Heating, cooling and ventilation with the solar-assisted heat pump based on the air solar collector

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Abstract

A new concept for solar-assisted heat pumps based on an air solar collector is discussed in this paper. The main objectives of the system have been set on a partial covering of the cooling demand of a building during summer season and simultaneous charging of the thermal storage for domestic hot water usage. Beside this, the proposed system fully covers the ventilation need of the building. The current paper presents the performance results of proposed concept for different weather conditions. The results demonstrate that such system is competitive with the existed solar-assisted heat pumps in terms of technical simplicity to cover broad range of tasks simultaneously.

Keywords: *air solar collector, heat pump, air conditioning, air cooling, thermal storage*

1. Introduction

Past decades brought various technologies based on renewable energy sources, which are promising alternatives to the dominant use of fossil fuels, including wind power, hydropower, waste energy, geothermal energy, bio energy and solar energy. Herein, solar energy has proven itself as a clean source for electricity and heat generation in the building sector. However, its performance strongly depends on time and local weather conditions which are not completely predictable. This time shift leads further to the issue of the decreased self-consumption of the solar power, especially, of the PV-plants. Use of energy storage (electrical batteries and thermal storage such as hot water boiler or others) can increase the fraction of harvested solar energy and shift gained energy to demand time zone (Tanguy et al., 2014). Another common way of increasing of the self-consumption of the electricity produced by solar PV-cells is to use a heat pump (HP) for storing the electrical energy in thermal storage for further electricity and heat production (Dumont et al., 2015).

On the other hand, the consequences of global climate change more and more shift the focus from covering of heat demand during the winter to providing the necessary cooling power to buildings during the summer season. Jurt et al. (2016) showed that the number of overheating hours will increase by 50 % to 100 % in the next 30 years, depending on building type.

In addition, there are compulsory requirements for the mechanical ventilation systems (Swiss Norms, 2006) in office and industrial buildings.

Summarizing the requirements, it is clear that in order to get high efficiency of all systems in building all the above mentioned tasks should be considered together. Typical combination of the water solar thermal collector and water-based HP which use the water tank as a daily or weekly thermal storage is presented by a number of research papers (Bucker and Riffat, 2016, Poppi et. al., 2016). Although the combination of system components varies greatly and generally increases the COP of a HP up to 6, however, these cases can be considered only for the solution of two tasks such as covering the heat load and increasing the consumption of the installed PV cells (Fischer et al., 2016).

Combination of ventilation system and HP for covering the cooling and heat load is presented by widely spread air-to-air and air-to-water HPs, which also increase self-consumption of the electricity produced by PV-cells. However, their application for covering the heating demand during winter has lower efficiency due to the lower temperature of the air. Use of thermo-chemical (Tanguy et al., 2014), sensible or latent (Kapsalis and Karamanis, 2016) seasonal heat storage provides an opportunity to increase efficiency during winter, but such systems suffer of a high technical complexity (Tanguy et al., 2014).

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Ventilation system based on solar air collector (SAC) also partially covers the building's heat demand and is not sophisticated. Sicre et al. (2015) measured and analyzed the efficiency of a 24 m^2 SAC as a system which simultaneously fulfills the ventilation requirements and heats up the indoor air. With an average energy conversion efficiency of 60 % this system covers only 28 % of the heat demand of typical factory building in Luzern, Switzerland, due to the obvious lower solar gains during winter. Air collector was also used as a cooling device during night using the sky radiation effect; the resulting cooling capacity was restrained to as little as 1 kWh per night. Another way to actively cool down incoming air using air solar collector is achieved by using a desiccant cooling wheel (Eicker et al., 2010). COP of such system is up to 3.2, but hygienic aspects may rise concerns.

Summarizing different concepts of system, combination of solar thermal plant such as SAC for assistance, of the standard air-to-water HP powered by PV-plant and coupled to a thermal storage is promising. The focus of the present paper is set on the design of such system that will cover simultaneously ventilation, domestic hot water (DHW) production and partially cooling. The goal of current research is to estimate the efficiency and working ability of a solar-assisted HP based on the SAC with an evaporator, which cools down the inlet air provided into the room during summer season, and a condenser, which simultaneously charges domestic hot water tank or other heat storage that is discharged later by consumer.

2. System concept

The proposed solar-assisted HP based on SAC can be well explained using the scheme of principle in fig. 1.

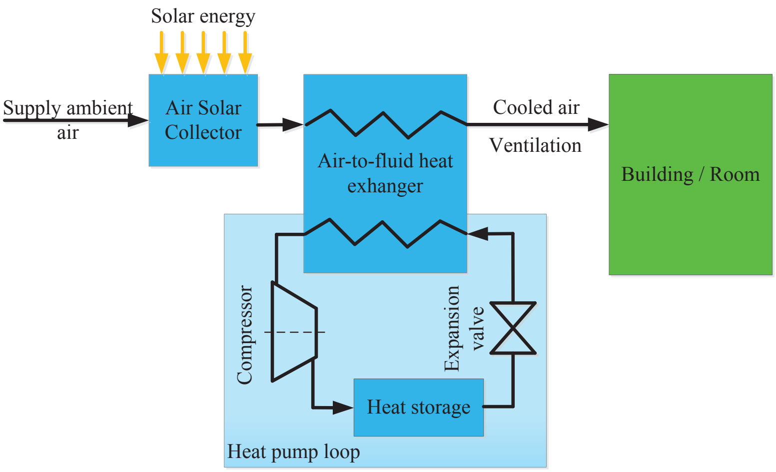

Fig. 1: Scheme of the system operation during summer season

Basically such system represents a solar-assisted air-to-water HP. Besides provision of cooling and heating, it also fulfils the function of building ventilation. During the summer season SAC sucks and heats the outside air, which is further passed through the heat exchanger, where the refrigerant of the HP evaporates. The resulting, relatively cold outlet air is sent to the rooms. On the other side, evaporated refrigerant from the heat exchanger is compressed by the compressor and supplied to the thermal storage, that may be a DHW tank or another thermal storage, which will be discharged later by consumer.

During the winter season HP can be used in combination with the SAC in a way described in Karagiorgas et al. (2010), where SAC serves during winter as an energy collector for the air-to-water HP. This solution allowed increasing the COP of the air-to-water HP by 30-50 % depending on the ambient temperature and available solar radiation.

SAC can be used alone without HP during autumn and spring to cover low heat demand (Sicre et al., 2015). Other way to cover the heat demand during winter is to use accumulated energy during summer; however seasonal thermal storage with high energy capacity is required.

Thermodynamic cycle of a HP in T-S diagram is presented in fig. 3. As a working refrigerant of the HP cycle tetrafluorethan (R134a) was chosen, due to its widespread application in cooling technologies and its critical temperature of 101,06 °C is acceptable for the investigated cycle (Lemmon et. al, 2013).

For the pressure raise simple one-stage piston compressor is used with the efficiency of 60 % (Bitzer Ecoline, 2016). Expansion of the mixture through the expansion valve assumed to occur with a constant enthalpy. In order to increase efficiency of the system the compression ratio of the compressor is changeable from 1.8 to 4.6 and depends on water temperature in storage, however, the evaporation temperature of the tetrafluorethan maintains constant and equals to 10 °C (fig. 3). But for the comparison purpose with existed systems, constant compression ratio of 4.6 is used in present paper (fig. 3 - cycle with highest compression ratio). The volume flow rate of the working fluid in a HP loop is regulated in a way that provides outlet air temperature equals to 21 °C. Technically it is fulfilled using variable speed compressor and adjustable expansion valve. Since the COP is proportional to the source temperature, the SAC HP will perform better in the summer when temperature of incoming air is increased by solar radiation in the SAC.

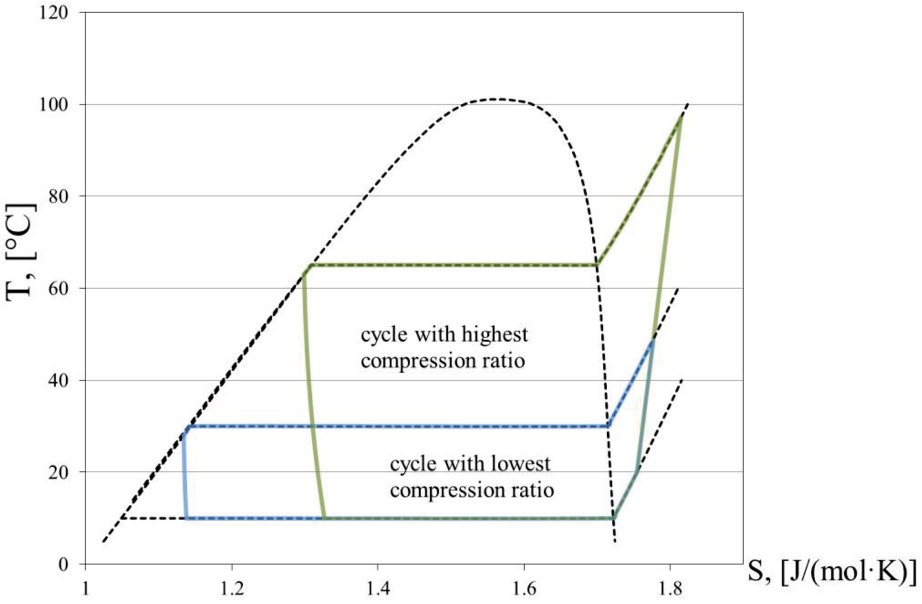

Fig. 3: T-S diagram of a HP loop

It is important to mention two running boundaries for the described system. On one hand, HP is not allowed to cool down the incoming air from the SAC below the set point temperature for the room (in present paper, 21 °C). If the ambient temperature is higher than a high room temperature limit (in present paper 26.5 °C according to Swiss Norms, 2014), use of SAC for further cooling purpose has less efficiency than direct cooling of the ambient air with the HP. Therefore, during summer operation of investigated system has lower limit of 21 °C of its outlet temperature and upper limit of 26.5 °C of the ambient temperature.

The standard characteristic of the HP cycle such as COP will be described in this case as follows:

$$COP_{cycle} = \frac{P_{heating}}{P_{compressor}+P_{ventilator}}, \qquad (\text{eq. }1)$$

where $P_{heating}$ is energy absorbed by thermal storage, $P_{compressor}$ – electrical energy provided for the compression the working fluid in the cycle, $P_{ventilator}$ – electrical energy provided to the ventilator for the maintenance of the required volume flow rate through the ventilation channel.

3. Performance calculation

Since proposed system can be applied for the residential, office or industrial building (Sicre et al., 2015, Peci et al., 2016); and ventilation systems and requirements vary greatly, building thermal simulation will not help to achieve the goal of covering all possible options. Instead one may try to estimate the heat production of 1 m^2 area of the surface of the SAC in dependency of the geographical location.

Area of SAC is dimensioned according to the required air exchange rate in the building. According to Sicre et al. (2015) 1 m^2 of the air collector surface provides 50 m^3/h with acceptable pressure losses in ventilation channel.

For the description of the air collector performance, following equation was used:

$$\frac{Q_{\mathrm{SAC}}}{\mathrm{A}} = G_{90} - 9.1 \cdot (T_{SAC} - T_{air}) - 1.87 \cdot 10^{-8} \cdot \left(T_{SAC}^{4} - T_{sky}^{4}\right) - 537 \cdot \frac{d(T_{SAC})}{d\tau}, \qquad \text{(eq. 2)}$$

where Q_{SAC} – useful energy produced by the SAC, A – surface area of the SAC, T_{SAC} – mean calculated temperature of the SAC, T_{sky} – sky temperature, T_{air} – ambient temperature.

Obtained temperature of the SAC and outlet temperature of tetrafluorethan from the condenser is used for the calculation of the volume flow rate of the working fluid needed to cool down the inlet air to 21 °C. Volume flow rate is further used for the calculation of the charging power of the water boiler.

System was simulated for 8 geographical locations, which represent Mediterranean, Atlantic and Continental climates of Europe. The annual weather data for the mentioned locations was generated using software package Meteonorm 7.

In order to evaluate system's profitability, it is compared with the reference case, in which HP cycle is not changed, but inlet air in the evaporator zone is provided directly from the environment and not from the SAC. In order, to make equal $P_{heating}$ for both cases without changing the cycle, the volume flow rate of the air for reference case is increased properly due to the lower inlet air temperature. It will lead to the higher power consumption of the ventilator and lower COP of the reference system.

4. Results

Both investigated and reference systems were simulated for summer season (92 days) with the time step of 6 seconds with the mentioned boundary conditions. Comparison of the average seasonal performance factor (SPF) of the investigated and reference systems during working days with low cloudiness are shown in figure 4. For such days the SPF of the reference system is higher in southern regions due to the higher ambient temperatures – which leads to the lower air volume flow rate through the evaporator of HP.

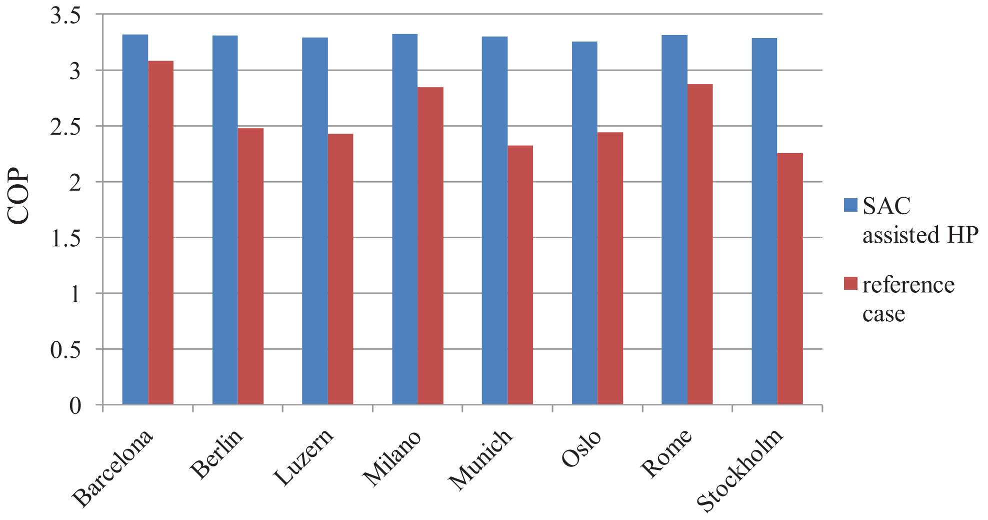

Fig. 4: Comparison of the average COP of the investigated and reference system for different geographical locations

The SPF of the investigated system is approximately the same for all geographical locations and equals 3.3. It occurs due to the application of the same governing equation (eq. 2) for the SAC in all cases with the same air volume flow rate. However, heat production of the systems in absolute values varies on geographical locations (fig. 5). The difference between average daily production per summer season and average production per cloudless day depends on the amount of the sunshine hours of each geographical location.

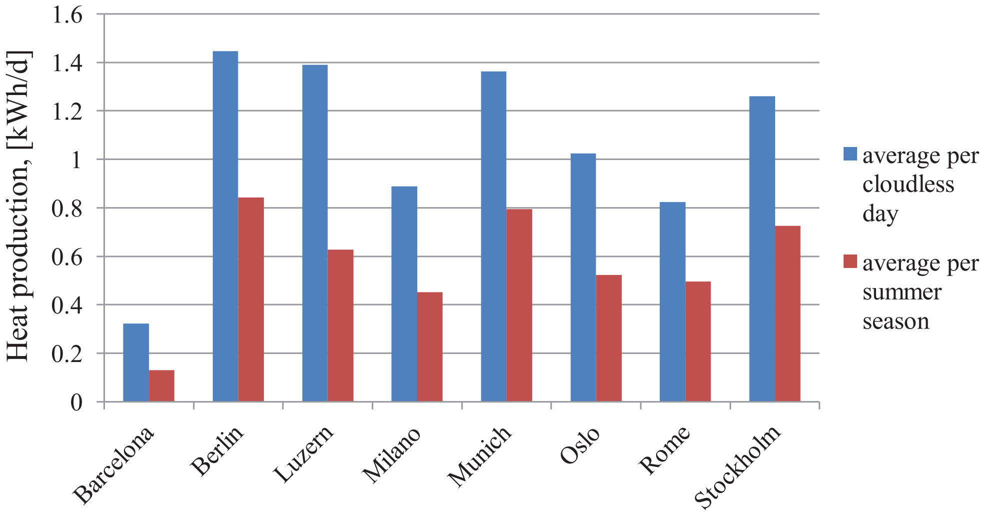

Fig. 5: Comparison of the average heat production of the investigated system with SAC area of 1 m^2 on cloudless day

From the figure 5 it can be seen that application of the SAC system has the highest production in central Europe. In the southern locations like Barcelona, Milano, Roma, ambient temperature is higher than the higher temperature set point (26.5 °C) and conventional cooling is needed. Due to this reason amount of hours during which investigated system can work is limited. On the other hand, solar radiation is lower in northern locations (Oslo and Stockholm). Useful fraction of the harvested solar energy in summer is shown in figure 6 and varies from 17 % to 26 % for office buildings, which use investigated system 5 days per week, and from 24 % to 36 % for residential buildings, which use investigated system each day.

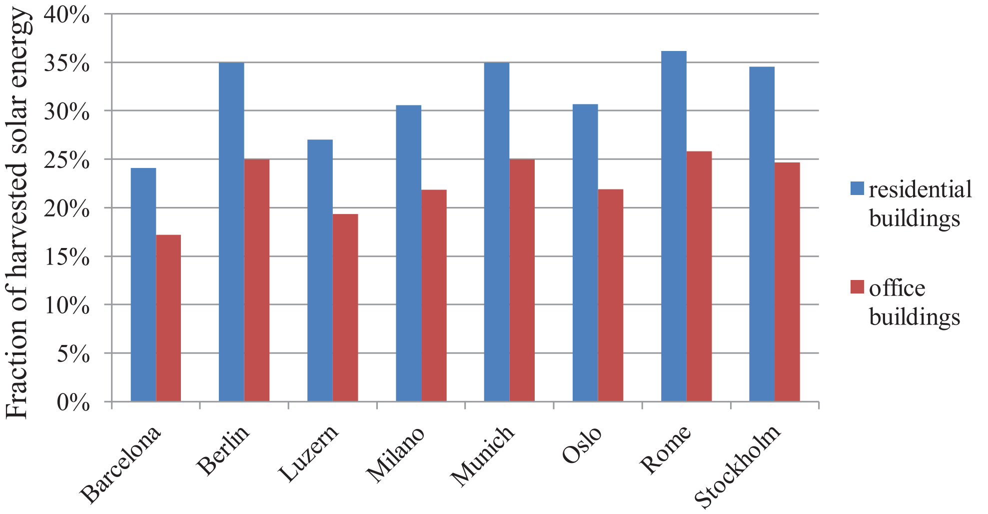

Fig. 6: Comparison of the fraction of harvested solar energy by the investigated system for different geographical locations

5. Conclusions and Discussion

This paper proposes an air-to-water heat pump cycle, which is assisted by solar air collector. Such system is handling several tasks simultaneously during summer season: ventilation and partial cooling of the rooms with internal gains, charging a thermal storage such as water tank and increasing the self-consumption of available PV-plants. It was shown that the $SPF_{heating}$ (which does not consider useful cooling energy produced by the system but only the heating up of the storage) of such system during summer season for cloudless days equals to 3.3. In comparison, the $SPF_{heating}$ of a HP-reference system would be 2.5 for central Europe.

The highest heat production can be achieved in central Europe and equals in average to 1.4 kWh/d for 1 m^2 of the solar air collector for cloudless days, which corresponds to 30 liters of water heated from 20 °C to 60 °C. The useful fraction of the harvested solar energy by the investigated system varies from 17 % to 36 % depending on the type of energy consumer (residential or office buildings). During the heating season system can run into two different modes. SAC can run standalone to cover low heating demand during autumn and spring or SAC can be used as a low temperature source for the existed heat pump which will further heat the rooms. Since the amount of energy produced by solar collector is relatively high, and the area of SAC is dimensioned according to the ventilation requirements, the amount of the heat production can be excessive and not be consumed at the same time. Therefore, accumulating of such energy also for the space heating can be promising. However, calculations should be made separately for specific building.

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