Passive Cooling in the System of a Heat Pump with a Vertical Ground Collector

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Abstract. Heat pumps from more than ten years are known as an alternative source of thermal energy. They are primarily used for central heating and domestic hot water preparation. Next to the solar collectors, they are the cheapest and easiest way to save energy. But heat pump can also be used for cooling. Heat can spontaneously flow from a colder to a hotter body. Flows from a body with a higher temperature to a body with a lower temperature are commonly known as the second law of thermodynamics. The heat pump pulled out of cooler ambient heat which may be used for central heating or for domestic hot water. There are many types of cooling pumps. This depends mainly on the type of pump, and actually kind of heat source that can be used in two ways: as a heat receiving surface - or as a source of cooling for utilization. Knowing the general principle of operation of the pump, we can introduce innovative technologies that allow more devices to reduce the operating costs. In this solution, the heat pump installation, initially designed only for heating or, ultimately, also for cooling purposes, enables the use of a system that will be based on the part of the installation associated with the lower heat source, but not as a source of heat but as a source of coolness. This system is often referred to as "natural cooling" or as a passive cooling system. In such a system, during the production of chilled water, a significant reduction in production costs is obtained due to the lack of energy consumption for the drive of refrigeration compressors, and only the use of circulation pumps for the lower and upper circulation of the heat source. The disadvantage of this solution is the limitation resulting from the situation of close connections between ground temperature and chilled water temperature in the supply, which causes the limitation of its use for the period beyond the maximum peak demand for cold in the cooling season, i.e. most often at the highest outside temperatures. Thanks to the economical use of electricity, we can contribute to protect the environment.

1. Introduction

In cooling systems for air conditioning, a relatively large share of costs in the entire system's functioning are costs associated with the production of chilled water, the cost of which due to the short cooling season is the main factor in financial analyses. Increasing the awareness of users of air conditioning systems regarding thermal comfort, especially during the summer, forces the use of cooling air and the need to produce expensive chilled water using compressor chillers cooled with air. In many facilities, there are modern heating solutions based on heat pump systems with horizontal and vertical collector, which gives the possibility to start a system that allows cooling from the ground, especially at vertical collectors, bypassing the existing heat pump in the summer. In this solution, the
heat pump installation, initially designed only for heating or, ultimately, also for cooling purposes, enables the use of a system that will be based on the part of the installation associated with the lower heat source, but not as a source of heat but as a source of coolness. This system is often referred to as "natural cooling" or as a passive cooling system. In such a system during the production of chilled water, a significant reduction in production costs is obtained due to the lack of energy consumption for the drive of refrigeration compressors, and only the use of circulation pumps for the lower and upper circulation of the heat source. The disadvantage of this solution is the limitation resulting from the situation of close connections between ground temperature and chilled water temperature in the power supply, which is the reason for limiting its use for the period beyond the maximum peak demand for cold in the cooling season, i.e. most often at the highest outside temperatures. During the greatest heat gains, the temperature of the water obtained from passive cooling is too small to obtain the correct temperature differences on the heat exchangers and to maintain the flow at the appropriate level, hence the need to produce chilled water by the active method using a heat pump with reverse flow or through the use of the so-called passive and active cooling modules, especially in the case of systems with a heating heat pump [1]. The article presents an analysis of the possibilities of using a heat pump system with vertical collectors for the production of chilled water for the air-conditioning of a commercial building with the use of passive cooling.

2. Types of systems for ice water production

Active cooling is said when the device operates with the compressors on. The resulting waste heat is removed from the condensers outside the installation, e.g. to the outside air or to the ground. In the winter season, the device works as a heat pump that draws energy from a given heat source. By reversing the process, the heat pump becomes a refrigeration unit in which the heat drawn from the building is actively transferred to the lower heat source [2]. Hot water heating, or additional supplies heat receivers can be carried out in parallel along with obtaining cold for installation. It is the most commonly used system for the production of cold in air-conditioning systems, but the heat is more often given to the outside air or used for other purposes [3]. Installation with a heat pump working alternately in the summer in active mode, during the transitional period in passive mode - by charging the cold directly from the lower source of cold, and in the winter as a traditional heat pump for heating purposes - shown in Figure 1.

![Diagram of heat pump systems with active and passive module](image)

**Figure 1.** Diagram of heat pump systems with active and passive module

The passive system has a number of advantages, of which the most important is the ability to produce cold in periods below the peak demand for cold, especially in installations with high internal
temperature. They may be installations serving rooms intended for people, especially those with high heat gains, but also typically industrial installations for storing products, which makes it possible to use the cooling system as a free-cooling system in winter and in the interim period [4]. The passive system is used in heat pumps with mainly vertical ground collectors. Nevertheless, there is a system with horizontal collectors, which are not usually the best solution, because the temperatures in the shallow layers below the surface of the earth are too high in summer for efficient cooling. The collector's temperature on August 1 is already around 15 °C, with no heat supplied. By supplying waste heat, the temperature of the collector will rise even more, which will start to fulfill the function of the energy storage [5]. One should also be afraid of violating the living conditions of flora and fauna on the surface of such a collector. Using a ground collector for the required cooling can lead to the drying of the soil around it. The associated shrinkage of the soil leads to loss of contact between the soil and the collector and the deterioration of heating operation efficiency. When using geothermal probes, a constant temperature level (approx. 8-10 °C) is used for deeper soil layers as a source of cold for cooling processes. Thanks to the closed circulation, there are no legal obligations related to water management. The transferable cooling capacities are generally not sufficient to ensure coolness throughout the season due to the low efficiency of the source (compared to the heat demand, the volumes required for cooling are much higher) and because of the low parameters of the chilled water in the wells. Therefore, passive cooling can only be a functioning system for a limited period of time, also due to the gradual heating of geothermal probes and reduction of the maximum cooling power. For the most part of the period when it is possible to obtain free energy for cooling from the ground with the help of an existing installation, which is mainly used to recover heat from the ground in winter for heating purposes, this installation is not able to produce water with parameters enabling air drying in transitional period - ice water [6]. Hence the idea of the so-called silent cooling, which took its name from the fact that it is not possible to condense water vapor from the cooled air due to too high parameters of cooling water. Using this characteristic feature, the silent cooling system is used in systems with surface heating as a cooling system.

3. Analysis of possibility of using passive cooling
A large commercial building with an existing air-conditioning system was analyzed using fan coil units and a VAV system. Cooling recovery takes place in the VAV unit and in the system with fan coil units. The commercial building also has a heat pump with vertical collectors, to which the passive and active cooling module should be selected. For the needs of the heat pump, it was also assumed to use a cold storage tank operating in 24 hours. For the purposes of the analysis, a gallery-type commercial building with a total area of 3 750 m² was taken into account. For such a building, a heat balance was made for the summer months and for the winter period, so that it was possible to interpolate the results in transition periods. The results are summarized in Table 1.

| Table 1. Statement of hourly heat gains for selected periods of the year |
|-----------------------------|-------------------|
| Calculation period | Heat gains, Qc, kW |
| April             | 22957,9           |
| August            | 22972,8           |
| Winter            | 15192,6           |

Figure 2 presents daily fluctuations in heat gains of solids independent of the external environment from sources such as people, lighting and others. This is a subjective assessment of the amount of these profits, which in large measure coincides with the period of use of this type of commercial buildings, largely from people. An analogous distribution is observed for the winter period, but these profits reach a lower value due to heat losses due to penetration through the external partitions. Figure 2 presents the daily schedule of external heat gains caused by the insolation of the facility in the month of April.
The amount of these heat gains is insignificantly small compared to "constant" heat gains and reaches a maximum of about 1.5%. Thus, the amount of cooling demand is basically determined by the internal heat gains outside the periods between 12 and 16 hours, when the maximum sun's efficiency per building is registered. Therefore, the total cooling demand for the entire building is presented in the form of the necessary cold for air-conditioning systems that maintain the microclimate in the room at the desired level. These quantities, determined according to generally accepted rules, are as follows:

- April $Q_{ch} = 5,582.9$ MW
- August $Q_{ch} = 9,574.9$ MW

For such assumptions, the cooling reservoir size for the active system, which stores the cold in the daily period was determined due to the very large variation in the demand for cold. Cooling accumulation, which takes place in a 24-hour cycle, can be performed as full, partial or with a capacity limit. During full storage, the cold is generated only during the off-peak hours (the cooling unit operates during the night tariff period). During partial storage, the cold during its greatest demand is delivered both from the storage tank and from the refrigeration unit.

![Figure 2. An exemplary distribution of external and internal heat gains for the month of April](image)

Storage with capacity limit combines the features of both of the above accumulation systems, allowing rational use of the night tariff and reducing the efficiency during the period of the daily tariff for electricity. [7] Assuming the accumulation, the partial power of the $Q_{chill}$ aggregate can be determined based on the schedule of the hour's cooling demand by the building according to the dependence (1).

$$\sum (Q_{chill} - Q_i) t_i = 0$$  \hspace{1cm} (1)

The $Q_i$ values represent the hourly cooling demand in kW, while the time $t_i$ is the unit of time for which $Q_i$ is determined. Assuming a 24-hour operation of the refrigeration unit and time interval $t_i = 1h$, the power of the $Q_{chill}$ Chiller finally assumes the value of 15 MW. The volume of the cold store depends mainly on the cold storage material and type of accumulation system. The most important is, however, the way energy is stored. Cooling energy can be stored in the form of explicit (SHS) or latent (LHS). The density of DLHS energy storage is not constant, but changes depending on the assumed temperature of the refrigerant at the inlet and outlet of the cooler. DLHS includes both latent heat as
well as the amount of sensible heat resulting from sub-cooling or overheating of accumulative material.

\[ DLHS = Q_{SL} \left( T_z - T_{st} \right) \]  

The SHS storage system was adopted. The energy storage density for chilled water with the parameters supply and return respectively 7/14 °C and values, \( Q_{SL} = 1.16 \text{ kW/Km}^3 \), \( Q_{DD} = 0.53 \text{ kW/Km}^3 \) assumes the value kWh/m³. The minimum size of the reservoir, depending on the density of stored energy, is calculated as:

\[ V = \frac{Q_{dst}}{DLHS}, \text{ m}^3 \]  

The amount of energy discharged from the unloading cycle of the \( Q_{dst} \) tank can be determined on the basis of histograms, Figure 2 showing the hourly demand for cold in a 24-hour period. This is the difference in the total demand for cold during the unloading hours of the container minus the amount of cold produced by the refrigeration unit during this period. The amount of cold required for this aggregate required for storage is set at 123.5 MWh - this is the amount of cold needed in the month of August. Thus, the necessary active volume of the chilled water reservoir will be 30 m³.

4. Passive cooling limit

The calculation of chiller power was made by interpolating the heat gain schedule. The chiller's power is the limit amount of cold, above which the cold storage container is discharged, and below it is charged with cold. The chiller power for the month of April is \( Q_{chill \text{ April}} = 14,500 \text{ kW} \), while for August \( Q_{chill \text{ August}} = 15,000 \text{ kW} \). Based on the results, you can link the chiller's power to the outside temperature \( T_z \). For April \( T_z = 19.5^\circ\text{C} \), while for August \( T_z = 30^\circ\text{C} \). These are temperatures between which cooling can occur only in the active system, while in the remaining period in the passive system or there will be no need for cooling - a transitional period. Based on the method of estimating the cooling demand on the basis of external and internal air parameters, the total coolness was determined, covering the cooling demand for the building during the whole year, which is \( \Sigma Q_{sez} = 484.4 \text{ MWh} \), of which the amount of cold can be obtained passively, i.e. when the temperatures are less than the active system's operation - below 26.2 °C, and yet the need to cool the building occurs due to large internal heat gains is \( Q_{sezpass} = 324.5 \text{ MWh} \). These data were obtained on the basis of dependence (4) and using meteo data for the Rzeszów-Jasionka station (Poland).

\[ Q_{CH}^{\text{rez}} = V_w \cdot \rho \cdot \sum \left[ \left( h_e - h_i \right) z \right] (1 - \eta) \text{ [kWh]} \]  

where:

- \( Q_{CH}^{\text{rez}} \) - amount of recovered cold during the season [kWh]
- \( V_w \) - amount of ventilation air [m³/h]
- \( \rho \) - air density [kg/m³]
- \( h_e \) - external air enthalpy [kJ/kg]
- \( h_i \) - indoor air hypotension [kJ/kg]
- \( z \) - the frequency of occurrence of external air enthalpy [h]
- \( \eta \) - exchanger efficiency for cold recovery [%]

For the calculations, it was assumed that the recovery efficiency of cold on the exchanger is 50%, while the stream of ventilation air is at the level of 647 400 m³/h. The values \( h_e \) of individual air enthalpies determined on the basis of data for Rzeszów-Jasionka meteo stations are presented in Table 2.
\( T_{\text{cool}} \) is the temperature interpolated from the meteorological station Rzeszów-Jasionka after rounding the enthalpy of the outside air to the integers \([7]\). This allows you to specify the temperature for which building cooling is not required. It follows that at an outdoor temperature of 18.1 °C, the external enthalpy equals the enthalpy of the air inside the room and cooling in this situation is unnecessary. To calculate the amount of chill possible in the passive system, the chilled water temperature was set at 7/14°C, ground temperature \( T_g = 8°C \). It was assumed that the chilled water can be cooled passively to the temperature \( T_z \), i.e.:

\[
T_{wz} = T_g + \Delta T \, ^[°C]
\]

\( \Delta T \) is a temperature difference between the ground and the cooling water supply temperature adopted at 4 °C.

**Table 2.** Air enthalpies and the frequency of their occurrence for the Rzeszów-Jasionka meteo station

| \( T_{\text{cool}} [°C] \) | \( h_e \) [kJ/kg] | \( z \) [h] | \( h_i \) [kJ/kg] | \( (h_e-h_i)*z \) |
|-----------------|-------------|--------|-------------|------------|
| 28.2            | 65          | 7      | 44          | 147        |
| 28.0            | 64          | 1      | 44          | 20         |
| 27.0            | 61          | 11     | 44          | 187        |
| 26.5            | 63          | 2      | 45          | 36         |
| 26.5            | 57          | 29     | 43          | 406        |
| 26.4            | 59          | 10     | 43          | 160        |
| 26.0            | 60          | 10     | 44          | 160        |
| 25.6            | 58          | 26     | 44          | 364        |
| 24.8            | 62          | 2      | 47          | 30         |
| 24.1            | 55          | 29     | 44          | 319        |
| 24.1            | 54          | 36     | 43          | 396        |
| 23.5            | 56          | 22     | 45          | 242        |
| 23.3            | 53          | 61     | 45          | 488        |
| 23.1            | 52          | 56     | 43          | 504        |
| 22.8            | 51          | 65     | 43          | 520        |
| 21.4            | 50          | 89     | 43          | 623        |
| 21.4            | 49          | 84     | 43          | 504        |
| 20.2            | 48          | 95     | 43          | 475        |
| 19.3            | 47          | 98     | 44          | 294        |
| 19.2            | 46          | 92     | 44          | 184        |
| 18.6            | 45          | 110    | 44          | 110        |
| 18.1            | 44          | 126    | 44          | 0          |

Figure 3 is a graph showing the possibilities of an active and passive system depending on the temperature.
Figure 3. The limit of using active and passive cooling depending on the outside temperature

The temperatures at which the cooling demand is located under the horizontal line are the temperatures at which passive cooling can be used, i.e. below 26.2 °C. At other temperatures, only active cooling can be used to maintain the assumed temperature in the facility [8].

5. Conclusion

On the basis of calculations, it can be concluded that the building should be cooled above the $T_{cool}$ temperature of 18.1 °C. We can passively cool down to a temperature of 26.2 °C, while above this temperature, passive cooling is inefficient and the building should be cooled actively. With natural cooling, you can save about 70% of the electrical energy necessary to drive a refrigeration compressor, and only 30% of the annual cooling demand is produced in the active use of the refrigeration system. It follows from the above that the passive and active module is very beneficial and allows to significantly reduce operating costs. Another reason why you should invest in a passive cooling system is that during the production of cold, the compressor is passive, so it can be used for parallel preparation of hot usable water [9]. During the heating season, the heat pump can be used as a source of heating for the building. A heat pump with a passive module is a very beneficial solution not only because of the possibility of saving money spent on operating fees, but also for ecological reasons. It is friendly to the natural environment and only to a small extent, because for 30% of the duration of the cooling season, it uses electricity obtained in Poland primarily from coal. However, before investing in such a solution, you should carefully consider the possibility of such an investment. Due to the type of ground heat exchanger, it should be ensured that it is possible to drill in the planned place. The installation of a heat pump with a passive cooling module is an expensive investment and logistics project, so that it should be fully profitable, it should be used for large buildings with a high heat load.

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