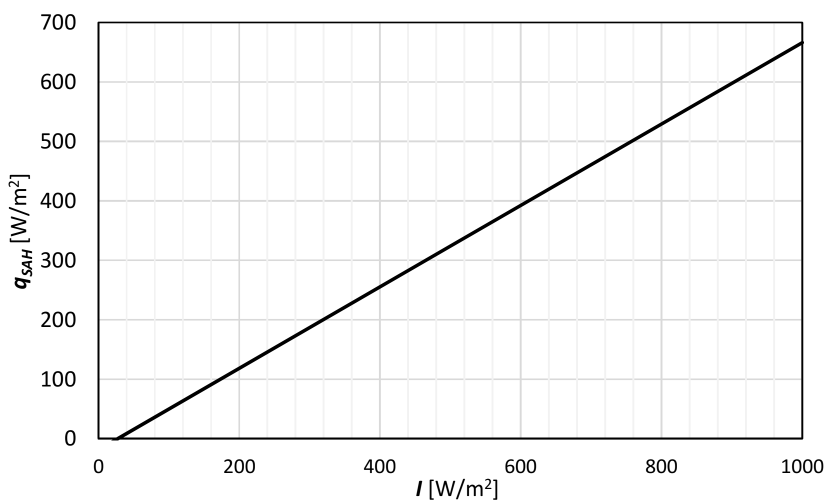

Fig. 7. The influence of solar radiation on the power output of the solar air heater

Another important parameter of the thermal performance is the efficiency of the solar collector η_A. This value is defined as useful energy, obtained through the conversion of solar radiation into heat energy, to the total radiation falling on the absorber. Instantaneous efficiency based on absorber area A_A can be obtained from Eq. (5).

$$\eta_A = \frac{V_a \cdot \rho_a \cdot c_p \cdot \Delta T_{SAH}}{I \cdot A_A}. \quad (5)$$

The results of the calculations performed on the basis of the collected measurement data are presented in Figure 8 for *Case I* and Figure 9 for *Case II*. The analysis of these graphs leads to the conclusion that the efficiency of the SAH falls within the range of 50% to 70%. The energy efficiency of the tested system increases with the intensity of solar radiation. As is clearly observable, both characteristics are similar. Thus, the turbulators have a positive impact on the intensification of heat exchange, even at lower air flow rates.

It should be pointed out that the efficiency of solar energy conversion of this tested novel device is not only comparable, but even higher than the efficiency of the best commercially available solutions – see chart at Figure 15 in (Zukowski 2015).

The quality of the experimental runs was estimated on the basis of the root-sum-square method (Mathioulakis *et al.* 2012). The maximum uncertainty in the thermal performance was 3.89% and the relative error did not exceed 0.058.

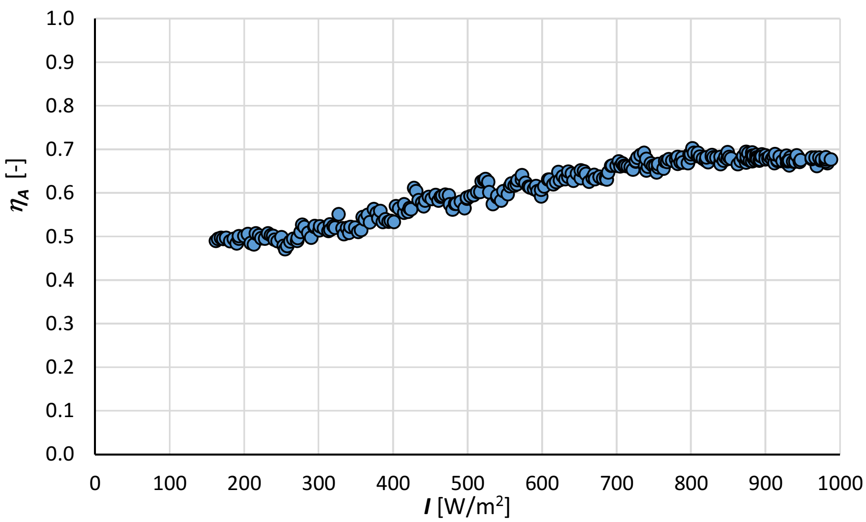

Fig. 8. Thermal efficiency of the SAH as the function of solar radiation for *Case I*

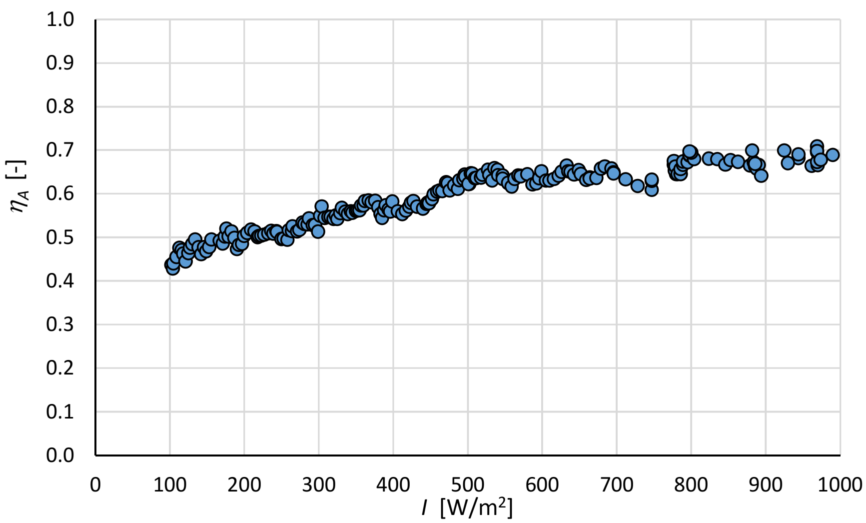

Fig. 9. Thermal efficiency of the SAH as the function of solar radiation for *Case II*

The Hottel-Whillier-Bliss model (Hottel, Whillier 1958) is often used to determine the thermal characteristics of all kinds of solar collectors. This method involves the application of the T_m^* parameter (Eq. (6)).

$$T_m^* = \frac{T_{in} - T_{amb}}{I} . \tag{6}$$

The collector was tested in an open circuit. Therefore, it was not possible to determine its characteristic based on the T_m^*, as the supply temperature T_{in} was equal to the ambient temperature T_{amb}. It is planned that the next stage of this project will involve building a test stand in a closed system. It will be equipped with the simulator of wind and an electric heater to change the inlet temperature of the air within a wide range. Only after implementing these enhancements it will be possible to determine the full thermal characteristics in the static and dynamic conditions.

Conclusions

The widespread use of renewable energy sources are an effective way to increase energy security at the local level, as well as to improve ambient air quality. The main goal of the present analysis has been to determine the thermal performance of the new type of the solar air collector for the purpose of preheating ventilation air in cold climates. The newly designed device is equipped with turbulators for the intensity of heat transfer.

The measurements taken have allowed to determine that the maximum temperature rise inside the tested SAH exceeds 40 °C and 27.5 °C for air flow rate equal to 80 m^3/h and 110 m^3/h, respectively. Both values can be regarded as a good result.

The thermal efficiency of the solar panel was related to the intensity of solar radiation. The highest efficiency (70%) appeared at the maximum insolation. The efficiency dropped to 50% when the radiation flux decreased to 200 W/m^2.

In conclusion, it should be noted that the use of turbulators can be regarded as a good technical solution, which allows the tested collector to compete with the best commercially available solar air panels.

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