Heat Pumps for Central Russia: Problems and Solutions

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Abstract. The article discusses the prospects of saving resources when using heat pumps for heating buildings. Based on climate data and new regulations in the construction industry, an indicator of the specific consumption of heat energy for heating one square meter of area for the central Russia is determined. For a typical building, it is shown that, in terms of the total cost of operation, a heat pump installation can successfully compete with an electric boiler and a liquid fuel boiler. The main problems that impede the wider introduction of heat pumps in Russia are identified. An example of a heating unit based on heat pumps for a rural school building is given.

1. Introduction

Rising prices of energy products such as oil and gas, as well as their limited resources, necessitate an increase in the use of renewable energy sources. This applies in particular to the energy that is used to heat buildings, that is, thermal energy available in different forms in the environment [1, 2, 3]. One of the solutions for the use of a renewable thermal energy is a heat pump (HP) [4, 5, 6]. This term adequately reflects the essence of the process carried out using HP. By the second law of thermodynamics, the natural heat transfer occurs in the direction of lowering the temperature potential. Thus, during the exploitation of heated buildings, heat from a source with an average potential, such as a gas or electric boiler, is ultimately transferred to an environment with a low thermal potential. The heat pump performs the reverse process - it transfers (“pumps”) heat from a low-potential source (environment) to a consumer with a higher potential. Heat pump, like a conventional pump, must consume energy for its drive. Currently, the vast majority of HPs use an electric drive due to its reliability and the relative cheapness of installation and maintenance; however, it is possible to use internal combustion engines or a hydraulic turbine drive.

The operating principles of HP associated with the use of heat absorbed and released during phase transitions of the working fluid have been well known for more than half a century [7]. However, the impetus for the intensive development of the heat pump technology was received only in the 1970s in the course of the world energy crisis. From this moment, there is a process of improving the working fluid (chlorofluorohydrocarbons), compressor technology and methods of transferring heat to and from the heating system.

According to the electronic journal of the energy service company Ecological Systems (Moscow), more than 10 million heat pumps of various capacities are operating in the world - from several kilowatts to hundreds of megawatts. In the USA about 30% of administrative and residential buildings are equipped with HP. In Sweden, in 2004 a record amount of HP was sold - 66,154 pcs [8, 9]. According to the expectations of the World Energy Committee, by 2020, in advanced countries, the share of heating and hot water from heat pumps can be up to 75%.

Heat pumps systems are also designed and implemented in Russia [10]. In addition to heating low-rise buildings, projects are underway to heat multi-story residential buildings, for example, heat supply to a sixteen-story residential building in the Nikulino-2 district (Moscow).

2. Why heat pump technology is acceptable for Russia

Autonomous heating of buildings can be managed on the base of the use of gas, coal, liquid fuel (fuel oil, light heating oil), and electricity. Besides some negative aspects (the higher price of heat energy), decentralization of a heat supply has also pros: the possibility of the flexible adjustment of a room...
temperature and the possibility of the use of energy-saving technologies. The latter includes the HP technology. Vapor-compression heat pumps, discussed in the article, get an average of 2/3 of the total heat energy from the environment for free, while only about 1/3 of this energy is generated due to the consumed electric power.

The installation of a heat pump and a system for extracting heat energy from the environment require significant investment. Therefore, when considering the possibility and advisability of using such a heating technology, it is important to answer two questions. The first of them is whether it is economically acceptable to use one of the most expensive energy carriers in Russia (electricity) for heating up buildings. Yet, it should be noted that there may be the situations when there is no alternative to electricity.

The second question is how heat pump can compete in economic terms with heat supply units using other types of fuels.

When operating buildings, heating costs make up a significant part of operational expenses. The general rise of the price of energy resources taken with and improvement of the physical characteristics of construction materials make it possible and necessary to reduce the specific consumption of thermal energy for heating.

Old single-family houses in central Russia take up to 600 kWh for heating 1 m² of area [10]. Until recently, this was considered acceptable. The situation changed with the adoption of the national Regulation “Thermal protection of buildings” (SNiP 23-02-2003) in 2004 [10]. This document sets the standard specific heat consumption $q_{ht}^{rec}$ for heating residential buildings significantly lower than before (see Table 1).

| Heated area, m² | $q_{ht}^{rec}$, kJ/(m²°C·days) |
|----------------|----------------------------------|
| 1 floor        | 2 floors                         | 3 floors | 4 floors |
| 60 and less    | 140                              | -        | -        | -        |
| 100            | 125                              | 135      | -        | -        |
| 150            | 110                              | 120      | 130      | -        |
| 250            | 100                              | 105      | 110      | 115      |
| 400            | -                                | 90       | 95       | 100      |
| 600            | -                                | 80       | 85       | 90       |
| 1000 and more  | -                                | 70       | 75       | 80       |

Design specific heat consumption $q_{ht}^{des}$ must be less than or equal to the normalized value of $q_{ht}^{rec}$, which is achieved when choosing a thermal, cold-resisting properties of building materials, space-planning decisions, the orientation of buildings, as well as the type, effectiveness and method of adjusting the used heating system. The mentioned values are normalized not only regarding the heated area of the building, but also heating degree-day, $D_d$, ° C·day, which are determined by the same SNiP 23-02-2003 according to the formula

$$D_d = (t_{at} - t_{ht})z_{ht},$$

where $t_{at}$ is the calculated average temperature of a room air, ° C; $t_{ht}$ - average outside air temperature, ° C; $z_{ht}$ - days of the heating period.

Heating degree day (HDD) is a specific measurement to determine the demand for energy needed to heat a building. HDD depends greatly on the outside air temperature. The consumption of heat by a building is assumed to be directly proportional to the number of HDD at the location of the building. More general parameter, heating-cooling degree-day is used for some applications [11, 12, 13].

For example, for the Ural region, Udmurt Republic (1200 km to the east from Moscow) the value of the indicator is determined by the Meteorological Office as

$$D_d = 5215°C.$$

This value allows one to compare climatic conditions of central Russia with the conditions in countries where the heat pump technology has been working successfully for a long time. For example, for Sweden, where it is believed a mild climate, the heating degree-day index $D_d$ varies from 3010 to 6388.
The obtained value \(Q = 152.1 \text{kWh/m}^2\) allows to estimate the specific seasonal heat consumption needed for heating a two-story building in central Russia. Comparison with the above values \(600 \ldots 800 \text{kWh/m}^2\) shows that energy-saving policy contributes to the greater use of electricity for needs heating, and therefore, we have a positive answer to the question of the economic feasibility of such use.

To answer the second question, a comparison was made of the cost-effectiveness indicators for heating two-story building with a total heated area of \(250 \text{m}^2\) [10]. It was accepted the specific heat loss of \(70 \text{W/m}^2\). In that case the power of heat losses (which determines the power of a heating unit) was assumed as \(17.5 \text{kW}\).

In the course of the analysis, it was calculated: the cost of various types of fuels for heating the investigated object for the heating period; the total cost of installing the heat unit, as well as the total cost of operating of all the alternatives for 10 and 15 years. Based on the above calculations, it can be seen that the heat pump payback period is 4 years compared with that of an electric boiler; and 6 years compared with a liquid fuel boiler (see figure 1). Beyond this period significant saving money takes place (about two million rubles for 15 years compared to an electric boiler).

![Figure 1. The total cost of operating a heating unit](image)

Thus, for the construction of energy-efficient buildings in conditions of constant rise in the cost of energy, the use of heat pumps for autonomous heating of buildings becomes economically feasible in comparison with electric boilers and boilers using liquid fuel.

3. Due installation is the key condition for successful exploitation of a heat pump unit

As a source of low potential heat for HP it can be used: outdoor air (the temperatures up to \(–15 \ldots –20 ^\circ \text{C}\)); exhaust air leaving the rooms through ventilation; water (underground or from a river/pond/reservoir); vertical earth-coupled systems; ground; and wastes of industrial enterprises. Here we are especially interested with an individual heating of low-grades buildings in rather severe climate, so we will focus mainly on earth, ground, and water.

A critical issue for the geothermal heat pump technology is how to extract a low-grade heat from the environment. There are four problems with using vertical and horizontal piping systems.

3.1. Dimensioning. The available Earth heat varies from region to region. Therefore, the calculation of the depth of the borehole or the length of a horizontal trench should be based on the geophysical data valid for a particular region.

3.2. Economy. The installations of vertical and horizontal earth-coupled systems are rather expensive, time- and labor-consuming.
3.3. Technology. When putting pipes into ground, groundwater pollution with the surface runoffs and working fluids should be prevented, and the underground water regime should not be violated. Besides there is a problem regarding the installation of the system of radiators, or the underfloor heating system. A heat pump refrigeration contour is affected to high extent by the heat source and heat sink contours. A radiator system may not be designed correctly both in terms of a unit’s heat power and a number of units. One of most frequent problems comes from a hydraulic resistance which is higher than designed. This can cause misalignment of all heat pump circuits. Over 10 years of installation and the in-field consulting experience, we were faced with the need to re-install all external systems in several fault installations.

3.4. Law. The issue of the geothermal licensing has not been resolved in the Russian legislation yet. Existing legislation allows drilling boreholes/wells up to 30 m in depth without any permission. Permission and detailed design project are required for drilling deeper wells. But at depths of up to 30 meters, the geothermal effects are negligibly small. The deeper vertical boreholes used as the energy wells, differ from ordinary water wells or oil wells in the design. After installing close-loop pipe systems they are filled with bentonite clay and, in fact, become a conglomerate with the surrounding rock. Since the energy wells are standardized by manufacturers of HP (only length is varying), it seems unreasonable to require an expensive a well design project in every installation. But this is still a problem in Russia. The problem of taking climatic conditions into account when dimensioning earth-coupled systems is compounded by the fact that up to 90% of the market for heat pumps of small and medium power in the Russian Federation is provided by imported equipment (manufactured in EU, USA, China). The optimal modes of these are configured for geophysical and climatic conditions in regions with milder climates. When formally following manufacturers' recommendations, two dangers are possible. Firstly, a HP does not receive necessary amount of a low-grade heat and, hence, will not produce the required heat output. Secondly, during many years of operation of incorrectly calculated vertical or horizontal loops, it is possible to freeze them down and break down the entire expensive installation. To the date, there are no national regulations the design and installation of earth-coupled systems for heat pump units in the Russian Federation.

It is known that the greatest economic efficiency of using HP is achieved when reversing is possible: that is, in a winter time the heat pump works for heating, and in the summer - for air conditioning. For example, air conditioners can generate heat and cold optionally. Such air conditioners - air heat pumps use the heat of the air outside the building. The ability for reversing the mode of operation is their advantage. However, they also have a number of disadvantages. The main one includes a decrease in the coefficient of performance (COP) with the decrease in the temperature of the outdoor air, which can reach 50 - 100% when switching from plus temperatures to temperatures below minus 20 degrees of Celsius.

At the same time, the use of heat from exhaust ventilation would allow to increase the heat pump COP or reduce the size of the earth-coupled system (external collector). In the summer time, the recovery unit could provide a decrease in the temperature of the indoor air without the use of an air conditioner. It also supplies the external collector with an additional amount of a heat. Thus, in the summer, an external collector would receive recharge of thermal energy, which it would take away in winter. Also promising is the operation of HP in conjunction with a solar collector, which also contributes in the increase of the COP. The use of solar collectors in the Russian climatic conditions requires research.

In the regions of the Russian Federation there is fairly large number of non-gasified settlements in which public buildings for various purposes are operated. Some of them have a large heat demand but are heated with electric boilers. With rising energy costs, this heating method should be recognized as extremely inefficient, thus, the task of determining the optimal composition of an energy-saving heat unit becomes relevant [10].

4. Case study: design of the heating of a rural school with HP
A heating system and heating unit are being designed for heating up a rural school building, in which 132 pupils study in the day time and 20 pupils live permanently all time. The volume of the building is 19,103 m$^3$.

The estimated power for heating is 415 kW. Taking into account the heat power demands for the ventilation system, the total power of the heating unit should be about 550 kW. It is advisable to divide this power between heat pumps (approximately 65% of the total power) and the heater of any type [14]. In particular, an electric boiler can be used for the remaining 35% [15].

In this case, 7 heat pumps with a thermal power of 50 kW each will be required. Because of the climatic conditions of central Russia, the most reliable solution is a vertical earth-coupled piping system for HPs.
However, with the high cost of design, drilling and installation of this system, the total project cost may exceed the cost of the HP units by 3-4 times. Yet there is availability of free space for burying a horizontal collector, in particular, under the stadium. The performance of the horizontal earth-coupled piping system is lower than that of a vertical energy well (approximately 10 - 14 W/m instead of 40 - 50 W/m) this should be included in the calculation of the total length of the horizontal piping system. Another feature of the building is its large volume and the presence of heat-generating devices (big stoves in the kitchen). It is reasonable to use the heat of the exhaust air that leaves the building through the ventilation system to feed an air-source recuperating HP. The proposed composition of the equipment for heating and ventilation of the school building is given in Table 2.

| Function   | Equipment                                | Heat power, kW | Source of low-grade heat | Amount of units | Total heat power, kW |
|------------|------------------------------------------|----------------|--------------------------|----------------|----------------------|
| Heating    | Water-source HP supplied with horizontal earth-coupled system | 50             | Total length of buried pipes is 6x400 m = 2400 m for every HP | 5              | 250                  |
|            | Electric boiler                          | 90             | No                       | 2              | 180                  |
| Ventilation| Exhaust Air-source recuperation HP        | 9              | The maximum amount of exhaust air passing through the HP is 500 m³ | 5              | 45                   |
|            | Outdoor air-source HP                    | 36             |                          | 2              | 72                   |

Figure 2 shows a schematic diagram of a heating unit with the use of heat recuperation. The system includes a storage water heater, used not only for ventilation needs, but also providing a hot tap water. Therefore HP units of this type can be installed in a dining room, bath, and other rooms with the need for a hot tap water.

![Figure 2. Schematic diagram of a recuperative heat pump installation using exhaust air](image)

The calculations of the consumed electric power show that the maximum saving in electric power of the proposed heating unit is 245 kW, which will not only allow significant money savings, but also reduce the load on the electric network. Economically viable alternatives to heat pumps for heating and ventilation of the building in question are gas and coal boiler units.

5. Conclusion
The heat pump technology is still not very popular in Russia. There are several reasons for this. There is a common delusion that climatic conditions in Russia are not suitable for this type of heating. The article shows that the degree-day parameter in the central Russia is comparable with this value for northern Europe. In addition, in Russia there are many climatic zones with a milder climate, ideal for implementing HP technology, especially if the energy-efficient technologies are used for a building insulation.

The next important reason is numeral technical errors when installing both HP units and the heating systems. Therefore, it is especially important to promote the renewable energy heating systems and run training centers for the installation service companies.

After all, national manufacturers of HP equipment should appear. The governmental policy in the field of energy saving and renewable energy should contribute to the solution of all the discussed problems.

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