Geothermal heat pump systems in cold regions: efficiency improvement by use of ambient air

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Abstract. We examine the problem of efficiency in both air-source and geothermal heat pumps in regions with low ambient air temperature, and the advantage of using a combination of both systems in one equipment. Both geothermal and air heat pumps have their advantages and disadvantages. Geothermal heat pumps are more expensive to install and, in colder climates, experience a progressive decrease in efficiency with constant use during the winter season because of chilling of the ground adjacent to geothermal heat exchangers during heat extraction. Air-source heat pumps are less expensive to install and experience a decrease in efficiency as ambient temperature is getting lower. A numerical model simulation was conducted using the program "INSOLAR.GSHP.12" for a 200 sq.m. house in Moscow. The model tested the efficiency of combined use of a ground heat pump at ambient temperatures below -10°C, and air heat pump for ambient temperatures above -10°C. The results were compared to simulation of using only a geothermal heat pump. The results show a 13.3% reduction in energy consumption using the combined ground and air heat pumps over the energy requirement of using only the geothermal heat pump.

1. Introduction
Heat pump systems become more widespread around the world, including regions with cold climate [1-4]. The two types of such systems: air-source heat pump system (AHPS) and geothermal heat pump system (GHPS) are used most widely. Both systems have their advantages and disadvantages. For instance, GHPS provide stable and reliable heat supply, but they have a high initial cost. In other turn, the efficiency and productivity of AHPS are highly dependent on the constantly changing environmental conditions. Functioning in cold regions has additional requirements for the heat pump system. The heating period in much of Russia territory is noticeably longer and the ambient temperatures are much lower than for example in Europe, all this leads to a significant decrease in ground temperatures during the operation of the GHPS, which in turn leads to a decrease in their efficiency. According to [5] ground thermal imbalance is a key problem inhibiting GHPS’ effective operation in cold regions. There are several ways to cope with this effect: increasing borehole space [6-7] modifying borehole layout [8] improving thermal properties [9-11] but the most effective way is to increase the length or the number of the ground heat exchangers [12]. This method, however, significantly increases the cost of the system, which is already quite high in comparison with the AHPS. In turn, the heat output of AHPS reduces significantly at ambient temperatures below 0 °C [13]. Also, at low outdoor temperatures, the effectiveness of ASHP is also low: according to the studies in [14] COP of an air-to-air ASHP was 1.8 and 1.1 corresponding to outdoor temperature 4.5 °C and -15 °C, respectively. In order to compensate the AHPS decreased productivity at temperatures...
below 0 °C, oversized units are sometimes suggested to meet high heating demand during extreme cold days [15]. But at the same time their cost increases: if usually AHPS are significantly cheaper than GHPS, since they do not require the ground heat exchangers establishing, in the case of an oversized unit this advantage is reduced. Comparative analysis of AHPS and GHPS is presented in [16-18]. A combined system that uses both ground heat and air heat is proposed in order to avoid price increasing of both system versions, while providing reliable heat supply in regions with a cold climate.

2. Methods

Comparative studies of the heat pump system operation using only the heat of the body of soil and operation of the system with combined use of heat both ground mass and atmospheric air at temperature above minus 10°C were conducted to estimate the effectiveness of such solution. In this regard, in the case of a combined system, the body of soil is used for a minor part of the heating season: only when ambient air temperatures are below minus 10°C. This temperature was chosen as a boundary point in accordance with the results of Swedish Energy Agency research presented in [19], according to which it is at this temperature that ASHP still provides a full coverage of the space heating demand. At lower outside air temperatures, the decreasing heat output of the heat pump is already less than the space heating demand, which, on the contrary, increases with decreasing outdoor temperature. Figure 1 shows the total amount of hours with different temperatures in Moscow for the heating period 2018-2019 in accordance with the weather station WMO ID 27612 data.

![Figure 1](image)

**Figure 1.** The histogram of the heating season 2018-19 temperatures in Moscow.

As can be seen from the figure, the total amount of hours of ambient air temperatures below minus 10 °C is only 10 - 12% of the duration of the heating season. At this time CHPS works from the ground. In the rest of the period, the system uses atmospheric air as a source of low-temperature heat. The functional scheme of the analyzed combined heat pump system (CHPS), which uses a combination of ambient air and soil mass as a low temperature heat source, is shown in Figure 2.
The low temperature heat collection system consists of a heat pump evaporator (1) connected in parallel to the ambient air heat exchanger (2) and a borehole heat exchanger (3). The electrically controlled three-way valve (4) by the signal from the ambient temperature sensor (5) switches the flow of the heat-carrying medium to the ambient air heat exchanger (2) or to the ground heat exchanger (3).

The authors conducted a numerical study to estimate the effectiveness of the proposed solution. The simulation was carried out using the program "INSOLAR.GSHP.12". This software is based on mathematical model of spatial non-steady thermal behavior of ground mass around BHE considering climatic conditions of the construction area, heat insulation of the building, performances of heat pumps, circulation pumps, heating devices, as well as their modes of operation [20]. While conducting the study a hypothetical house with the area of 200 sq.m. was considered. For this house numerical experiments were performed to simulate the operational modes of CHPS in the soil and climatic conditions of Moscow. The duration of the heating season was assumed equal to 205 days in accordance with the current climatological norms [21]. The basic initial data for the numerical experiment are presented in the table 1.

| Parameter                                                                 | Dimension | Value       |
|---------------------------------------------------------------------------|-----------|-------------|
| The radius of the borehole heat exchanger (BHE)                           | m         | 0.080       |
| Borehole heat exchanger depth                                            | m         | 50.00       |
| Heat-carrying medium flow in the heat collection system                  | m³/hour   | 5.513       |
| Undisturbed ground temperature                                           | °C        | 5.4         |
| Building thermal protection efficiency of per 1 borehole heat exchanger   | W / °C    | 288.684     |
| Electrical equipment capacity                                            | kW        | 4.613       |
| Kinematic viscosity of the heat-carrying medium in heat collection system| Sq.m / s  | 1.789E-06   |
| Coefficient of heat transfer from ground to heat-carrying medium         | W/(m² · °C)| 86.000     |
| Heat capacity of the heat-carrying medium                                | W·h/(kg · °C)| 1.047   |
| The volumetric weight of heat-carrying medium                            | kg / m³   | 1 020.000   |
| Horizontal thermal conductivity of ground                                | W/(m · °C)| 2.000       |
Vertical thermal conductivity of ground  | W/(m·°C) | 2.000
--- | --- | ---
Coefficient of the heat transfer from the ground surface  | W / (m²·°C) | 23,260
Ground heat capacity  | W·h/(kg·°C) | 0.642
Volumetric ground weight  | kg/ m³ | 2 000.000
The design internal air temperature of the room (winter)  | °C | 20.00
The design outdoor air temperature  | °C | minus 28
The duration of the heating season  | month | 7
Heat pump type  | Ground-water
The installed electric capacity of the heat pump drive  | kW | 2,500
Condensation temperature  | K | 323
Thermodynamic efficiency of heat pump  | - | 0.650
Temperature pressure in the condenser  | K | 5
Temperature pressure in the evaporator  | K | 5
Temperature pressure between the inside air and heat-carrying medium of heating and cooling system  | K | 10
Installed electric capacity of the circulation pumps of the evaporator circuit  | kW | 0.100
Efficiency of the circulation pumps of the evaporator circuit  | - | 0.8
The installed electric capacity of circulation pumps of heat fan system  | kW | 0.050
Pressure losses in the evaporator  | m H₂O | 2

As a criterion of the heat pump system efficiency coefficient of performance (COP) and the total cost of electricity during the heating season were accepted. The system work was simulated with two heat source configurations:
- Ground;
- Ambient air and ground.

3. Results and discussion

1. Figure 3 shows the obtained values of the coefficient of performance for the two reviewed variants of the heat pump system during the heating period.

![Figure 3. Coefficient of performance (COP).](image-url)
2. As can be seen from the graphs, the GHPS transformation coefficient gradually declines due to the cooling of the soil massif, and only by the end of the heating season slightly increases due to a decrease in the heating load. In the case of CHPS during the entire heating period the transformation ratio is higher, including due to less intensive cooling of the soil massif, and by the end of the heating season it is significantly increasing due to the predominant use of the heat of already sufficiently warmed ambient air.

3. The energy consumption of the system was determined taking into account the change in ground temperature during long-term heat extraction, herewith also was taken into account the heat inflow from the surrounding ground, due to which the temperature is restored during periods of low or lack of loads in the ground heat exchanger. Thus, the energy consumption of the system was calculated for the 5th year of operation. Energy costs for defrosting the ambient air heat exchanger were not taken into account. Details on the electrical energy consumption during the heating period for the reviewed options are presented in Table 2.

| Table 2. Electrical energy consumption |
|---------------------------------------|
| Units  | Quantity       |
| GHPS   | KWh            | 14 903          |
| CHPS   | KWh            | 12 917          |

4. From the data presented, it can be seen that the combined use of low temperature heat of the body of soil and ambient air makes it possible to reduce energy consumption by the system by 13.3% in comparison with GHPS.

5. Based on the executed calculations a combined system experimental model for the house in DPK "Aleko" in the Moscow Region, shown in the picture of Figure 4, was developed.

![Figure 4. Photo of the house, where the experimental model of the combined system was installed.](image)

6. Mnemonic scheme of the applied combined system with additional utilization of the heat of ventilation emissions is shown in Figure 5.
4. Conclusions

1. The results of numerical simulation confirm the effectiveness of the proposed solution in terms of both selected performance indicators - COP and the total costs of electric energy during the heating period.

2. The CHPS coefficient of performance (COP) is higher than the same indicator for the GHPS for the entire heating period.

3. The energy saving in the case of a CHPS use is 13.3% compared to GSHP.

4. This article addresses the use of the ambient air heat by means of a system with an intermediate heat-carrying medium, which is not the most efficient solution because of the temperature losses in the intermediate heat exchangers and the additional energy input on the circulation pump drive. To increase the efficiency of ambient air heat utilization, the authors advise to consider the variant of CHPS using a refrigerant-air heat exchanger.

5. Using a combination of heat sources and an appropriate reduction in the load on the ground heat exchangers will allow to maintain higher ground temperatures and thereby improve the heat pump efficiency. At the same time, the use of ambient air at the beginning and the end of the heating period, when the ambient air temperature is higher than the ground temperature, also increases the efficiency of the heat pump system.

6. In regions with a cold climate, combined use of ground and air as heat sources for the heat pump system due to load sharing between the two sources avoids the increase in the size of the ground heat exchangers in the GHPS version. Thus, the capital cost of combined system construction will be lower than the GHPS creating cost. It is expected that a relatively small ambient air heat exchanger, used in periods with moderate outdoor temperatures, will be cheaper than additional ground heat exchangers.

7. The temperature when the CHPS switches to the ground heat exchangers can be proposed as one of the criteria for optimizing the CHPS operation efficiency. In the present study, this temperature is assumed to be minus 10 °C, but since a significant decrease in the characteristics of AHPS is observed already at 0 °C, this temperature can be considered as a boundary temperature. As can be seen in Figure 1, even in this case, CHPS will use air for more than half of the heating period.

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