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Section: Energy for Buildings

Simulation of ventilation system with unglazed solar collector and air heat pump

Violeta Misevičiūtė, Lukas Rudzinskas

Deparment of Building Eneregetics, Vilnius Gediminas Technical University, Saulėtekio al. 11, Vilnius 10223, Lithuania

Abstract

The European Directive on Energy Performance of Buildings (EPBD) obliges to accept measures for improving the energy efficiency in buildings. As buildings become more airtight ventilation takes an important role in building. Ventilation efficiency as a rule is achieved using heat recovery. The efficiency of the air heat recovery is varies depending on the applied type of heat exchanger and changes during the year. A dozen of heat recovery units, renewable energy sources and technologies can be applied to ventilation system to increase an efficiency of it. It should be an opportunity to add ventilation system with renewable energy sources. Such energy recovery and renewable energy technologies as air heat recovery unit, air-to-water heat pump, and unglazed solar collector (UTSC) for ventilation system of the building are analyzed. TRNSYS simulation tool is applied. Simulation results of three technologies (heat recovery unit, air heat pump and unglazed solar collector) using ventilation system performance during the year is presented. Main indicators of UTSC are presented. Simulation results and obtained experimental data of individual cases of such system are compared.

Keywords: air-to-water heat pump; heat recovery; TRNSYS; unglazed solar collector; ventilation.

Nomenclature

c_p	heat capacity (kJ/kgK)
I	solar irradiance (W/m^2)
A	unglazed solar collector area (m^2)
U	heat transfer coefficient (Wm^2/K)
L	supplied or extracted airflow rate (m^3/h, m^3/s)
m	mass flow rate of air (kg/s)
t	temperature (°C)
Greek symbols	
Δ	difference
ρ	air density (kg/m^3)
□	efficiency (%)
Subscripts	
coll	collector
ex	external
heated	*heated air*
UTSC	after unglazed solar collector
Abbreviations	
AHU	air handling unit
COP	coefficient of performance
EER	seasonal energy efficiency ratio
EPBD	European Directive on Energy Performance of Buildings
HEX	heat exchanger
HP	heat pump
HVAC	heating, ventilation and air conditioning
ST	storage tank
UTSC	unglazed transpired solar collector

Corresponding author: Violeta Misevičiūtė. E-mail address: violeta.miseviciute@vgtu.lt
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1. Introduction

Nowadays, the environmental impact and availability of energy sources has become increasingly important. Buildings across the European Union represent about 39–40% of the gross energy consumption in Europe and emit approximately 35% of carbon dioxide emissions [1]. Although buildings consume huge amounts of final energy there exist potential savings. The European Directive on Energy Performance of Buildings (EPBD) requires using as much as possible renewable energy sources in building engineering systems. Achieving reduction in the energy consumption of buildings is a significant challenge for the European Union. Some solution of this problem could be solar thermal systems. Literature review, theory, experimental analysis has shown that high efficiency can be achieved using unglazed transpired solar collectors (UTSC). The UTSC can also be integrated with other technologies, e. g. heat pump (HP) and photovoltaic [2]. The heat load of buildings can be reduced by use of solar systems [3]. UTSC are a relatively new development in solar collector technology, introduced in the early nineties for ventilation air heating. UTSC can be involved to indoor climate system to provide required by hygiene norms indoor air parameters.

The use of UTCS can serve as energy saving measure in building engineering systems as well as in ventilation system. The active solar walls as well as passive solar walls contribute to the recuperation of solar energy for heating the buildings [4].

Solar energy can be used for many purposes such heating building to maintain comfortable indoor air climate especially in the winter season [5]. Although UTSC succeed in industrial ventilation applications, solar fraction is very low when they are used in space heating in cold climates due to the lower exit air temperature [6]. Oztop *et al.* [7] presented the classification of solar air heaters. The heaters are classified according to collector cover, absorber materials, flow pattern, shape of absorbing surface, flow shapes, hybrid collectors and their applications [8].

Although UTSC have low efficiency but can improve the efficiency of air preparation system. Integration of corrugated UTCS with photovoltaic systems, thereby generating electricity and heat, resulting in overall efficiencies that can be reached up to 70% [9], [10]

Van Decker *et al.* [11] and Kutscher [12] have reported that around 62% of heat gain is obtained from the warm surface boundary layer on the front surface of the collector, 28% occurs in holes and the remaining 10% from the back surface of collector. Kutscher [13] stated many parameters which affect the performance of UTSC, e. g. porosity, type of grid the holes form, geometry of holes, plenum dimensions, material and absorptance of the collector, approach velocity, plenum velocity, surface coatings, wind effect and profile of collector. Shukla *et al.* have noted that different parameters have benefits in changing location and climate [2].

This paper analyses application of air-to-water HP, UTSC for ventilation system with heat recovery unit. Dynamic modelling of HVAC system is extremely important for control analysis toward building energy saving [14]. Energy simulation software tools are an important support used for building designers to reduce the cost of energy in buildings as allow to determinate with accuracy some variables that can support designers to take decisions about the best measures to apply for any building to built or already existent. Simulation of the system with TRNSYS is carried out. Several elements of investigated system are validated experimentally.

2. Object

2.1. Engineering systems

The research objective is air handling unit (AHU) which uses UTSC and air-to-water HP to preheat air. Analyzed system is used in **Laboratory of Building Energy and Microclimate Systems** in Department of Building Energetics of Vilnius Gediminas Technical University. UTSC is presented in Figure 1.

(a) (b)

Fig. 1. The laboratory of Department of Building Energetics, UTSC (a) and its' structure (b)

This laboratory (113 m^2) is equipped with series of renewable energy technologies and equipment those use renewable energy. Air-to-water HP as well as UTSC are used for heating of laboratory is presented in Figure 2a. AHU with plate heat exchanger (HEX) which provides laboratory with a fresh air is presented in Figure 2b. The use of UTSC helps to reduce electricity consumption as well the actuation of HP is reduced.

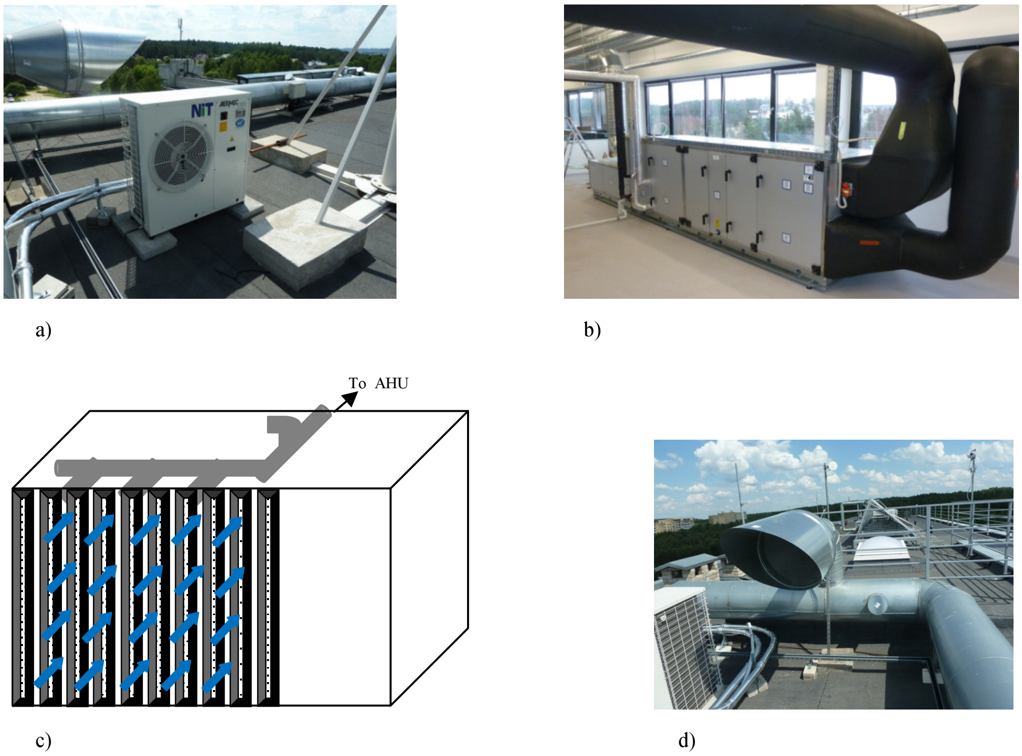

Fig. 2. Air-to-water HP (a), AHU (b), UTSC (c) and by pass duct of UTSC for summer application (d)

Ventilation system also is used as heating system for laboratory. Air preparation unit excluding other elements presented in Figure 3 consists of air heater with ethylene glycol which takes heat from the storage tank (ST). The mixture of water and ethylene glycol of ST is heated by air-to-water HP close circuit using HEX. Fresh air goes first through the UTSC where is preheated. The air is supplied directly to the premises if the temperature is sufficient otherwise it is heated by mixture of water and ethylene glycol from the ST. The temperature is controlled by temperature controller. ST is used for heat transfer between an air and ethylene glycol in it. HP works in heating mode during the cold period and heats the ST. ST is supported by 50 °C temperature water. The mixture of water and ethylene glycol circulating in the cooler when HP works at cooling mode.

UTSC can be used to preheat the air for ventilation. It can be used as well for cooling air. The principal scheme of UTSC for both applications (heating and cooling) is presented in Figure 2c and 2d.

The bypass duct (Fig. 2d) is used in summer to cool an air by passing UTSC. The space between the absorber (perforated sheet) and back plate is sealed to create an air channel also known as a plenum. The perforations generally cover a very small fraction of total area of UTSC (also known as porosity). The fan sucks the air through the collector, which draws ambient air to pass through the holes and collect heat from the absorber surface and the heated surface boundary layer. Then solar heated air is drawn up through the air channel and goes to distribution ducting.

The examined scheme which covers all above mentioned equipment is presented in Figure 3.

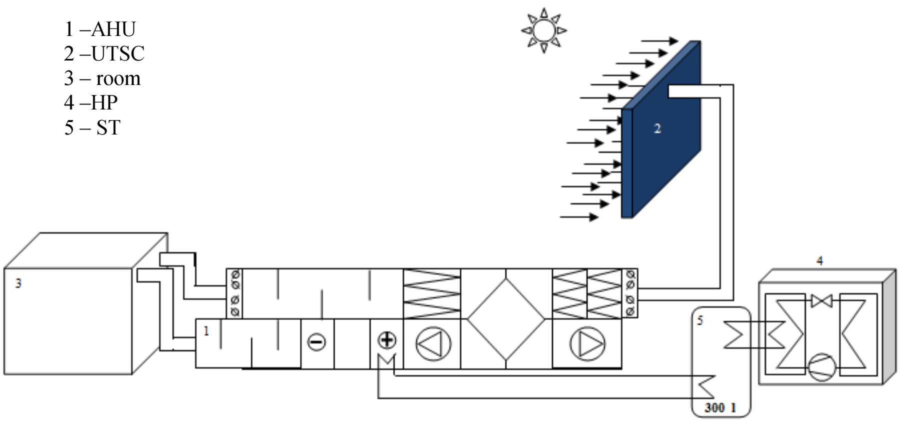

Fig. 3. Investigated systems' scheme

Main characteristics of systems' elements are presented in Table 1.

Table 1. Main characteristics of systems' elements

Equipment *element*	Technical data										Notes
AHU	capacity (kW)	efficiency (%)	COP	EER	heigth (m)	airflow rate (m^3/h)	water flow rate (l/h)	refrigerant flow rate (l/h)	volume (l)	area (m^2)	
Heater	10.64	–	–	–	–	1450	–	–	–	–	–
Cooler	4.87	–	–	–	–	1450	–	–	–	–	–
HEX	–	64.6	–	–	–	1450	–	–	–	–	plate HEX
UTSC	–	–	–	–	16.6	–	–	–	–	100	3 sections
HP	7.87	–	2.57	–	5.93	3500	1354	–	–	–	heating mode 47 °C/55 °C, outdoor temperature: 7/6 °C DB/WB
	6.84	–	–	2.84	5.13	–	1176	–	–	–	cooling mode12°C /7 °C, outdoor temperature: 35 °C
ST	–	–	–	–	1.3	–	–	–	300	–	–

UTSC is installed vertical on Vilnius Gediminas Technical University south façade side (Fig. 4).

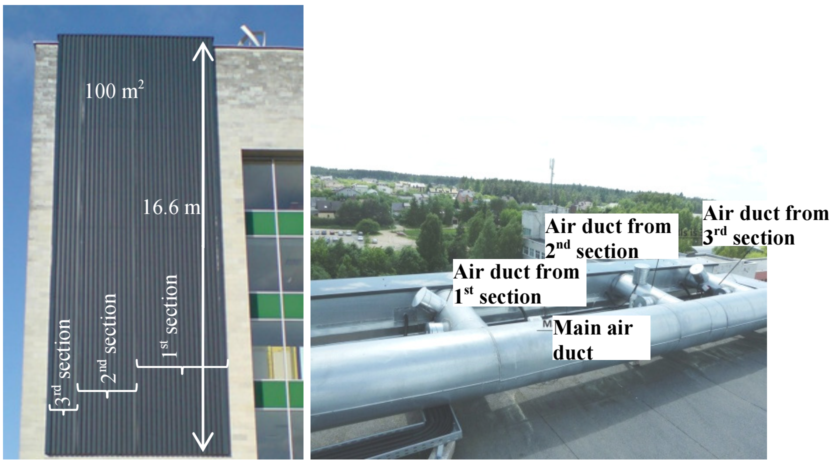

Fig. 4. UTSC on the building wall

The use UTSC is considered to be one of the most effective methods of reducing heating, ventilation and air conditioning (HVAC) loads in the buildings. A perforated absorber plate is installed in a location where it is exposed to solar. Air is drawn through the perforations, and into the fresh air intake of an HVAC system. This pre-warmed air could make a significant contribution towards decreasing the energy used for heating [15]. It consists of three sections those differ by the length and are respectively equal to 3 m, 2 m and 1 m (Fig. 4). Air goes from each section of UTSC to the main air duct and is directed to the AHU. Airflow rate can be regulated with valves or stopped closing them. The supply air temperature to the AHU can be changed by replacing the position of valves. The surface of UTSC consists of black covered plate due to reach the higher degree of blackness. The plate is perforated for fresh air movement to the AHU. The heat transfers of the transpired plate occur at the front-of-plate, the holes and the back-of-plate. Such parameters as hole diameter, pitch, plate porosity and airflow velocity are the key factors influencing air heating capacity required to heat an air.

2.2. Building

Laboratory is used for 6 persons; sometimes it could serve for the bigger number of persons, for example, up to 15 persons. The laboratory is divided into two zones: working and technical area. The room temperature is set 20 °C for the simulation. The buildings' envelope properties are presented in Table 2. These characteristics are used for building input data in TRNSYS.

Table 2. Building characteristics

Envelope	Characteristics			
AHU	Heat transfer coefficient (Wm^2/K)	Heat loss (W/K)	Infiltration loss (W/K)	Ventilation heat loss (W/K)
External walls	0.12			
Windows	1.2	69	91	165
Roof	0.15			

The heat loss of the analyzed premises is calculated according simplified methodology. The energy required for heating of the laboratory is 14 kW.

3. Methodology

3.1. Simulation

The simulation and some experiments for system analyzed are used. Simulation of system presented in Figure 5 is carried out with TRNSYS simulation tool. The input data is taken from the characteristics of equipment used in laboratory. Some data used for simulation of the system are given in Table 1.

The simulation of analyzed system combines components of TRNSYS presented in Figure 5. Climatic data of Kaunas city is used for simulation of the system as TRNSYS contains only this Lithuania city climatic data.

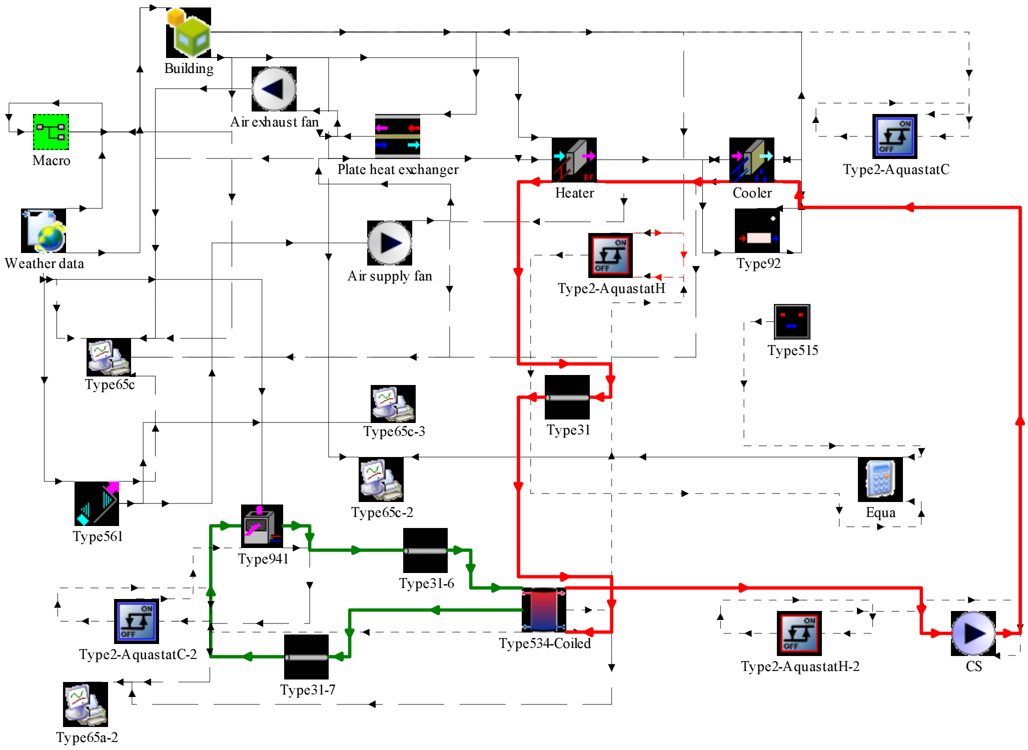

Fig. 5. The model of ventilation system with HP, UTSC in TRNSYS

The results of simulation must be validated. The mathematical modelling and experimental study was applied. The mathematical expressions are used for calculations is discussed in next section.

3.2. Mathematical modelling and experimental study

The basic heat loss theory for UTSC is explained in detail by various researchers [16]. The heat capacity required to heat air in the UTSC is expressed by Eqn (1):

$$Q_{UTSC} = L_s \cdot \rho \cdot c_p \cdot \left(t_{heated} - t_{ex}\right) \quad (1)$$

where: Q_{UTSC} – heat amount given to the heated air, kW; L_s – supplied airflow rate, m^3/s; ρ – air density, kg/m^3 (ρ =1.2 kg/m^3); c_p – specific air heat, kJ/kgK, (c_p= 1,005 kJ/kgK); t_{heated} – heated in UTSC air temperature, °C; t_{ex} – external (outdoor) air temperature, °C.

The thermal efficiency of UTSC can be estimated from an energy ratio transfers, i. e. from the ratio of the useful heat gain delivered by the collector divided by the incident irradiation on the collector surface. UTSCs' efficiency can be determined by the following Eqn (2) which also evaluates heat loss due to irradiation to the environment:

$$\eta = \frac{Q}{IA_{coll}} = \frac{Mc_P \varepsilon_T (t_{coll} - t_{ex})}{IA_{coll}} = \frac{\varepsilon_{coll}}{\left(\dfrac{1+\alpha_{coll}}{\varepsilon_T \rho c_P V_S}\right)} = \frac{\varepsilon_{coll}}{\left(\dfrac{1+\alpha_{coll} A_{coll}}{Mc_P \varepsilon_T}\right)} \tag{2}$$

where: Q – heat given to heated air, W; I – solar irradiation, W/m^2; A_{coll} – surface area of collector, m^2; ε_{coll} –UTSC radiation absorption coefficient; ε_T – thermal efficiency of UTSC; α_{coll} – convective heat transfer coefficient between UTSC and ambient, W/m^{2}K; M – air flow rate, m^3/h; t_{coll} – the temperature of UTSC surface, °C; t_{ex} – outdoor air temperature, °C.

The temperature efficiency of UTSC first was described by Kutscher (1992) [12]. The expression of temperature efficiency is presents Eqn 3:

$$\varepsilon_T = \frac{t_{UTSC} - t_{ex}}{t_{coll} - t_{ex}} \tag{3}$$

where: t_{ex} – outdoor air temperature, °C; t_{UTSC} – heated in UTSC air temperature, °C; t_{coll} – the temperature of UTSC surface, °C.

Presented formulas expresses mathematical expressions used for the evaluation of thermal and temperature efficiencies of the UTSC.

4. Results

The air temperatures distribution in ventilation system with renewable energy technologies is presented in Figure 6.

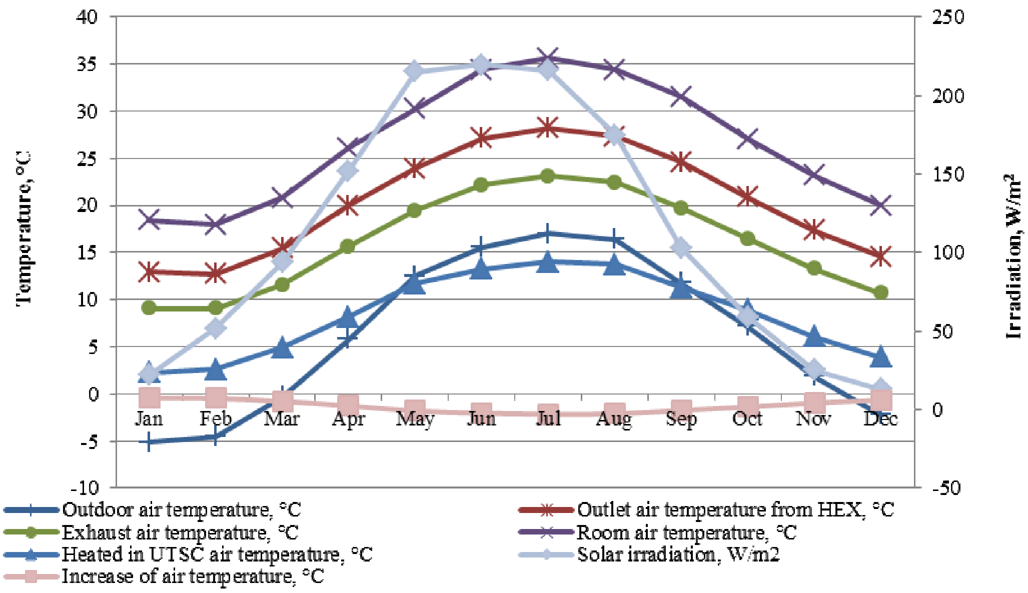

Fig. 6. Temperatures distribution in ventilation system with renewable energy technologies

The temperatures in Figure 6 show that sometimes it is insufficient temperature in premises. This indicates need of the auxiliary heater or cooler. This paper does not analyze the auxiliary devices for heating or cooling. As can be seen in Figure 6 the minimal outdoor air temperature is –19.47 °C, the maximal is 28.70 °C. The average outdoor temperature is equal to 6.39 °C in Kaunas city.

The irradiance has an impact for heating air in UTSC, the higher the irradiance the warmer air outlets from the UTSC. The change of outdoor air temperature and heated in the UTSC air is named temperature increase. The hotter air outlets from the UTSC the less energy is needed to use to heat air by heater of AHU. This can be seen in Figure 6 and Figure 7.

It can be seen (Fig. 7) that average value of temperature increase due to UTSC approximately is equal to 4 °C during the cold period. The air in UTSC can be heated from 2 °C up to 9 °C.

The experimental data (Fig. 7) shows that the biggest measured temperature increase (5.08 °C) of air temperature is observed on April. Simulation results have shown that the biggest increase of temperature is on January (7.42 °C) (Fig. 6). The attention is only paid on the UTSC performance during the cold period.

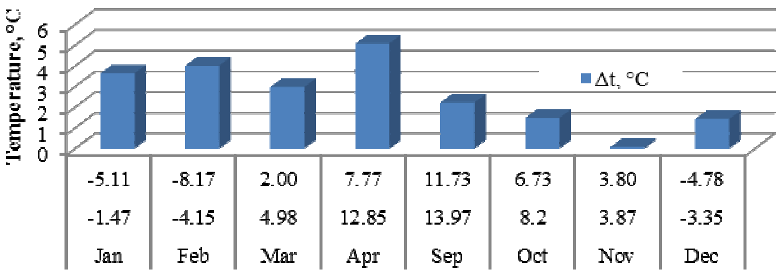

Fig. 7. Measured increased of temperature in UTSC

The air always outlets of higher temperature from UTSC. The upper given temperatures present outdoors air temperatures, the lower – the temperatures of air which outlet from the UTSC. The temperature increase is presented by quantity Δt (Fig. 7). The discrepancy can be due to the different location of the building. The measurements are performed for the building in Vilnius.

The HP COP and EER coefficients are presented in Figure 8. The COP of HP varies from 3.07 to 3.52 (15%) during the cold period and from 3.54 to 3.67 (4%) in warm period of the year. The seasonal energy efficiency ratio (EER) has the same distribution as the COP.

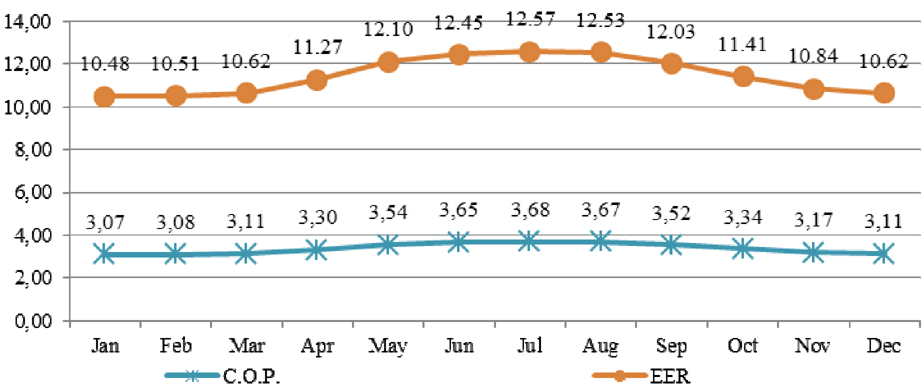

Fig. 8. HP COP and EER coefficients

Useful heat gain and absorbed solar energy by UTSC are presented in Figure 9.

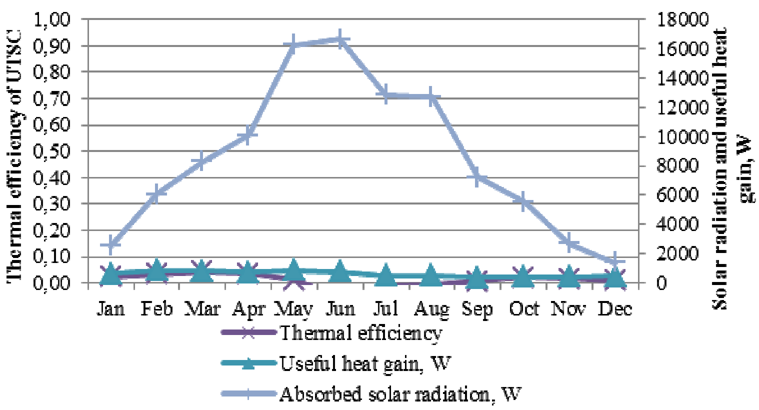

Fig. 9. The distribution of useful heat gain and absorbed solar energy

Thermal efficiency of UTSC varies from 1% up to 5%. As can be seen in (Fig. 9) the increasing of solar radiation seems to have limited effect on the UTSC efficiency.

5. Conclusions

The results obtained during the simulation and experimental study of ventilation system with renewable energy technologies and separate elements have shown:

1. The UTSC used for ventilation system has a positive impact as always warmer air outlets form the collector. The average value of temperature increase due to UTSC usage approximately is equal to 4 °C during the cold period. The air in UTSC can be heated from 2 °C up to 9 °C.
2. The experimental data of cold period has shown that the biggest measured increase (5.08 °C) of air temperature is observed on April otherwise as simulation results have shown that the biggest increase of temperature is on January (7.42 °C).
3. Increasing of the radiation have a very limited effect on the collector efficiency. This small effect on UTSC may be due to the reduction of the absorber plate temperature, resulting in lower losses from the collector at low irradiation levels. The simulation has shown thermal efficiency of UTSC varies from 1% up to 5%.

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