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THE USE OF A HEAT PUMP AND SOLAR ENERGY IN THE HEAT DEMAND

The article presents the energy performance of a heat pump. The coefficient of performance was taken into account, which is the ratio of the heating energy obtained to the supplied electrical energy necessary for the compressor operation. The focus was on the issue of operating costs of using heat pumps. These costs are mainly influenced by two factors. Firstly, energy performance and the purchase price of electricity. The second factor is investment costs. Heat gains from solar energy were characterized. The value of the solar radiation transmission coefficient for the double glazing was assumed (TR = 0.7). Solar gains were shown in January for windows on the eastern and western facades. The analysis covered the seasonal heat demand for heating. The studies and calculations took into account the occurring heat losses and heat gains from the sun and internal sources with their utilization rate. Particular attention was paid to the fact that the peak power of heating appliances can be calculated by knowing the value of the annual energy demand for heating a building that takes into account the most severe external conditions prevailing in a given climate zone, i.e. the minimum outside temperature.

Keywords: heat pump, solar energy, Coefficient of Performance COP, energy performance, heat losses and gains, heat power, heat source, heating, heating appliances, temperature, investment costs, heat demand

1. Introduction

Heat pumps pump heat in the opposite direction to natural running [1]. It can be said that the pumps are not a source of heat, they only move it to the place where it is effectively used [2].

Heat pumps are widely used as heating or air conditioning appliances for single-family houses and small rooms. During the heating season, they are used as a heat pump. In the summer season, they are air conditioners operating in the reverse cycle. The thermal power of these devices usually ranges from a few to several dozen kilowatts. The compressors are mainly used and these are: air-air, air-water or water-water, water-air (surface, i.e. floor, ceiling and wall). Research shows that heating individual buildings is less efficient than the system

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of more consumers with the use of associated heating systems. According to statistical research, the air-air heat pump meets the consumer's needs for heat for space heating and hot water during the year in the case of [3, 4]:
– multi-family buildings – 70÷80%,
– a complex of single-family houses – 60÷70%,
– single-family detached houses – 50%
of annual power demand.

It is stated that a device with a capacity of several kilowatts is sufficient for preparing hot usable water for consumers.

In various types of technical installations there is a flow of fluids in channels with a wide range of diameters, from very small (in mini- or microscale) to large (in macro scale). Technological progress in recent decades has led to the miniaturization of a number of technical devices in all branches of industry. This also applies to heat exchangers used in industry. Boiling heat transfer coefficients α are an order of magnitude higher than in single-phase, forced fluid motion and reach values of about 10^5 W/m^2 K for conventional devices [5]. Direct formulas obtained for conventional channels cannot be directly used to calculate heat exchange and flow resistance for mini- and microchannels. The phenomenon of generating vapour bubbles in a limited space and a significant predominance of capillary forces over gravitational forces are more important than viscous energy dissipation and axial conduction in single-phase flows [6, 7].

2. Use of a heat pump

When using a heat pump, its energy performance is particularly important. It was found that the performance of the heat pump (compressor, condenser, expansion valve and evaporator) is determined by the ratio of the amount of heat obtained in the condenser, i.e. the heat source with a higher temperature to the amount of energy used to drive the compressor. It is called the coefficient of performance COP. The coefficient of performance is the ratio of the heating energy obtained to the supplied electrical energy necessary for the compressor operation. The higher, the heat pump works more efficiently [8, 9].

$$COP = \frac{Q_g}{P_e} \tag{1}$$

where: Q_g – upper heat source power [kW];
P_e – mechanical power of the drive motor [kW].

The size of the coefficient depends on the design of the heat pump and on the temperature of the lower and upper heat sources. Energy performance depends primarily on the temperature difference between the lower and upper heat sources. The influence of these factors on COP is described by equation [8, 9]:

$$COP = 4,77 + 0,081T_D - 0,041T_G \quad (2)$$

where: T_D – lower heat source temperature [°C];
T_G – upper heat source temperature [°C].

According to the presented dependence (2), the temperature of the lower heat source has a different impact on the coefficient of performance than the temperature of the upper source. As the temperature of the lower source increases, the COP increases – a change of temperature by 10°C causes a change of this coefficient by 0.81. On the other hand, an increase in the temperature of the upper source by 10°C causes a reduction of this coefficient by 0.44. Significantly weaker effect of the upper heat source temperature compared to the lower heat source temperature is particularly beneficial from the point of view of the heat pump's operation for preparing hot usable water or heating residential premises.

The size of the COP coefficient says simply about the expected costs of heating. If the annual heat demand in the building is known, then after dividing it by the coefficient of performance, one will get the payable amount of energy. Operating cost is limited to the cost of purchasing electricity.

The lower heat source is one of the basic conditions for the effective operation of a heating system with a heat pump. In Poland, groundwater or soil is most often used as the lower heat source, much less air due to the fact that it is characterized by high temperature variability both in the 24-hour period and the whole heating season.

The soil is a good heat accumulator, because it maintains relatively uniform temperatures throughout the year (in the order of 7 to 13°C at depth 2 m). Soil energy can be taken through the horizontal collector or through the vertical collector – ground probes. The length of the collectors is determined on the basis of the heat pump's set heating power. Through the collector or ground probes flows brine, which is a mixture of water and glycol (does not freeze at subzero temperatures). This medium absorbs heat from the ground and transports it to the heat pump's evaporator. However, the horizontal collector requires a large plot area. If there is not enough space for putting a horizontal collector in the ground, then ground probes placed vertically in the ground can be used.

In order to take heat from groundwater, one needs to drill two wells. From one of them, water is pumped into the heat pump. The second well (discharge) drains the chilled water back to the ground. The advantage of groundwater as a lower heat source is that they have a high temperature of 8 to 12°C, constant throughout the year. The problem is the mutual location of the recharge and discharge well due to the direction of groundwater flow. It cannot be that the chilled water from the discharge well returns to the well that supplies the heat pump. The unchanging efficiency of the recharge well must also be ensured.

3. Operating efficiency

The study did not deal with the calculation of heating costs; it was limited to operating costs, in which only the costs of fuel and energy were included. The operating costs of using heat pumps are mainly influenced by two factors. On the one hand, energy performance and the purchase price of electricity. On the other hand, investment costs. Operating costs vary within wide limits. For example, for the upper heat source temperature 55°C and the lower heat source temperature -7°C energy performance is 1.75; respectively, for temperatures 30°C – underfloor heating and 5°C – ground, performance will be 3.55. This means that in this particular case the cost of obtaining a heat unit may vary from 0.113 PLN / kWh (with the electricity price 0.46 PLN / kWh and performance 4.06) to 0.25 PLN / kWh (at the price of 0.46 PLN / kWh and performance 1.75). Therefore, the guideline for low operating costs is to find a heat source that will have the highest possible temperature. The annual energy cost for heating the building and water, depending on the COP, is presented in Table 1 [10].

Table 1. Annual energy cost for building heating and hot water depending on the COP [10]

Lower heat source temperature [°C]	Upper heat source temperature [°C]	Energy performance COP	Energy performance COP	The cost of electricity for generating one kWh of heat [PLN/kWh]	The cost of energy for heating the building and hot water [PLN/a]
12	30	4.50	4.06	0.113	1 279
10	30	4.35	3.91	0.118	1 332
5	30	3.94	3.55	0.130	1 467
0	40	3.13	2.81	0.164	1 853
-5	45	2.52	2.26	0.204	2 304
-7	55	1.94	1.75	0.263	2 976
5	50	3.12	2.81	0.164	1 853

Decreasing the temperature difference between the receiver (upper source) and the lower source causes the efficiency of the heat pump to increase significantly. The greatest benefits from using a heat pump are obtained in low-temperature underfloor heating, where the water temperature is around 28–30°C and by using groundwater as the lower heat source assuming that it has a temperature of around 10°C. In this configuration, the COP coefficient reaches the highest values. One should definitely be discourages from using heating with a heat pump in a system with radiators or with a radiator-floor system, because the minimum temperature of the upper source is then 50°C, which causes the COP to drop considerably below the value of 4. The basic advantage of the heat pump is lost, which is the low heating costs. Therefore, when designing the installation, it is necessary to take very close attention to the temperature, because only then one can expect low operating costs. It all depends on the conditions in which the heat pump works.

4. The use of solar energy

This article focuses on heat obtained from solar energy. The analysis carried out refers to the heating of a passive house. Heat gains from solar energy are calculated from the formula:

$$Q_{SL} = 0.6A_S \cdot TR \cdot S \cdot Z \text{ [kWh/month]} \quad (3)$$

where: A_s – total area of windows on a given facade [m^2];
TR – coefficient of solar energy transmittance of windows;
S – monthly sum of total solar radiation per unit of area in a given month [kWh];
Z – shading coefficient;
0.6 – frame share in the window area.

Monthly sums of total solar radiation in watt-hours per one square meter [Wh/m^2] for differently oriented surfaces are shown in Table 2 [11].

Table 2. Solar radiation [Wh/m^2] for variously oriented surfaces [11]

Solar energy		
Month	Orientation	
	West	East
January	14 880	13 392
February	29 568	26 208
March	49 848	49 104
April	66 960	71 280
May	81 840	95 976
June	81 360	87 840
July	92 256	89 280
August	75 144	78 864
September	46 800	49 680
October	29 760	34 224
November	12 240	13 680
December	8 184	9 672

The windows in the building are located on the east and west facade. The shading coefficient is equal to one for both facades, because in the vicinity of the building there are no obstacles that would hinder the inflow of solar radiation to a given facade [12, 13]. The values of the solar radiation transmission coefficient, depending on the type of glazing, are presented in Table 3 [11].

Table 3. The values of the solar radiation transmission coefficient depending on the type of glazing [11]

Type of glazing	Solar radiation transmission coefficient TR
Single	0.82
Double	0.7
Single or triple glazing pane with one low-E coating	0.64
As above, but the space between the panes filled with argon	0.64
Double glazing pane with a low-E coating	0.55
Special glass	0.5

The value of the solar radiation transmission coefficient for the double glazing was assumed (TR = 0.7). Solar gains in the month of January for windows on the east facade, based on (3): $Q_E = 0.6{\cdot}9.66{\cdot}0.7{\cdot}13.392{\cdot}1 =$ $= 54.3$ kWh; for the west facade: $Q_W = 0.6{\cdot}13.63{\cdot}0.7{\cdot}14.88{\cdot}1 = 85.1$ kWh. In the remaining months, the calculations were made identically and the results are summarized in Table 4.

Table 4. Total solar gains [kWh / month]

Solar gains			
Month	**East facade Q_E**	**West facade Q_W**	**Total gains**
January	54.3	85.1	139.5
February	106.3	169.2	275.5
March	199.2	285.3	484.5
April	289.2	383.3	672.5
May	129.8	156.1	286.9
September	33.5	44.6	78.2
October	138.8	170.3	309.2
November	55.5	70.0	125.5
December	39.2	46.8	86.0
		Total [kWh/a]	2 457.3

5. Heat demand for heating

Seasonal heat demand for heating Q_h is calculated as the difference between heat losses and heat gains from the sun and internal sources, taking into account the use of heat gains. Thanks to the use of mechanical ventilation with heat recovery, it is possible to minimize losses to the heating of ventilation air, as well as to use internal and solar gains in their entirety. The following efficiency of heat recovery was adopted η = 85%. The calculations of the annual heat demand for heating include the following data:

– annual heat loss by penetration calculated as the sum of losses from all months of the heating season: Q_{ASEZ} = 8 938 [kWh/a];
– annual ventilation heat loss calculated as the sum of losses from all months of the heating season: $Q_{went\ SEZ}$ = 1 8984.7 [kWh/a];

– internal heat gains calculated as the sum of gains from individual months in the heating season: $Q_{zysk\ wew}$ = 3 459.4 [kWh/a];
– solar heat gains calculated as the sum of gains from individual months in the heating season: $Q_{zysk\ S}$ = 2 457.3 [kWh/a];

Annual heat demand for heating:

$$Q_H = Q_{ASEZ} + Q_{went\ SEZ} - Q_{zysk\ S} - \eta\left(Q_{went\ SEZ}\right) \quad \text{[kWh/a]}$$
$$Q_H = 8938,24 + 18984,72 - 3459,4 - 2457,3 - 0,85 \cdot 18984,72 = \tag{4}$$
$$= 5869,2 \quad \text{[kWh/a]}$$

Annual heat demand indicator with respect to the area of 211 m^2:

$$E_0 = \frac{Q_H}{A_f} = 27,8 \quad [\text{kWh/(m}^2 \cdot \text{a)}] \tag{5}$$

where: A_f – the area A_f = 211 m^2.

The calculations show that the demand for energy for building heating has dropped almost eightfold. As a result of the use of insulation ensuring the heat transfer coefficient of 0.15 W/m^2 K for walls and roof, windows and doors with 0.8 W/m^2·K insulating power, losses have been drastically reduced by external partitions. Despite the high insulating power of partitions in the building balance, ventilation losses are a significant part of the losses. Only high-efficiency heat recovery from the exhaust air gives the opportunity to significantly reduce the energy consumption of the building.

The selection of thermal power of heat sources in a building is of crucial importance. The peak power of heating appliances can be calculated by knowing the value of the annual energy demand for heating a building that takes into account the most severe external conditions prevailing in a given climate zone, i.e. the minimum outside temperature [14]:

$$q_{moc} = \frac{Q_H\left(T_i - T_e\right)}{24Sd} \quad \text{[kW]} \tag{6}$$

where: Q_H – annual heat demand Q_H = 5 869.2 kWh;
T_i – internal calculation temperature, T_i = 20°C as the average temperature of all heated rooms in the building;
T_e – the lowest external calculation temperature in the given climate zone, for the first climatic zone T_e = -18°C [15];
Sd – number of degree days for the building location according to meteorological data from PN-B-02025 calculated for internal temperature;
T_i = 20°C, Sd = 3924.

The demand for thermal power at the peak load is:

$$q_{moc} = \frac{Q_H\left(T_i - T_e\right)}{24Sd} = \frac{5869,2\left(20-\left(-18\right)\right)}{24\cdot 3924} = 2,36 \quad [\mathrm{kW}]$$

The demand for thermal power at the peak load in the building before modernization is:

$$q_{moc} = \frac{Q_H\left(T_i - T_e\right)}{24Sd} = \frac{40559,1\left(20-\left(-18\right)\right)}{24\cdot 3924} = 16,36 \quad [\mathrm{kW}]$$

The demand for thermal power of the source dropped almost sevenfold. With such a small heat demand, when the building is well insulated, the computational power of the heat source can be increased due to the heating hot water by 0.25 kW for each user [8]. Therefore, the power that a heating system should have at a time when the building is used by four consumers should be 3.36 kW.

An important element of the building is to minimize the energy demand during operation. The effectiveness in limiting this demand is so great that, in theory, the building itself may no longer require any other active heating sources. In practice, reheating is needed, often with the use of a heat pump or solar plant. Such buildings can most definitely be used in Polish climatic conditions. It is connected with an increased investment cost by 10÷20% [16]. The problem is also the design and construction of the building, as this type of construction (passive) is very dependent on many factors (orientation of the building in the area, the presence of trees or other objects that can obscure the sun, shape of the building, etc.). In the event of even the smallest executive errors, the payback time can be extended up to three times.

Passive houses are among the so-called “smart homes”. A smart home is where electrical installations and devices, such as lighting, audio/video devices, ventilation, an alarm system, automatic garden spraying, have been integrated and operating according to the user’s wishes [17]. They require accurate ventilation control and additional heat sources. The goal is to achieve high technical quality of the building and the comfort of its users with the least possible environmental burden and minimal energy consumption. In passive construction, ecological premises are combined with economy and quality. Smart air conditioning control enables constant maintenance of comfortable temperature. An intelligent lighting concept is key in the pursuit of minimizing electricity consumption.

6. Summary

Increasing prices of energy carriers from year to year mean that rational energy management is being increasingly discussed. Heating costs are rising, therefore a group of building users and investors is expanding, and they understand the need to save energy. Many buildings undergo thermo-modernization, newly constructed buildings are being built to meet European energy consumption standards.

In building designs, more and more often there is a carefully designed thermal insulation of good materials with insulation parameters far exceeding the standard recommendations. Good windows or ventilation with heat recovery (recuperation) are slowly becoming the standard [14, 18].

The application of the heat balance equation to the building's room arrangement requires the assumption that it is one zone (all rooms have the same internal temperature). The air exchange rate calculated with this assumption determines the average ventilation intensity in all rooms of the building, so that heat is lost to the external environment, and the heat gains are limited to house-related, from solar radiation through transparent partitions and from electrical devices in the building.

Solar gains are the result of the greenhouse effect and occur in every room where there are windows. The solar radiation penetrating through the glass turns into heat inside. To determine the amount of heat obtained, the orientation, shading and radiation transmittance are determined for all windows. Based on the location of the facility, the long-term average solar radiation intensities are determined.

The modern installation is responsible for overseeing and regulating the other devices that support the building. The temperature and air quality can be measured and optimized by adjusting the parameters of the fan supplying the air. Sensors installed in rooms can automatically turn off the light if the room is left for a long time. Proper control and management of the building requires a good recognition of its structural solution, the whole and individual elements, including the implementation technology and the construction materials used. Obtaining full optimization of energy consumption and minimizing heating costs as well as low failure rate of heat pumps will affect energy efficiency.

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