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GROUND-SOURCE AND AIR-SOURCE HEAT PUMPS AS THE HEAT SOURCE FOR A SINGLE-FAMILY FREE-STANDING HOUSE

GRUNTOWA I POWIETRZNA POMPA CIEPŁA JAKO ŹRÓDŁO CIEPŁA DLA BUDYNKU JEDNORODZINNEGO WOLNOSTOJĄCEGO

Summary: In the paper, information concerning the ground and air pumps to supply a free-standing, single family house with thermal energy has been presented. The principle of functioning of the heat pumps, based upon the Carnot cycle and Linde cycle has been discussed. There was also discussed COP, i.e. Coefficient of Performance, indicating to what degree the heating equipment utilizes the heat from natural environment in relation to electric energy, supplying the heat pump. Working factors, as employed in the heat pumps, have been presented, as well.

Keywords: ground-source pump, air-source pump, Carnot cycle, Linde cycle, heat source, working liquid, bivalent system, ventilator

Streszczenie: W artykule przedstawiono informacje dotyczące gruntowej i powietrznej pompy ciepła zastosowanych do zasilania energią cieplną budynku jednorodzinnej wolnostojącego. Przedstawiona została zasada działania pomp ciepła w oparciu o obieg Carnota i Lindego, omówiono również współczynnik COP wskazujący, w jakim stopniu urządzenia grzewcze wykorzystują ciepło pozyskane ze środowiska naturalnego w stosunku do energii elektrycznej zasilającej pompę ciepła. Przedstawione zostały również czynniki robocze stosowane w pompach ciepła.

Słowa kluczowe: pompa gruntowa, powietrzna, obieg Carnota, obieg Lindego, źródło ciepła, płyn roboczy, układ biwalentny, wentylator

Introduction

The heat pump is a device which collects a heat from a lower low-temperature source and transmits it upwards to the upper source with a higher temperature. The direction of the heat flow is always reverse to a natural one and requires the appropriate energy supply. We can distinguish compressor heat pumps and the absorption and adsorption heat pumps [1]. The most popular solution includes the heat pumps, equipped with the electric energy-driven compressors.

In the case of the absorptive and adsorptive heat pumps, the thermal energy necessary for working of the mentioned pumps may be produced in the process of natural gas combustion which is supplied in a liquid or gaseous form.

The lower heat source should be characterized by a sufficiently high and stable temperature; it is important as during the heat intake, its temperature should not be too much lowered; therefore, the source heat energy should be successively supplemented [2, 4]. The air is a popular lower heat source. The heat pump utilizing air as the lower heat source is the cheapest as investment but such solution becomes less effective when the air temperature drops below 5°C [3]. Under the climatic conditions, occurring in Poland, it is necessary to adapt the construction of the building, insulation, ventilation system and the method of

heating the building to variable effectiveness of the work of heat pumps.

The heat pumps, collecting thermal energy from the air, as being the only one source of the buildings' heating, may be adapted to heating of the buildings, corresponding to the standards of low- or zero-energetic buildings [7, 8, 9].

Surface and ground waters are the effective source of heat for the pumps; such solution should be, however, precisely analyzed as the situations may occur when after a dry weather period, the level of water will be low and/or water will freeze in winter time [10, 11, 12].

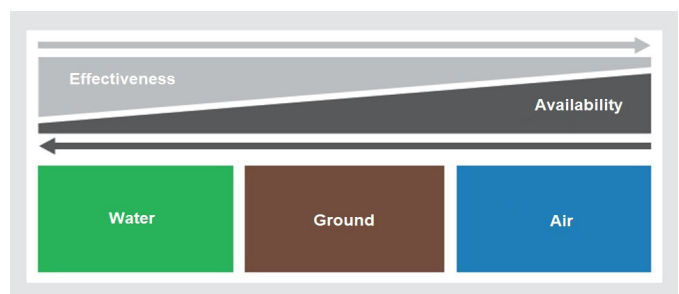


Fig. 1. Evaluation of primary sources

From Fig. 1 it is followed that the effectiveness of the heat pump has the highest value when water is the lower heat source, however, the availability of ground water is limited.

In the case when the ground is the heat source, we may assume that the effectiveness of the heat pump and the availability of the heat source are sustainable.

In the case when the air is the heat source, its availability is unlimited but the air temperature variations may result in lowering of the effectiveness of the pump work; it is especially unfavourable at a low air temperature and simultaneous high demand on heat for warming [12, 13, 14].

In the case when water or ground are the lower heat source, the circuit of lower source should be filled by factory-made glycol solution or with brine, possessing the certificate which confirms the suitability to work in such application [15].

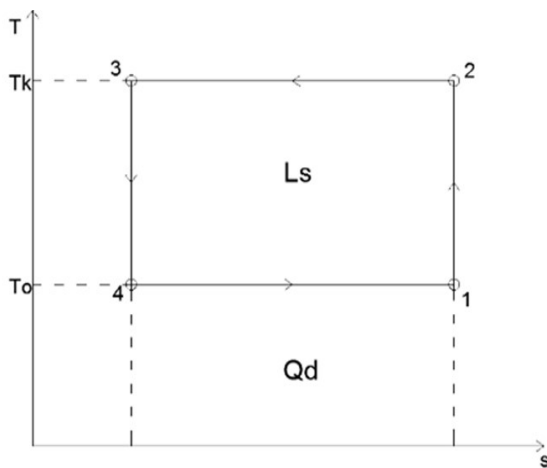


Fig. 2. Left-hand Carnot cycle

where:

T_0 – temperature of boiling

T_k – temperature of condensation

Q_d – the supplied heat in evaporator

L_s – work of compressor

$Q_g = Q_d + L_s$ – dissipated heat in condenser

The circuit which defines the state and thermodynamic transformation of refrigerant, circulating in the heat pump is called the Linde cycle [9].

The principle of functioning of heat pumps

The heat pump transmits the thermal energy from the lower source with a low temperature (e.g. water, ground or air) to the source, or upper source with a higher temperature (e.g. heating installation).

The set of transformations, after which the status of working liquid – after the passage of the successive conversions – comes back to the initial point, is an ideal circuit, the so-called Carnot cycle in which all transformations are reversible. In the case of heat pump, the Carnot cycle is a course of changes, illustrated in coordinates T-s, running in the counter-clockwise direction. The mentioned cycle is a left-hand Carnot cycle [10].

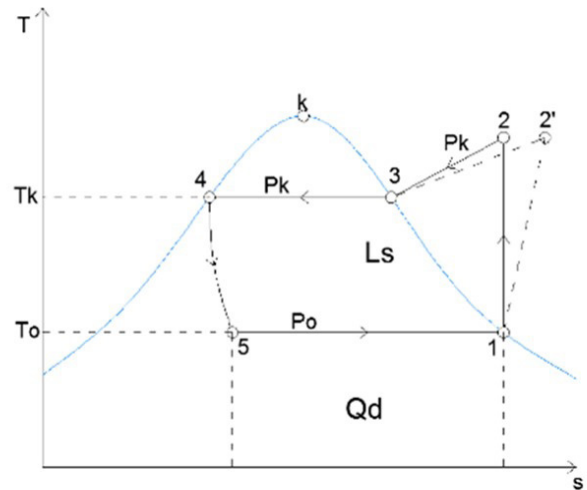


Fig. 3. Linde cycle

where:

1-2 – isentropic compression of vapour

2-3 – cooling of overheated vapour

3-4 – condensed vapour

4-5 – isentropic throttling

5-1 – boiling at the constant pressure of evaporation P_o and constant temperature T_0 .

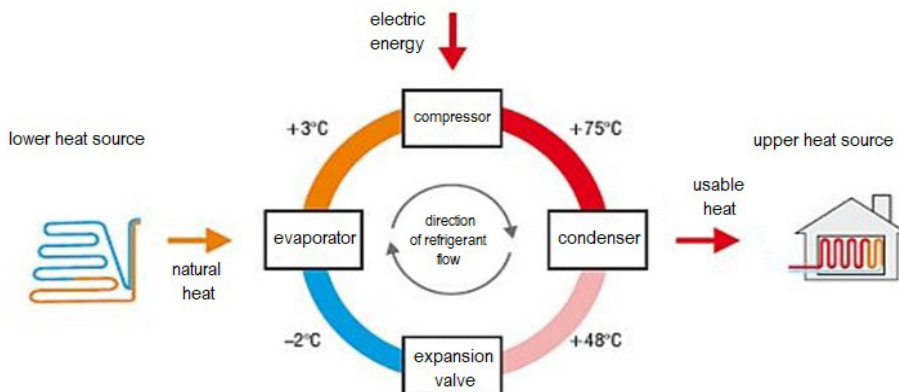


Fig. 4. Scheme of heat pump work

The blue line illustrates the saturated internal curve inside which the area of wet vapour is found.

In the circulation of compressor heat pump, there are 4 basic elements, through which the refrigerant flows successively: evaporator, compressor, condenser and expansion valve (throttling element) [10].

In the heat pumps for which water or ground is the lower heat source, the plate heat exchangers are employed; their construction ensures high efficiency of heat exchange, especially in the case of installation distributing the refrigeration factor in the exchanger. The uniform distribution of refrigerant on the whole surface of heat exchange ensures optimum utilization of the evaporator's surface [10, 11, 12].

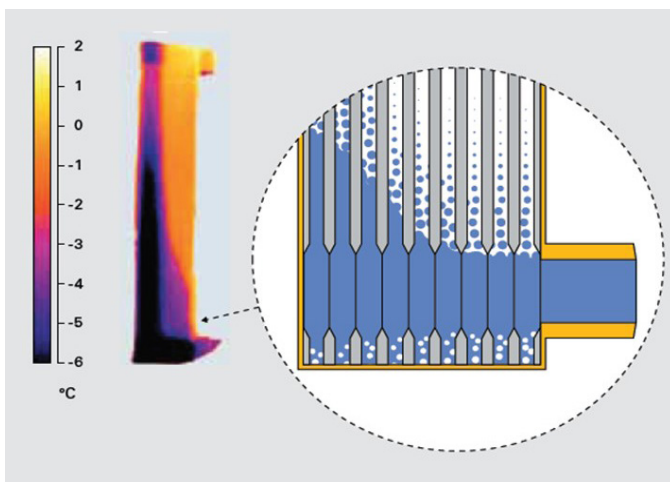


Fig. 5. Heat exchanger without distributing installation [6]

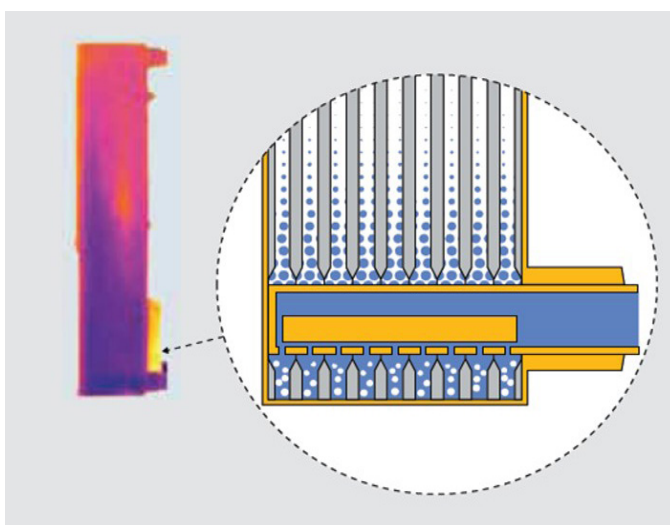


Fig. 6. Heat exchanger with the distributing installation [6]

The above thermographic illustration show how the refrigeration liquid is distributed in evaporator. The refrigerant without support of distribution may fill the space of evaporator unevenly; then the surface of heat exchange is ineffectively utilized. In the case of distribution of the mentioned factor, the uniform penetration of the evaporator is possible.

The heat pump for which the air is the lower heat source is furnished with lamellar heat exchangers. They are characterized by a high surface on the side of the air (primary side) because the thermal capacity of the air is smaller than the heat capacity of the mixtures of glycols or brines, used in the case when ground or water is the lower source of heat [11, 8, 5, 6].

The compressors increase the pressure and temperature of the factor, flowing out from the evaporator. The electric motor-driven compressors are most frequently employed; they are most convenient under the domestic conditions. In the modern heat pumps, there are used rotary and spiral compressors; vane compressors and piston compressors are older devices. The work of vane compressor is calmer as compared to piston compressor because its working part is not moving by reciprocating movement but by circulating and steady, uniform movement; it is accompanied by smaller vibrations. It is smaller in size and has smaller number of elements which are responsible for gas compression. Such features make it reliable and very stable [7, 8]. Construction of compressors has been constantly improved, aiming at betterment of their durability and energetic effectiveness.

During the condensation process, plate heat exchangers are employed at first; they are characterized by a high value of the stream of heat exchange; the other constructions of heat exchangers are employed as late as in the range of heat power above 100 kW.

The task of the expansion valve of heat pump is to lower the pressure of liquid refrigerant which after dissipation of heat to heating system in condenser remains still under a high pressure, until the pressure at which its evaporation takes place; it enables the intake of heat by refrigerant in lower heat source. The expansion valve regulates the flow of refrigerant so as the quantity of in-flowing refrigerant may completely evaporate in the evaporator and the overheated vapour passes to compressor [16, 17, 18]. To maintain the stable values of the temperature and pressure of the refrigerant before entrance to the compressor, it is purposeful to install the expansion valve, driven by thermostatic or electronic sensor [1, 2, 3, 4].

It is advantageous to employ the so-called economizer in the heat pump. The mentioned device consists of heat exchanger and additional expansion valve. The stream of working factor in a liquid form after leaving the condenser is divided into two parts: a lower part of the stream (10-20%) is directed to additional expansion valve and the exchanger of the economizer where it is heated up by the remaining part of the stream with a higher temperature which flows through the exchanger; it is injected to the compressor as the overheated vapour. The greater part of the factor's stream, after cooling down in the exchanger of the economizer, is directed to the main expansion valve and then, to evaporator [8].

The increase in temperature of the vapour in the exchanger of the economizer is higher than lowering of temperature of the factor in a liquid form. The application of the economizer protects the compressor from a flow of liquid factor and decreases the demand on driving power (intake of electric energy) of the

compressor, improves the effectiveness of the process and durability of the compressor [4, 5].

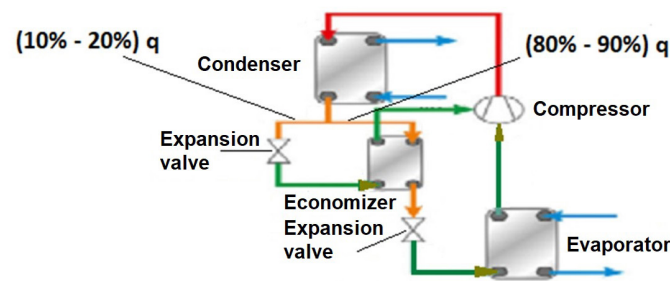


Fig. 7. Scheme of the heat pump with economizer [8]

Working liquid in the heat pumps

Factors R410A and R407C together with polyester oil for greasing of the compressor are most frequently used as refrigerators in the heat pumps. R-410A is the azeotropic mixture of difluoromethane (R-32) and pentafluoromethane (R-125). R-407C is the zeotropic mixture of difluoromethane (R-32), pentafluoromethane (R-125) and 1,1,1,2-tetrafluoroethane (R-134a). Both mentioned above factors are colourless and have an ethereal fragrance.

Factor R410A is employed in the heat pumps with inverter compressor (with a variable efficiency); it facilitates work of the compressor in a high spectrum of its performance and the working temperature of R410A is higher than that one of R407C [8, 9].

Effectiveness of COP coefficient

The effectiveness of the heat pump is measured by the coefficient of performance (COP) [2, 3]. COP is a ratio of value of thermal energy, generated in the heat pump which is used for utility purposes and value of the energy necessary for the supply of motor of the heat pump compressor.

$$\text{Formula: } \text{COP} = P_g / N_{el}$$

where:

P_g – heating power of the heat pump {kW},

N_{el} – power necessary for the drive of the compressor's motor, consumed from the electric network [kW].

The coefficient of refrigeration performance (*eng.* **EER**, energy efficiency rating) is a ratio of refrigeration power, obtained in the refrigerating equipment and power, consumed by the mentioned device (power of compressor); it is employed for evaluation of the efficiency of the heat pump and of refrigeration, [2].

The relationship between COP and EER of the compressor-based heat pump is simple: $\text{COP} = 1 + \text{EER}$. If we speak about ideal heat pump where the losses of energy do not occur, then we receive the formula of the efficiency coefficient as follows:

$$\text{COP}_{\max} = T_s / T_s - T_p$$

where:

T_s – is a temperature of liquid in condenser [K],

T_p – is a temperature of liquid in evaporator [K].

From the above formula it is followed that the coefficient of performance is the highest, the smallest is a difference of temperature between the evaporator and condenser of the pump.

In the case of heat pumps, the lower is the temperature of the lower source, from which the evaporator consumes the heat, the lower the performance of the system is.

Value of COP coefficient is significantly affected by energy losses which may result from friction between the elements of the compressor, friction of working liquid flowing in the heat pump and deficiencies of thermodynamic processes, occurring in the circulation of the pump; if we consider the mentioned above losses, we may assume that the real value of Cop is by a half lower than the theoretical value [4, 5].

The efficiency of the heat pump is one of the most important criteria of the choice of specified equipment, determining the costs of its operation. The comparison of COP values is reliable when the mentioned coefficient was determined (calculated) under the same conditions for each of the equipment elements [6, 8]

Air-source heat pump

The installation of the air-source heat pump is relatively simple and it belongs to the advantages of the discussed equipment. The cheaper devices with a simple construction are most popular; they are not adapted to work at a low air temperature and in practice, they may be operated at the air temperature in the limits of -7o to 5oC.

There are also manufactured heat pumps which are adapted to the work at the air temperature lower than -10oC, but they are more expensive devices.

The air-source pumps which do not work effectively at sub-zero air temperatures should not be the only one equipment for heating of the house; on the other hand, they may be used in bivalent system for the support of the work of boiler during the heating season (in spring-autumn period); they may be also employed in preparation of domestic hot water at the period when the demand on energy for heating is small [8, 9, 10]. In such case, we may utilize cheaper devices, with lower power compressors and smaller heat exchangers [6].

The heat pumps with the traditional compressors, operating on the principle "switch on/switch out" consume more electric energy with the jumping (discrete) consumption of energy during start of compressor what results in decrease of the pump's efficiency.

In most of the working conditions, the discussed above pumps produce the excess of heat what often forces the application of additional buffer tanks which take over the heat excess and then, give it back gradually to heating installation. It results from the necessity of maintaining the minimum time of the compressor's work and limiting to minimum the frequency of its start-ups [2, 2].

More advantageous solution includes the application of inverter compressors which are not switched out but change smoothly the number of their revolutions and adapt the compressor's performance to its actual demand on heat energy. It is also possible to use two compressors in one heat pump (or two-rotor compressors) what enables better adaptation of heating power to varying demand on the heat.

The application of economizer in the heat pump system facilitates also the flexible adaptation of the heat pump heating power to the demand on the heat in a building [4, 5].

When the pump operates in monovalent system, the heat power of the pump should be chosen in accordance with the planned thermal charge which should be calculated in conformity with the requirements of Standard PN-EN 1283. In the case of bivalent system, that is, work of the air pump, supported by electric heaters, the sum of the power of two operating devices should always correspond to the planned thermal charge. The power of the pump is dependent on the bivalent point, i.e. air temperature at which the second heating device, supporting the pump, is started up [12, 13, 14].

$$P_{pc}/P_{ma} = t_w - t_o/t_w - t_z$$

where:

P_{pc} – is the heat power of the heat pump,

P_{max} – is the power of thermal charge,

T_w – is the temperature of the heated accommodation,

T_b – is the temperature of bivalent point

T_z – is the external temperature

The heat pumps (air, water) are produced in the following variants:

- for assembling at home – such solution is not recommended due to the fact that, the air must be supplied and extracted additionally,
- for assembling outside the house – external devices of Split type; it is easier to install them and recommend at the situation when the site near the house is available, Generally, there is no problem with such possibility. Many models of Split type have the outer unit, which is suitable for fixing it to the house façade; it is also possible to place it at a certain distance from windows. To fix the pump, the even hardened surface at a small distance from the house is necessary [14, 15].

Ground-source heat pump

The heat contained in the ground is received using heat exchangers, most frequently with pipe construction. We may distinguish vertical and horizontal types.

Vertical ground-source heat exchanges are classified into:

- single – U-pipe,

- double – U-pipe
- coaxial

Horizontal ground-source heat exchangers are linear and spiral.

In Polish climate conditions, the mean air temperature during a year near the ground is equal to 7-9oC whereas the mean temperature of the earth surface has a value approximate to the annual mean air temperature what results from the effect of the following factors: heating of the ground by solar radiation, radiation of the heat from the ground and effect of geothermal heat [2, 3, 4].

The temperature in the ground is changed dependently on the season of the year e.g. the range of the temperature changes in the ground (t_{gw}) at the depth $h_{gr} = 1.5$ m is found in the limits of 6 – 13°C [11, 12].

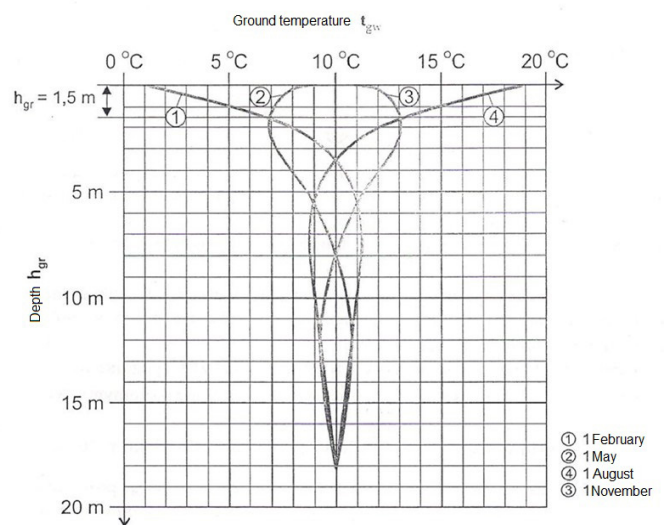


Fig. 8. Run of changes in temperature of the ground during a year, depending on the season of the year and the depth of the ground

In order to calculate the size of vertical ground heat exchanger, we have only to know the refrigeration power of the heat pump. If we do not have such information, it is sufficient to know that it corresponds to the heat power, decreased by the power of compressor. On the other hand, if we do not have information about the power of compressor, but we possess the knowledge on the COP coefficient, the refrigeration power will be calculated according to the following formula:

$$Q_{cht} = COP - 1/COP * Q_{grz}$$

Before assembling the vertical heat exchanger, we should examine the ground on which the mentioned heat exchanger will be placed because we must determine the thickness and the coefficient of thermal conductivity λ of the particular ground layers, and calculate the mean value of the coefficient of thermal conductivity λ for the area where the pipe of the exchanger is to be placed [1, 2]. If we know the mean coefficient of the ground conductivity, we may determine the unit heating capacity g_v ,

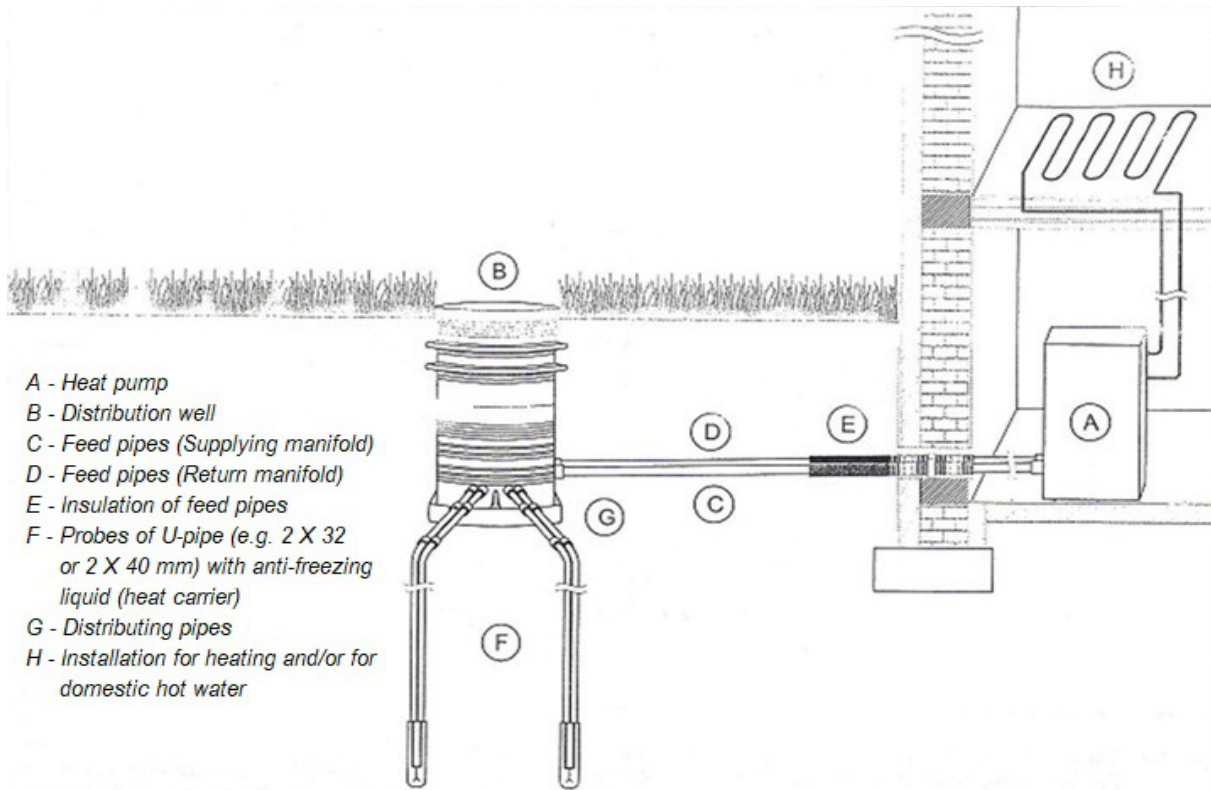


Fig. 9. Scheme of installation with vertical ground heat exchanger [8]

[W/m], and calculate the depth of placing the exchanger from the following formula:

$$L_o = Q_{cht} / g_v \text{ [m].}$$

In the case of exchanger, consisting of the pipes arranged horizontally, the depth of 0.2 – 0.5m below the limit of freezing is considered as optimum. If water course is found at the small depth, the favourable solution includes placing the pipes just there because the heat pump will reach the higher COP coef-

ficient in such situation. The pipes of horizontal heat exchanger should be arranged in the earlier prepared excavation; they should be laid in a form of coil in the whole surface of the exchanger, with the preservation of a specified space between the neighbouring segments [6, 7, 8]. The spaces should not be lower than 0.4 m or higher than 1.2 m. They should be adapted to the type of the ground as it determines its regeneration ability. The heat capacity of the exchanger results not only from the length of the pipe but also from the size of the ground area on which the pipes are arranged [1].

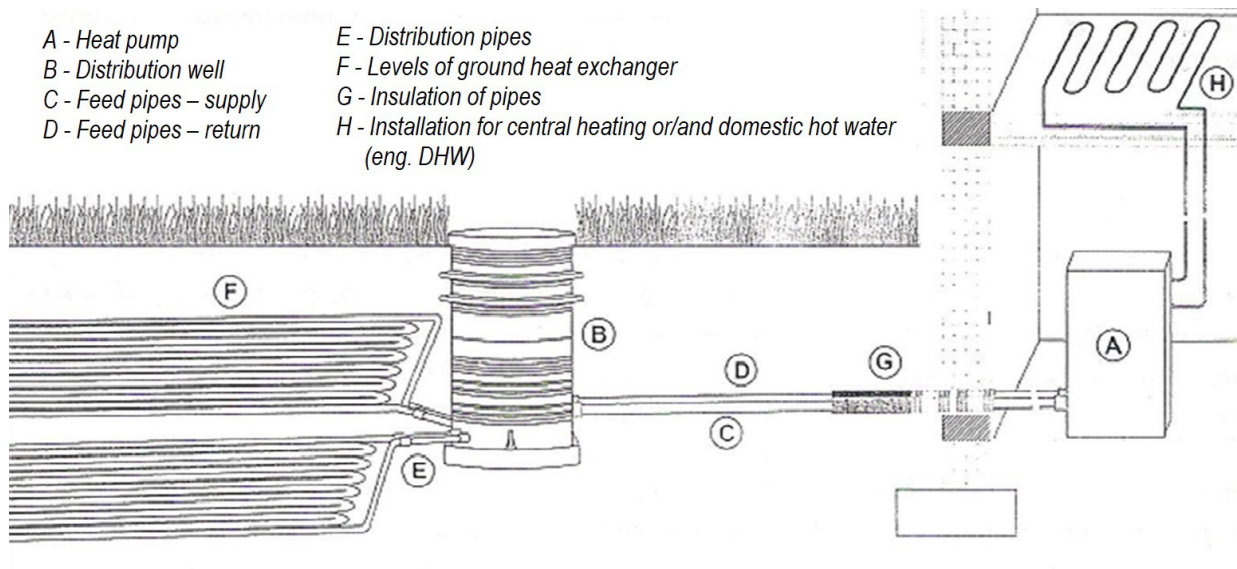


Fig. 10. Installation with the horizontal ground heat exchanger [4]

Characteristics of building, supplied with thermal energy, generated by the heat pumps

The air-source and ground-source heat pumps have been installed in a single-family building with the following characteristics: free-standing, single-family building, without cellar, with the habitable attic, with the total surface amounting to 189 m² and cubature of 625 m³ and with the gable roof. The thickness of the outer walls was 40 cm together with the insulation. The discussed building is situated in the first climatic zone for which the minimum external temperature is equal to -16°C. The number of inhabitants of the mentioned building does not exceed 5 persons.



Fig. 11. A single-family, free-standing building with a gable roof [17]

Air-source heat pump as the heat source in the single-family building

There is presented hereby the air-water heat pump with the external and internal unit of VAILLANT type VWL plus 102/3 with capacity of 10kW and COP coefficient = 2.5. It cooperates – in bi-valent system – with two-function gas boiler with a closed combustion chamber of VUW 202/3-5 type, with capacity of 20kW [7, 8]. The air-source pump and the boiler are found in a storage room. The tank made of stainless steel with capacity of 175 dm³ is used for storage of the domestic hot water [6, 7].

In the storage room, there was placed also a tank by Vaillant company type allSTOR VPS/3, of 300 dm³ capacity for heating of water [4,5], which functions as a buffer, collecting thermal energy and allowing to limit frequency of the heat pump switching on.

The boiler starts up, supporting the work of the heat pump when the outer temperature is lowered down to -°C. When the outer temperature falls down below -12°C, the pump shuts down and the boiler remains the only one source of heat.

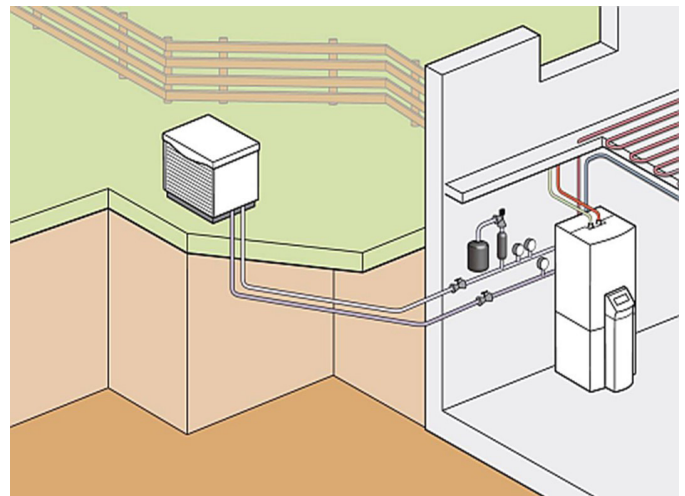


Fig. 12. Air-source heat pump by VAILLANT [12]

Ground-source heat pump as the heat source in the single-family building

The heat pump based upon brine and water, as manufactured by VAILLANT of type geo THERM VWS 171/3, with capacity of 17.4 kW and with tank heater for domestic hot water of type VIH R 150 by Vaillant company is operated in mono-valent system [11,12]. The pump is found in the storage room. The lower source consists of 4 ground probes, being 97 m long each of them; they are made of HDPE pipes with diameter of 32 x 2.9 mm. The diameter of feed pipes is 63 x 5.8 mm (the diameters of the pipes were chosen according to the heating capacity when propylene glycol was the liquid in the circuit of the lower source (33%)). The ground installation of vertical heat exchanger was performed in conformity with the guidelines of designing and acceptance of the installation together with the heat pumps [3, 4].



Fig. 12. 13. Ground-source heat pump manufactured by VAILLANT [12]

Comparison of air-source and ground-source pumps which feed the installation for central heating and domestic hot water in single-family, free-standing building

From the viewpoint of the operating costs, application of the installation with the ground pump is more profitable solution. It is determined by the lower source from which the heat is taken, i.e. ground. The temperature of the ground is more stable than the temperature of the air. Therefore, the ground pump works at a small range of the changes in the temperature of liquid in evaporator and its sub-elements may be cheaper as compared to the parts of air pumps [2].

The advantages of the ground pump include a high COP coefficient amounting to 4.9 and the possibility of work in monovalent system. In the case of correctly designed and performed ground heat exchanger, the ground pump may be independent heating device, covering the demand on the heat energy in the building.

The COP coefficient of the air-source heat pump, as being equal to 2.5, is by a half lower than in the case of the ground-source heat pump. Besides it, the thermal capacity of the air pump is decreased together with the decline of the air temperature, that is, in the period when the demand on the thermal energy for heating of the house is increasing [1].

The defect of the air-source heat pump consists in the emission of the noise, which is caused by the work of outer unit (ventilator of evaporator). The level of acoustic pressure in the case of location of the external unit at the distance of 18 m from the building is equal to 34.9 dB, i.e. it is found at the limit of the permitted standard of the noise, penetrating the residential building.

The advantages of the application of the air-source heat pump include the costs of performing the whole heating system, including the air pump, operated in the bivalent system, with the double-function gas boiler. In this case, the costs are significantly lower as compared to the costs related to the ground-source heat pump.

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