IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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To cite this article: T Orzechowski *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **214** 012044

Domestic hot water supply with air-source CO_2 heat pump

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Abstract. Heat is mainly used for space heating purposes, domestic hot water production and air conditioning. In Poland, this represents more than 31 % of the total energy consumption. A quarter of the value above is needed to generate domestic hot water. Heat pumps are considered to be environmentally friendly means of energy generation and they are particularly suitable as a replacement for conventional heating devices in energy upgrading of buildings. They are easy to install and to be integrated into the existing heating systems. The proper choice of such equipment requires taking into account not only the heat demand, but also the local climatic conditions. The paper analyses the coefficient of performance COP_{bin} of the air-to-water heat pump, with CO_2 as a working fluid. The pump is applied to the heating of domestic hot water under climate conditions in the city of Kielce recorded in a single year. Heat pump performance at partial loads is also taken into account.

1. Introduction

In the 21st century, the global warming effect is one of the most commonly articulated problems. One reason for this is rapidly growing consumption of non-renewable fuels and excessive accumulation of carbon dioxide in the atmosphere [1]. Hence, the most important engineering task is to develop modern technologies that consume less energy and reduce the degradation of the human environment [2].

Both the residential and commercial building sectors are one of the three major energy consumers. Heat is mainly used for space heating purposes, domestic hot water production and air conditioning. In Poland, this represents more than 31 % of the total energy consumption. A quarter of the value above is needed to generate domestic hot water. High energy consumption makes it necessary to reduce conventional heat production, which will be a priority for the coming years. This often applies to historical buildings. Obtaining funds for renovation of such buildings depends on ecological benefits produced by upgrading [3]. Among others, air-to-water type heat pumps are particularly suitable as a replacement for conventional heating devices in energy upgrading of buildings [4]. They are easy to install and to be integrated into the existing heating systems. External collector or boreholes are not required [5]. Air is a good source of renewable energy, and it is possible to combine that with solar collectors, which offers one of the most effective solutions [6]. The authors of the paper [7] indicate that a system comprising solar panels and an air-source heat pump significantly reduces the demand for electricity. Substantial benefits are obtained with hybrid systems that use both ambient air and ground as heat sinks in the cooling mode [8]. Heat pumps are considered to be environmentally friendly means of energy generation. However, their wider use is rather limited, which is mainly due to the relatively high investment costs. Comparison of energy, economic and environmental performance of CO_2 heat pump water heater system and coal and natural gas boiler heating systems was discussed in [9]. The cost of such installations is also related to their oversizing, especially in regions with high summer temperatures and low winter temperatures [10]. Those can be compensated by an increase in environmental fees associated with emissions and in the costs of individual design of the installation [11]. The final result will be a correct selection of the system devices and their optimal control due to minimum cost. The influence of such factors as water supply temperature, water circulation rate, tank stratification, and condenser configuration was considered in [12]. For installation reasons, it is always cheaper to use air-to-water electric heat pumps. Their heating capacity is dependent on the air temperature, which changes continuously during their operation [13]. As a result, the proper choice of the type of equipment requires taking into account not only the heat demand, but also the local climatic conditions [14].

Refrigerants suitable in compressor heat pumps are mainly hydrofluorocarbons [15], which are thought to have adverse effect on the environment by contributing to global warming. After any maintenance, their re-use requires special procedures so that they could not leak into the atmosphere. Such a requirement is very difficult to meet. In the years to come, the availability of refrigerants in Europe will change, mainly due to the withdrawal of the media that are environmentally problematic. Therefore, natural refrigerants such as hydrocarbons, ammonia and others are considered [16]. Global warming potential (GWP) is a relative measure of the heat trapping effect, in the atmosphere, of a gas compared with an equal mass of carbon dioxide over a given time period. R134a, for instance, has a GWP of 1300 over a 100-year time span. Improvement in energy efficiency and use of environmentally friendly working fluids are the main goals of current European policies [17]. It is not possible to completely eliminate refrigerants with high GWP values, therefore it is necessary to look for substitutes [18]. One of them is carbon dioxide, which is characterized by GWP=1. Carbon dioxide is non-toxic, non-flammable and, additionally, non-explosive unlike ammonia. Very high volumetric capacity allows it absorb more than five times more heat compared to hydrofluorocarbons. Its main disadvantage is high operating pressure. At temperatures above 31°C, vapour cannot condensate and the properties of temperature and pressure are no longer related. Heating hot water to the recommended temperature requires heat pump operation according to the transcritical cycle. Exemplary diagrams for subcritical R134a and transcritical CO2 cycles are shown in Figure 1.

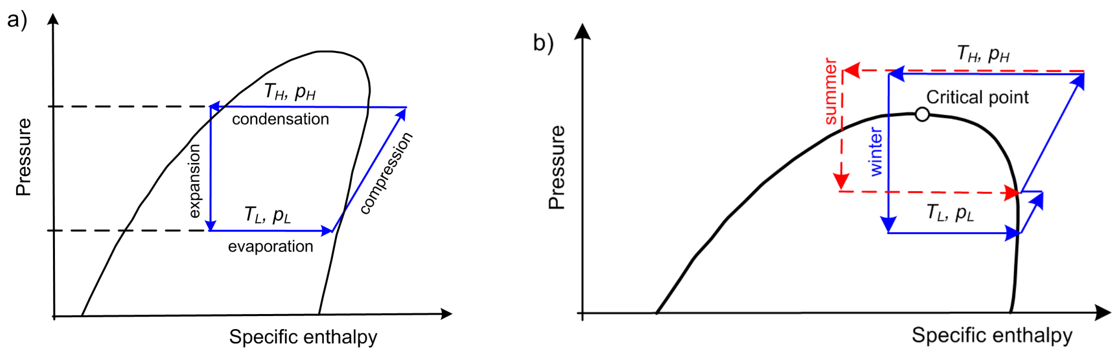

Figure 1. *P-h* diagrams: subcritical cycle (a) and transcritical cycle in summer (dashed line) and winter seasons (solid line) (b).

The heat pump with refrigerant R134a usually operates at the following parameters: evaporating temperature T_L= -30°C, pressure p_L= 84.4 kPa, condensation T_H= 55 °C and p_H = 1.492 MPa (see Fig. 1a). Carbon dioxide requires much higher pressures, in the considered system, it equals 15 MPa. Moreover, in the constant pressure exchanger, the CO_2 temperature successively drops from about 120°C to 55°C due to the heat transfer in the range above the critical point. If the heat pump is designed to operate in summer cooling mode, with suitably selected compressor pressures, the temperature and pressure in the evaporator can be changed to the following: T_L= -5°C, p_L= 3 Mpa. That which has a positive effect on heating and cooling efficiency. Such systems can also be used to maintain comfort conditions inside the cabin of an electric car [19].

Due to its properties, CO_2 is appropriate for high temperature hot water supply [20-23]. When selecting a heat pump, it is necessary to estimate its seasonal coefficient of performance (*SCOP*) depending on local climate conditions, which has a major impact on the operational cost compared with the old heating system. The paper analyses the coefficient of performance COP_{bin} of the air-to-water heat pump, with CO_2 as a working fluid. The pump was employed to heat domestic hot water under climate conditions in the city of Kielce recorded in a single year. Heat pump performance at partial loads was also taken into account.

2. Problem formulation

Compressor heat pumps use electrical energy. The effect of their operation is a heating power. The ratio of the heating capacity to the effective electric power consumed by the heat pump assembly is called the coefficient of performance (*COP*). Both the heating power and *COP* change with the temperature of the bottom source. They also have different values when the temperature of the heating medium changes.

Both parameters given by the manufacturers refer to the operating conditions of the heat pump defined in accordance with the standard [23]. The characteristics curves specified in this way do not take into account the temperature variation of the lower and upper source, or their modifications due to the time – varying demand for heating power. Sample characteristics of three heat pumps given by their producers are shown in Figure 2.

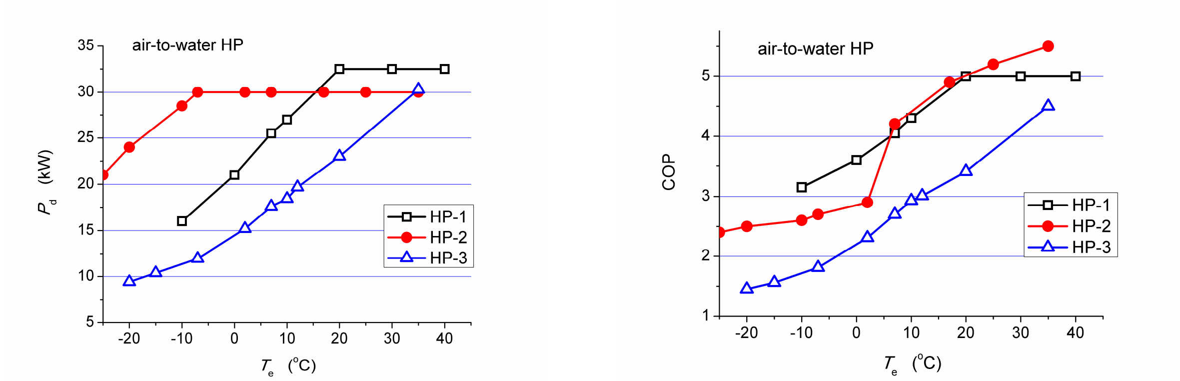

Figure 2. Characteristic curves of air-to-water CO_2 heat pumps (HP-1, HP-2) and HP-3 with refrigerant as a working fluid.

Two of them, i.e. HP-1 and HP-2, are heat pumps in which the working fluid is carbon dioxide, the third one, HP-3, uses a synthetic refrigerant. The HP-2 is essentially dedicated to the production of the domestic hot water. Its characteristic feature is the ability to maintain constant power output over a wide range of outdoor air temperatures T_e. As regards the HP-1 pump, in the temperature range above 20°C, the value of *COP* is very high and almost constant. On the other hand, the greatest changes in the delivered power and heating capacity are found in the HP-3 pump operating with synthetic refrigerant. It is a two-stage pump but for domestic water heating it is assumed that it operates in only one mode, the characteristics of which are shown in Figure 2. If the outdoor temperatures decrease below 2 °C, the second stage is activated when the energy demand for space heating of the building increases. This mode of heat pump operation is not considered in this paper.

The outdoor air temperature is the factor that decides on the operating parameters of air heat pumps. Evaluation of their operation and optimal selection in terms of heating efficiency and *COP* make it necessary to estimate the variability of both values with change in outdoor temperatures. The temperature distribution in Kielce for August and March are shown in Figure 3. Their registration was conducted at the meteorological station in Suków with a frequency of 1/hour [24]. It should be noted that considerable changes in weekly temperature are observed. For example, in August 2015, the highest recorded temperature value was about 35 °C, and the lowest below 10 °C. In other months of the year, similar differences were recorded. Large spread of outdoor temperatures translates to differences in effectiveness of the air-to-water heat pumps (see Figure 2).

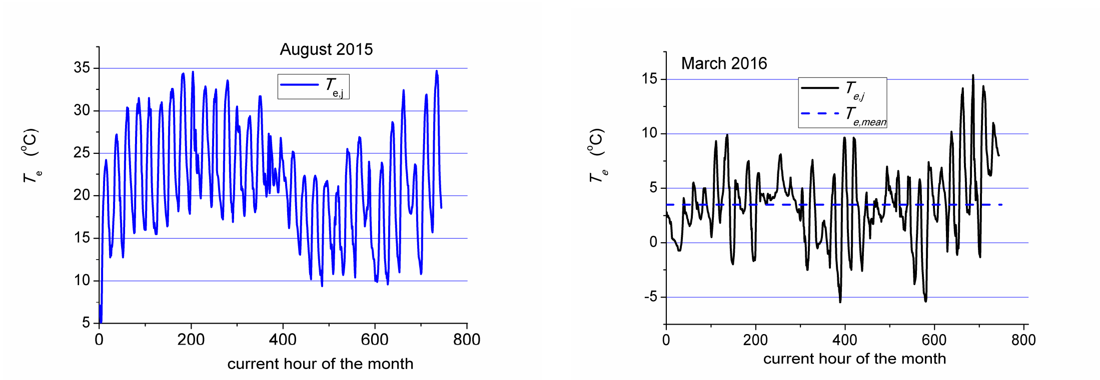

Figure 3. Temperature distribution in August 2015 and March 2016 in Kielce.

3. Analysis

At temperatures higher than the bivalent point, the heat pump power exceeds the demand. This difference increases as the outside temperature rises. It is necessary to match the power, which can be done by turning the device on and off. A frequency converter changing the rotational speed of the compressor, or several compressors operating according to variable demand can be used. The advantages and limitations of particular solutions are given by heat pump manufacturers.

The necessary thermal power of the building is a function of the outside temperature. Therefore, the heat pump does not always operate at full power, or it is also periodically switched on and off. Its capacity ratio, *CR*, can be calculated as follows:

$$CR_j = P_d\left(T_{e,j}\right) / P_h\left(T_{e,j}\right) \quad (1)$$

where $P_h(T_{e,j})$ is a thermal load, and $P_d(T_{e,j})$ is the heating power at that temperature.

The degree of adaptation of the momentary load affects the *COP* values achieved. Information of that kind is usually not available. *COP* estimated values at a given outdoor temperature $T_{e,j}$ can be calculated with the following dependence:

$$COP_{bin} = \frac{COP_j}{Cc + (1 - Cc)CR_j} \quad (2)$$

Cc is a reduction factor due to on/off losses at partial load. It should be adopted on the basis of the tests of the device, or according to [25], it can be assumed as 0.9 when it is not given by the manufacturer.

To estimate the operation of heat pumps, the characteristic curves are necessary, as shown in Figure 2. They are based on the example of heating of the domestic water. Its daily demand at 60°C was ~ 1 m^3, which corresponds to 5 kW of power supplied continuously for 24 hours. Water heating can be realized according to different scenarios. The easiest way is to have the system adjusted to current needs. However, this method is rarely implemented. The reason is the daily variation in the amount required, which is compensated by selecting a tank of adequate capacity (usually the one that covers the maximum hourly demand).

In the case of air heat pumps, the tank may be chosen to meet other criteria, for example its ability to use higher outdoor air temperatures that typically occur in the afternoons. Here, it is assumed that water heating starts at 6 am, which is related to the morning demand. Different pump operating times ranging from 8 to 24 hours were tested. The results of simulations for all three pumps and both months (see Figure 3) are shown in Figure 4 for August, and Figure 5 for March, respectively. The average values of the coefficients of performance under partial load shown are given for the whole month and weeks as a function of the number of hours in which the amount of water is equal to the daily demand.

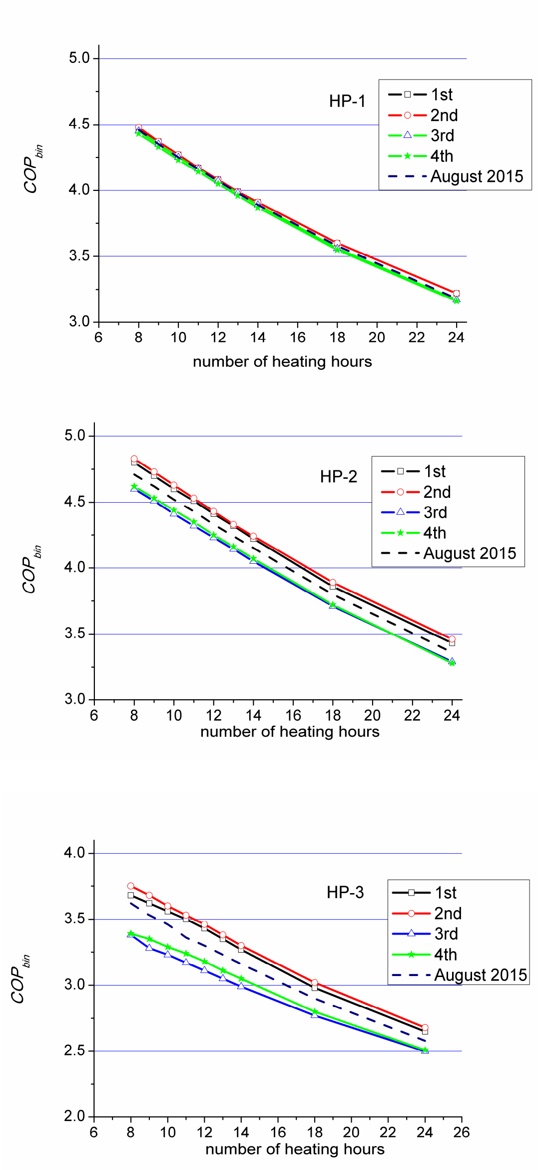

Figure 4. Average COP_{bin} at different heating times in August.

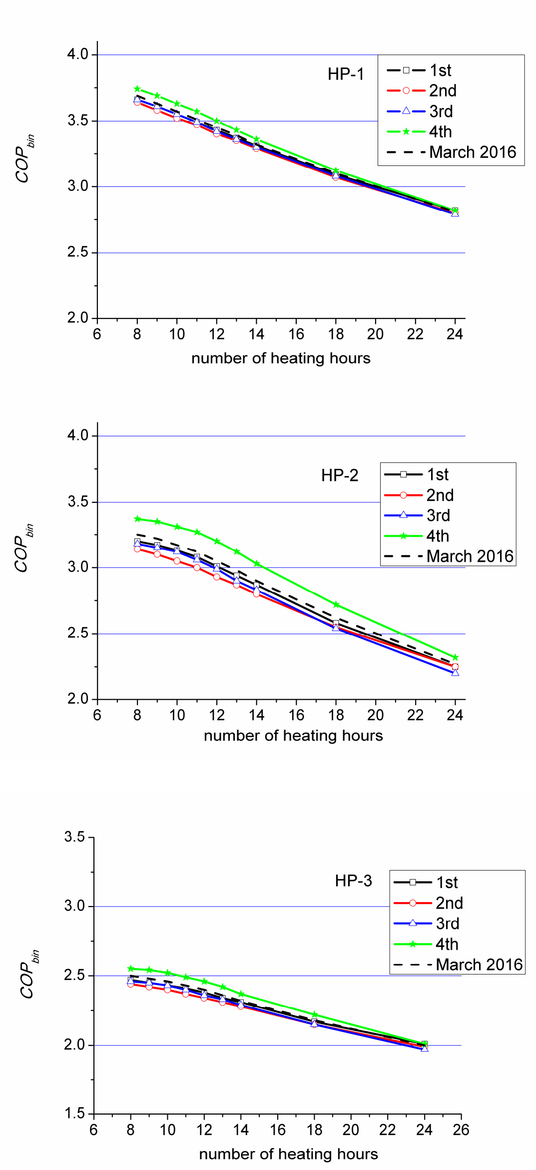

Figure 5. Average COP_{bin} at different heating times in March.

Figure 6 shows average monthly coefficients of performance calculated for the different pumps and the two months considered for different periods of domestic hot water preparation.

The calculated coefficients of performance for the heat pump operating in the mode of heating domestic water are visibly higher for supercritical CO_2 pumps, compared with heat pumps using a synthetic refrigerant. As shown in Figure 2, HP-1 and HP-2 pumps have different characteristics, which considerably affects their heating efficiency (i.e. C*OP*). HP-1 pump operates more efficiently at higher ambient temperatures and HP-2 is more efficient at lower temperatures.

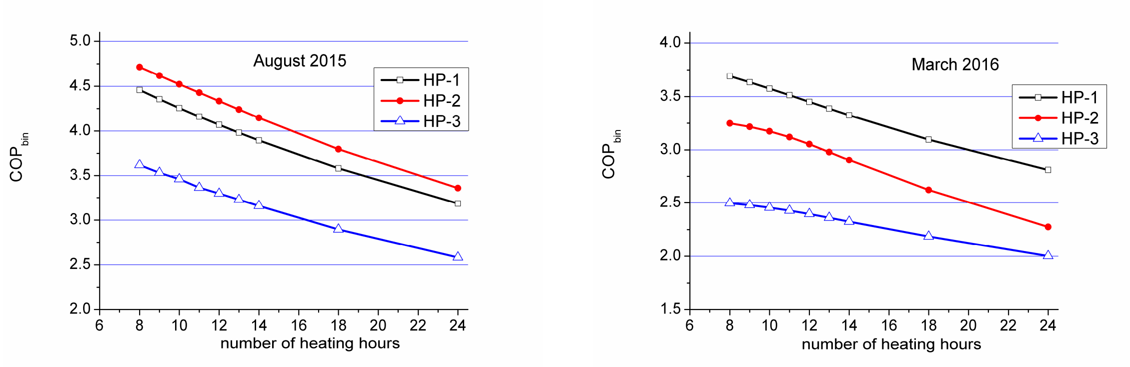

Figure 6. Average COP_{bin} at ambient air temperatures in August and March, respectively.

A slight improvement in performance can be achieved by selection of more advantageous operation time of heat pumps, as shown in Figure 7 for the periods of concern. Calculations were made for all pumps working for 8 hours, but at different times of the start of their operation. In the first case, they were turned on at 6 a.m. and in the other at 10 a.m., i.e. at higher outdoor temperatures.

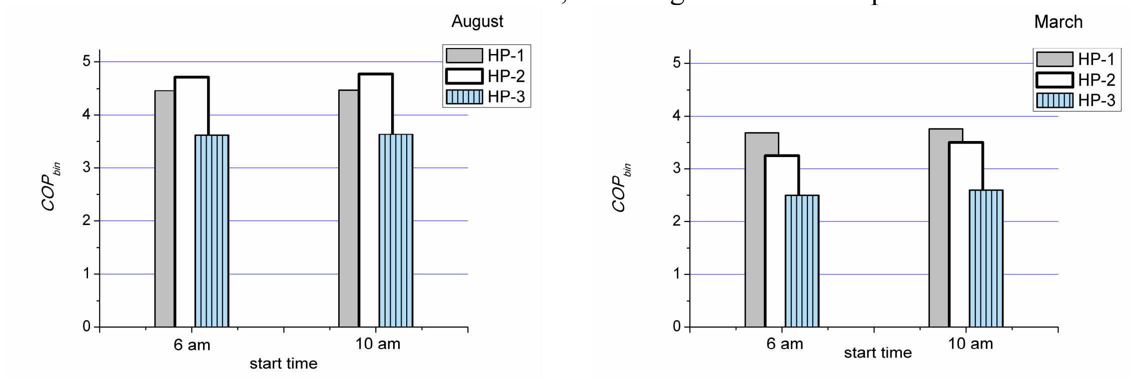

Figure 7. Average COP_{bin} for pumps starting operation at 6 and 10 in the morning.

4. Conclusions

Simulation tests of domestic hot water (DHW) heating were carried out for three air-to-water heat pumps. In two of them, carbon dioxide was a working fluid, in the third one, it was R134a. The characteristics of these devices, i.e. the power delivered and the coefficient of performance as a function of the outside temperature, are given in Figure 1. Sample calculations were carried out for March and August. The calculated average temperature in March was almost the same as for the entire heating season, and August, according to many years of observation, is the warmest month of the year. Average changes in the coefficient of performance in the domestic hot water generation shown in Figures 4 and 5 indicate that their values, which is obvious, depend on the outside temperature and decrease with temperature drop. Increase in time, in which the amount of water is equal to the daily demand, leads to a significant decrease in COP_{bin} for both warmer and colder periods. Comparison of mean COP_{bin} values calculated for a weekly cycle indicates that HP-1 pump is the least susceptible to changes in atmospheric air temperature. For this reason, programming its work is the simplest and the least risky.

Growth in April coefficient of performance is almost imperceptible and oscillates around 1%. However, with less favourable climatic conditions in March, an almost 7.7% increase in the average monthly COP_{bin} value for HP-2 pump is observed, while for HP-2 it is 3.9 % and 2 % for HP-1 pump respectively.

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