Perfection of an Energy-Economic and Environmental Parameters of the Ground Source Heat Pump Systems with Preventing Freezing of the Soil around Ground Pipes

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Abstract. This article is devoted to the methods for perfection of energy, economic factors, environmental factors and work modes of the ground source heat pump systems with the account of climate conditions. The purpose of the work is to predict and prevent freezing of the soil during long term of exploitation of the low-power and high-power ground source heat pump systems for justifying rational conditions of implementation GSHP in Ukraine and South-East Regions of Europe. This goal is achieved by solving the following problems: determining the energy-economic and environmental factors based on considering the work modes of the ground source heat pumps; evaluation of the operating efficiency of ground source heat pump systems based on minimizing fuel consumption and greenhouse gas emissions; perfection of solutions enable implementation of ground source heat pumps friendly to the environment and justifying rational conditions of implementation the ground source heat pumps for residential sector. The important results of the work are the obtained and analyzed data on the influence of energy and economic factors both environmental criteria on the work modes and scheme-constructive solutions of ground source heat pumps. Modeling of heat exchange processes in the soil around the soil tube shows that in order to avoid freezing of the soil, the minimum permissible specific number of vertical tubes should be at least 0.12–0.15 pieces/m^2 of heated area. The significance of the results consists in the possibility of using the results of numerical simulation for preventing freezing of the soil around ground pipes of the ground source heat pump systems.

Keywords: efficiency; ground source heat pump; preventing freezing; ground pipes, temperature fluctuations.
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Îmbunătățirea performanței energetice, economice și indicatorilor de mediu a sistemelor de pompe de căldură geotermale cu prevenirea înghețului solului în jurul țevilor din sol

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Rezumat. Acest articol este dedicat metodelor de perfecționare a energiei, factorilor economici, factorilor de mediu și modurilor de lucru ale sistemelor de pompe de căldură la sol, ținând cont de condițiile climatice. Scopul lucrării este de a anticipa și de a preveni înghețarea solului pe termen lung de exploatare a sistemelor de pompe de căldură terestre de putere mică și mare pentru a justifica condițiile raționale de implementare a GSHP în Ucraina și Regiunile de Sud-Est ale Europei. Acest scop se realizează prin rezolvarea următoarelor probleme: determinarea factorilor energetico-economici și de mediu pe baza modurilor de lucru ale pompelor de căldură terestre; evaluarea eficienței de funcționare a sistemelor de pompe de căldură pe bază de minimizarea consumului de combustibil și a emisiilor de gaze cu efect de seră; perfecționarea soluțiilor permite implementarea pompelor de căldură terestre prietenoase cu mediul și justificând condiții raționale de implementare a pompelor de căldură terestre pentru sectorul rezidențial. Rezultatele importante ale lucrării sunt datele obținute și analizate cu privire la influența factorilor energetici și economici atât a criteriilor de mediu asupra modurilor de lucru, cât și a soluțiilor scheme-constructive ale pompelor de căldură terestre. Modelarea proceselor de schimb de căldură în solul din jurul tubului de sol arată că, pentru a evita înghețarea solului, numărul specific minim admisibil de tuburi verticale trebuie să fie de cel puțin 0,12–0,15 bucăți/m2 de suprafață încălzită. Semnificația rezultatelor constă în posibilitatea utilizării rezultatelor simulării numerice pentru prevenirea înghețului solului în jurul țevilor de sol ale sistemelor de pompe de căldură la sol.

Cuvinte-cheie: eficiență; pompă de căldură terestră; prevenirea înghețului; țevi de pământ, fluctuații de temperatură.

Совершенствование энерго-экономических и экологических показателей геотермальных теплонасосных систем с предотвращениеv промерзания грунта вокруг грунтовых трубок

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Аннотация. Статья посвящена методам совершенствования энергетических, экономических показателей, факторов окружающей среды и режимов работы грунтовых теплонасосных систем с учетом климатических условий. Целью работы является прогнозирование и предотвращение промерзания грунта в течение длительного срока эксплуатации грунтовых теплонасосных систем малой и большой мощности для обоснования рациональных условий внедрения. Поставленная цель достигается путем решения следующих задач: определение энерго-экономических и экологических факторов с учетом режимов грунтовых теплонасосных систем; оценка эффективности их работы за счет минимизации расхода топлива и выбросов парниковых газов; за счет совершенствования решений, позволяющих внедрить экологически чистые геотермальные тепловые насосы и обосновать рациональные условия их внедрения для жилого сектора. Это позволяет снизить потребление углеводородного топлива в структуре регионального теплового баланса и обеспечить помимо экономического значительный энергосберегающий и экологический эффект. Важными результатами работы являются полученные и проанализированные данные о влиянии энергетических и экономических факторов, а также экологических критериев на режимы работы и схемно-конструктивные решения теплонасосных систем с использованием энергии грунта. Моделирование процессов теплообмена в грунте вокруг грунтовой трубки показывает, что во избежание промерзания грунта минимально допустимое удельное количество вертикальных трубок должно быть не менее 0.12–0.15 штук/м^2 отапливаемой площади, что позволяет избежать сезонного снижения температуры грунта вокруг грунтовых теплообменных трубок. Анализ распределения температур в грунте вокруг грунтовой трубки показывает, что после 48-часовой остановки теплового насоса система выходит из негативного состояния тепловой релаксации грунта за счет естественной способности грунта накапливать энергию. Значимость результатов заключается в возможности использования результатов численного моделирования для предотвращения промерзания грунта вокруг грунтовых труб теплонасосных систем. Результаты моделирования способствуют внедрению инновационных технологий и могут способствовать экологически безопасному внедрению систем геотермальных тепловых насосов.

Ключевые слова: эффективность; грунтовый тепловой насос; предотвращение замерзания; грунтовые трубы, колебания температуры.

INTRODUCTION

Over half the country's electricity in the Ukraine is produced with nuclear power. The Ukraine produces all fossil fuels (in 2018: 14.4 million tons of oil equivalent [Mtoe] of coal, 16.5 Mtoe of natural gas and 2.3 Mtoe of crude oil), but in quantities insufficient to meet total energy demand. The Ukraine’s energy mix is relatively diversified, with no fuel representing more than 30% of the energy mix. In 2018, the share of coal (the country’s primary fuel) dropped to 30%, followed closely by natural gas (28%) and nuclear (24%) [1]. The Ukraine depends on imports for around 83% of its oil consumption, 33% of its natural gas and 50% of its coal. In 2018 the Ukraine imported 8.5 Mtoe of natural gas, 13.8 Mtoe of coal and 10.4 Mtoe of oil products. Belarus is the Ukraine’s main supplier of refined products. Still, nearly 65% of the Ukraine’s total energy demand is covered by domestic production. This high self-sufficiency is explained by nuclear energy production, as Ukraine is the world’s seventh-highest producer (83 TWh in 2019). Over half the country’s electricity is produced with nuclear power. The Ukraine is the top energy consumer among EU countries. Its primary energy supply was 93 Mtoe in 2018, corresponding to around 90% of Poland’s consumption [1 – 2]. Today, the Ukraine heavily depends on fossil fuels, which accounted for some 70% of its primary energy supply in 2020. The Russian invasion has resulted in the occupation (the Zaporizhzhya nuclear power plant and about 44% of total thermal power capacities) and destruction of critical energy infrastructure triggering a sharp decline in total energy supply, while electricity demand had fallen by 40% by October 2022.

In view of their high untapped potential in the country, bioenergy, hydro, solar and wind generation could constitute the building blocks of the Ukraine’s future energy system, contributing up to nearly 80% of the total energy generation by 2050. Provided key strategies and investments are put in place, and complemented by nuclear, renewables could propel the Ukraine towards a carbon-neutral future. These are the main findings of the pathway scenarios developed by UNECE, based on it’s the UNECE Carbon Neutrality Toolkit, published ahead of the Ukraine Recovery Conference (London, 21-22 June) [2 – 3].

The Ukraine Energy scenario is substandard from the past few decades. The energy shortfall is around 4500 MW since the last five years [1 – 3] which is considered to be the hindrance in economic, scientific and technical growth.

District heating system capacities in Ukraine are excessive, and their technologies are inefficient and outdated; capital stock is in a critical state, with most assets close to or beyond the end of their design lifespans. Energy losses are considerable (hence much gas is wasted) and operating costs are high, largely due to inadequate maintenance [3 – 4].

Ukraine has enormous untapped energy efficiency potential: although the end-use data are still limited, current indications are that energy efficiency potential is greatest in industry (34% of the total), the residential sector (33%) and energy transformation at coal-fired power plants (22%) [3]. Consumption in the residential sectoris compared with the EU benchmark of 90 kWh/m^2 of floor area.

Because of climatic differences, the EU average cannot be used as a benchmark for residential efficiency in Ukraine. In fact consumption for heating, hot water and lighting per m^2 is higher even in energy-efficient countries with milder climates such as Denmark (142 kWh/m^2) and Germany (186 kWh/m^2).

Total final energy consumption in the agriculture, industry, construction, services and residential sectors, as well as energy transformation at fossil fuel decreased by 30.9 Mtoe (–36.4%) from 2012 to 2017.

However, only one-third of this decline resulted from the energy efficiency improvements, with the remaining two-thirds stemming from a dropin activity in 2014–2015 and structural changes within sectors (Figure 1) [4].

The greatest energy efficiency improvements over 2012-17 were recorded in the residential sector (+22.7%) and agriculture (+27.7%), while the energy efficiency index for industry rose by 13.2%.

No energy efficiency improvement was recorded for fossil fuels energy transformation; in fact, it even decreased by 1%. Overall, energy efficiency improved to 12.5% during 2012-2017.

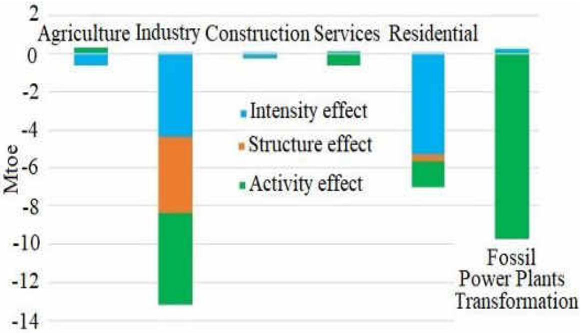


Fig. 1. Ukraine energy consumption decomposition.

Renewable energy accounted for 4.6% of TPES in 2018: 3.4% biofuels and waste, 1% hydro and 0.2% for other renewable power. The Ukraine experienced a renewable power deployment boom in 2018-19. The share of renewable power in the electricity generation mix increased by 3.6 times – from 1% in 2015 to 3.6% in 2019 [3].

Economic strategy of a sustainable development imposes certainly to promote efficiency and a rational energy use in buildings as the major energy consumer in Ukraine and countries of the European Union (EU). Buildings represent the biggest and most cost-effective potential for energy savings. Also, studies have shown that saving energy is the most cost-effective method to reduce greenhouse gas (GHS) emissions. The buildings sector is the largest user of energy and CO_2 emitter in the Ukraine and EU's. At present heat use is responsible for almost 80% of the energy demand in houses and utility buildings for space heating and hot water generation, whereas the energy demand for cooling is growing year after year. There are more than 150 million dwellings in Europe [5] and more than 11 million housing units in the Ukraine [6]. Around 30% are built before 1940, around 45% between 1950 and 1980 and only 25% after 1980. Retrofitting is a means of rectifying existing building deficiencies by improving the standard and the thermal insulation of buildings and/or the replacement of old space conditioning systems by energy-efficient and environmentally sound heating and cooling systems [7 – 8]. The European Parliament adopted the Renewable Energy Directive, establishing a common framework for the promotion of energy from renewable sources [9]. This directive opens up a major opportunity for further use of heat pumps for heating and cooling of new and existing buildings. Therefore, the energy used to drive heat pumps should be deducted from the total usable heat. Furthermore, the EU member states must stimulate the transformation of existing building undergoing renovation into nearly zero-energy buildings. In order to realize the ambitious goals for the reduction of fossil primary energy consumption and the related CO_2 emissions besides improved energy efficiency the use of renewable energy in the existing building stock have to be addressed in the near future [9–10].

At present, the problem of energy saving can be solved both by assimilation of the innovation technologies of generating, distribution, and consumption of energy [11]. The most efficient technology of the energy saving is the implementation of the heat pumps, due to their possibility to use a renewable energy sources (RES) for heating [12 – 14].

Following the above described problem: despite the need for application and numerous researches in the field of thermal energy, the wide implementation of the ground-source HP for regional conditions of the Ukraine and South-East Regions of Europe, is hindered by the insufficient efficiency of existing solutions enable to prevent freezing of the ground during long term of exploitation ground source heat pump (GSHP) systems which operate at the temperature of the outside air of t_0 = – 16…8 °C, typical for the South-Eastern Europe [10].

However, the works presented in literature, which describe the peculiarities of the use of the heating tools for the low-temperature water heating, ventilation and heat water supply, are insufficient [15—16]. The foreign researches [17—20], lack the methods, which would describe the alternative HPI and conditions of their practical application in the heat supplying systems with different heating units for the environmental conditions of the South-Eastern Europe. In [20, 21], the effect on the replacement rate by the scheme-construction solutions and operational modes of the alternative heat-supply system is not considered. Therefore, the issue of conditions of the efficient use of the heat pump technologies needs a systematic approach.

Our work differs from those foreign papers presented earlier in that this article analyzes the energy efficiency of the ground-source heat pump heating systems for energy saving technologies using models, results of numerical simulation of processes in GSHP and experimental studies for the South-Eastern Europe, which allows us to predict and prevent freezing of the soil around ground pipes and don't disturb vegetation.

This makes it possible to perform a rational choice of the conditions for the efficient operation of the heating system in winter period at the outside temperature of t_0 = –18…8°C typical for the South-Eastern Europe.

This reduces the consumption of the hydrocarbon fuel in the structure of the heat balance of the regions and ensures the substantial energy saving and ecological effects in addition to those economical.

The attention payed by the foreign works [22—25] is insufficient, concerning the justification of the choice of the scheme-construction solutions in the alternative system of the heat supply, taking into account the effect of the basic elements of the system and the modes of its operation on the GSHP replacing possibilities on the subsoil waters.

Heat pumps are efficient at transferring heat from a colder heat carrier to a hotter one through evaporation and condensation, using the heat of almost all environments: water, air, soil. Heat pump units have proven their efficiency due to the fact that they transfer 3…5 times more energy to the consumer than they spend on its transmission. In addition, heat pumps use environmentally friendly technologies with virtually no emissions of harmful substances into the environment [10].

The purpose of the work is to predict and prevent freezing of the soil during a long term of exploitation of the low-power and high-power ground source heat pump systems and justifying rational conditions of implementation of GSHP for the Ukraine and South-East Regions of Europe.

2. METHODS FOR DEFINITION THE OPPORTUNITY OF IMPLEMENTATION GROUND SOURCE HEAT PUMPS

Low-power (up to 100 kW) and high-power (up to 30 MW or more) heat pumps at the base of ground sources, subsoil waters etc. for heating using different heating modes of operation have become widespread in high-tech countries. The GSHP are compact, reliable, and environmentally friendly, operate at low outside temperatures in winter, and are also capable of air conditioning rooms in the warm season [10–11]. Low-power heat pumps can be combined in cascades to obtain higher capacities. The market of low-power heat pumps is rapidly developing around the world [10]. Their operating parameters are given in the Table 1 and in Figure 2.

Table 1. The operating parameters of low-power heat pumps iPump T 3-13 with digital system Navigator 2.0 [10]

Type of HP	Work point	Heat capacity, kW	COP	Electric power, kW
Ground-water iPump T2-8	B0/ W35	6,60	5,01	1,32
	B0/ W35	13,28	3,70	3,59
Water - water	W10/ W35	8,70	6,01	1,29
	W10/ W35	13,25	5,26	2,2

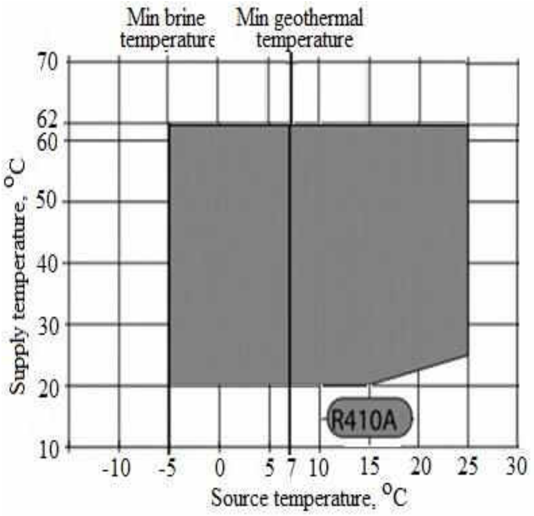


Fig. 2. Temperature range for heating the GSHP iPump T2-8.

Usage features of high-power heat pumps are studied insufficiently. Considering this fact, it is necessary to evaluate the prospects for using high-power heat pumps for rising efficiency of its implementation for heat supply systems.

Their advantages compared to low-power heat pumps are as follows:

– lower specific capital investments per 1 kW of thermal power;

– cheaper both in terms of the main equipment (heat pumps) and in terms of additional equipment and complexity / cost of installation;

–smaller footprint compared to a large number of low-power heat pumps;

– higher technical and economic indicators of some elements: efficiency of the compressor and the heat pump as a whole.

The production capacity of high-power heat pumps used in Ukraine is concentrated in Austria. In Ukraine, the largest vapor compression heat pumps soil-water or water-water Terra Max 280 – 275 kW and 362 kW, respectively [11]. Their operating parameters are given in the Table 2 and in Figure 3.

Table 2. The operating parameters of High-power GSHP TERRA SW 280 Max H with digital system Navigator 2.0 [11]

Type of HP	Work point	Heat capacity, kW	COP	Electric power, kW
Ground-water iPump T2-8	B0/ W35	275,59	4,61	59,78
	B5/ W35	310,04	5,09	60,93
Water - water	W10/ W35	362,13	5,79	62,54
	W10/ W35	323,82	5,28	61,33

The heat capacity of the cascade system is up to 1500 kW. Where B (brain) – heat is extracted from brine, W (water) – from water.

The numbers show the corresponding temperature. In our example, the values of COP are correct when at the beginning the temperature of the coolant is equal to 0°C and the coolant income to the system with the temperature of 35°C.

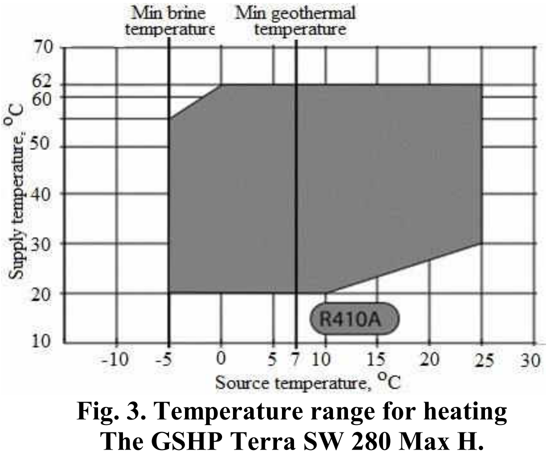


Fig. 3. Temperature range for heating The GSHP Terra SW 280 Max H.

The effectiveness of the use of heat pumps largely depends on the ratio of prices for electricity and heat energy [8]. Comparison of the cost of the energy component of heat produced using a compression heat pump unit with COP=3.0…4.5 and when burning gas in a traditional boiler house, shows that if the price of gas is over 200 Euro/1000 m^3, and electricity is over 0.024 Euro/kWh, there is no alternative for using the heat pumps (Figure 4).

Heat pumps enabling the use of ambient heat at a useful temperature level need electricity or other auxiliary energy to function. Therefore, the energy used to drive heat pumps should be deducted from the total usable heat. Geothermal and hydrothermal heat energy captured by heat pumps shall be taken into account for the purposes provided that the final energy output significantly exceeds the primary energy input.

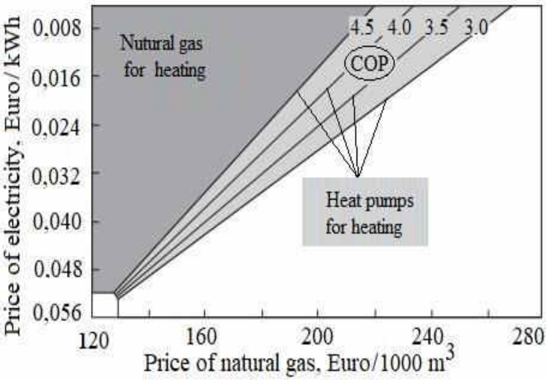


Fig. 4. Impact of energy prices on feasibility of using the heat pumps instead of gas boilers.

The amount of ambient energy captured by the heat pumps to be considered renewable energy E_{REN}, shall be calculated in accordance with the following formula [24]:

$$E_{REN} = E_U \left(1 - \frac{1}{SCOP}\right), \tag{1}$$

where: E_U is the estimated total usable thermal energy delivered by heat pumps; *SCOP* – the estimated average seasonal performance factor for these heat pumps.

Only heat pumps for which $SCOP > 1.15/\eta$ shall be taken into account, where for EU countries η=0.4 is the average ratio between total gross production of electricity and the primary energy consumption for electricity production. Meaning that a minimum value of seasonal performance factor should be $SCOP > 2.875$. Heat pump enables the use of ecological heat (solar energy accumulated in the soil, water and air) for an economic and ecological heating and cooling. For practical use of these energy sources we have to respect the following criteria: sufficient availability, higher accumulation capacity, higher temperature, sufficient regeneration, economical capture, reduced waiting time. In the development of modern constructions with improved thermal insulation and reduced heat demand use heat pumps are a good alternative.

where: E_U is the estimated total usable thermal energy delivered by heat pumps; *SCOP* – the estimated average seasonal performance factor for these heat pumps.

The performances of the heat pump and the system building heating installation is determined based on economical and energy indicators of these systems. The opportunity to implement a heat pump in a heating system results on both energy criteria and the economic [25].

Usually the heat pump (HP) realizes a fuel economy ΔC (operating expenses) comparatively of the classical system with thermal station (*TS*), which is dependent on the heat pump type. On the other hand, the heat pumps involve an additional investment I_{HP} from the classical system I_{TS}, which produces the same amount of heat. Thus, it can determine the recovery time t_R, in years, to increase investment, $\Delta I = I_{HP} - I_{TS}$, taking into account the operation economic indicator realized through low fuel consumption $\Delta C = C_{TS} - C_{HP}$:

$$\tau_R = \frac{\Delta I}{\Delta C} \le \tau_{Rn} \quad , \tag{2}$$

where: τ_{Rn} is normal recovery time.

It is estimated that for t_{Rn} the number of 8−10 years is acceptable, but this limit varies depending on the country's energy policy and environmental requirements. Next economic indicator is a total updated cost:

$$t_{uc} = I_0 + \sum_{j=1}^{\tau} \frac{C}{(1+\beta_0)^j} \quad , \tag{3}$$

where: I_0 is the initial investment cost, in the operation beginning date of the system; C – annual operating cost of the system; β_0 – the average rate of the inflation; τ – number of years for which the update (20 years) is made.

The equality (4) could be rather easily demonstrated:

$$\sum_{j=1}^{\tau}\frac{1}{(1+\beta_0)^j} = \frac{(1+\beta_0)^{\tau}-1}{\beta(1+\beta_0)^{\tau}}, \qquad (4)$$

and the update rate is defined:

$$r_a = \frac{(1+\beta_0)^{\tau}-1}{\beta(1+\beta_0)^{\tau}}. \qquad (5)$$

Taking into account (4) and (5) equation (3) gets the following form:

$$t_{uc} = I_0 + r_a \cdot \mathrm{C}. \qquad (6)$$

The operation of a heat pump is characterized by such an energetical indicator as the coefficient of performance ($COP = \varepsilon_{HP}$) or thermal efficiency (ε_{HP}), defined as the ratio between useful effect produced (useful thermal energy E_U) and energy consumed to obtain it (drive energy E_D): Energetical indicators.

$$COP = \varepsilon_{HP} = \sum_{j=1}^{\tau}\frac{C}{(1+\beta_0)^j}. \qquad (7)$$

If both usable energy and consumed energy are summed during a season (year) is obtained by equation (7) annual seasonal coefficient of performance ($SCOP$), which is often expressed as SPF.

In the heating operate mode the COP is defined by equation:

$$COP = \frac{Q_{HP}}{P_e}, \qquad (8)$$

where: Q_{HP} is the thermal power of heat pump, W; P_e is the drive power of heat pump, W.

The sizing factor (F_S) of the heat pump is defined as a ratio of the heat pump capacity Q_{HP} to the maximum heating demand $Q_{\max}$:

$$F_S = \alpha_{HP} = \frac{Q_{HP}}{Q_{max}}, \qquad (9)$$

where: Q_{HP} is the thermal power (capacity) of heat pump, W; P_e – the drive power of heat pump, W.

The sizing factor can be optimized in terms of energy and economic, depending on the source temperature and the used adjustment schedule. From the energy balance of the heat pump:

$$E_U = E_S + E_D, \qquad (10)$$

where: E_U is the useful thermal energy; E_D is the drive energy.

Taking into account the energy losses Π_J that are accompanying both the accumulation and release heat from the real processes, the real efficiency $\varepsilon_{HP,r}$ and its expression is:

$$\varepsilon_{HP} = [t_c/(t_c - t_o)]\cdot(1-\sum \Pi_j), \qquad (11)$$

where, t_C, t_0 are the temperatures of condensation and vaporization of refrigerants, K.

Figure 5 represents the real efficiency variation of the heat pumps according to the source temperature t_S and temperature t_U at the consumer.

The real efficiency of the heat pump with the compressor with electric drive is [18]:

$$COP = \frac{t_U + t_C}{t_U + t_C - (t_S - t_0)}\eta_r\eta_i\eta_m\eta_{em} + \dots + \eta_m\eta_{em}(1-\ \eta_i) \qquad (12)$$

where: t_U, t_S are the absolute temperature of hot and cold source, respectively;

t_C, t_0 are the temperature differences between the condensation temperature and hot source temperature, respectively, between the cold source temperature and vaporization temperature; η_r – efficiency of the real cycle toward a reference Carnot cycle;

η_i, η_m – internal and mechanical efficiency of the compressor; η_{em} – mechanical efficiency of the electromotor; Q_{HP} – thermal power of the heat pump.

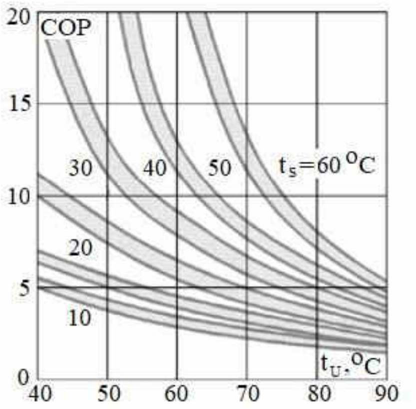


Fig. 5. Real efficiency variation of heat pump.

Specific consumption of electricity is the energy indicator for heat pumps W_{HP} , kW/GJ:

$$w_{HP} = \frac{1000}{3.6\varepsilon_{HP,r}} \qquad (13)$$

The electricity consumption for heat pumps depending on the heat source temperature t_S and consumer temperature t_U is shown in Figure 6.

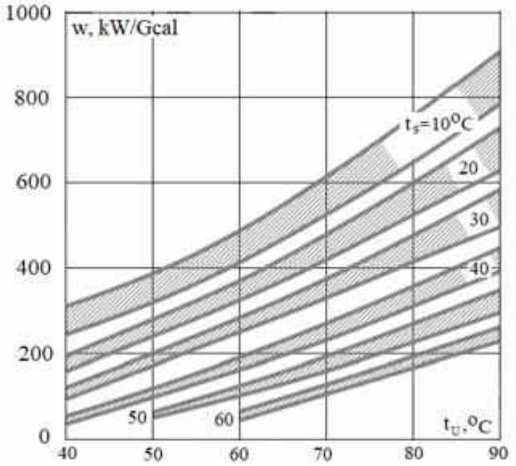


Fig. 6. Electricity consumption for the heat production.

The energy indicators of heat pumps are determined as average values, taking into account the annual heat consumption variation.

The variation of the average annual electric energy consumption, depending on F_S and different graphics adjustments is represented in Figure 7.

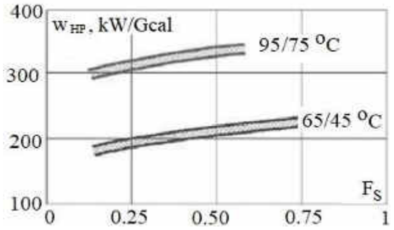


Fig. 7. Variation of the average annual electricity consumption.

The annual fuel economy variation ΔB, obtained by using heat pump, expressed as percentage of total annual fuel consumption in a referential classic system is presented in Figure 8.

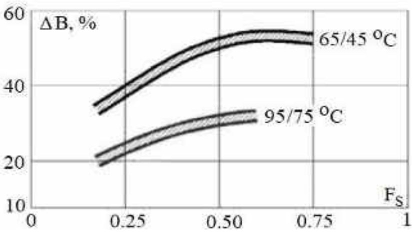


Fig. 8. Variation of annual fuel economy.

In order to properly compare the performances of various heat pumps types, have to uniform the action energy.

In this sense, is reported the useful heat delivered annually $Q_{u,\ year}$ at annual equivalent fuel consumption $B_{f,\ year}$ necessary for driving power production, achieving the degree of fuel use φ_{year}, in kW/kg [25]:

$$\varphi_{year} = \frac{B_{u,year}}{B_{f,year}}, \qquad (14)$$

The fuel economy depends by heat pump type, according to Figure 9.

Reduction of Greenhouse gases (GHG) emissions, key to limiting global warming is associated with the replacement of classical solutions for heating using heat pumps, especially GSHP. But items related to electricity production must also be taken into account, mainly used to drive them.

Nowadays it is not recommended to replace a heating gas boiler with electrically operated heat pump if electricity is produced using coal or based on old technologies, because resulting carbon dioxide emissions may increase with 1−2 tons/year.

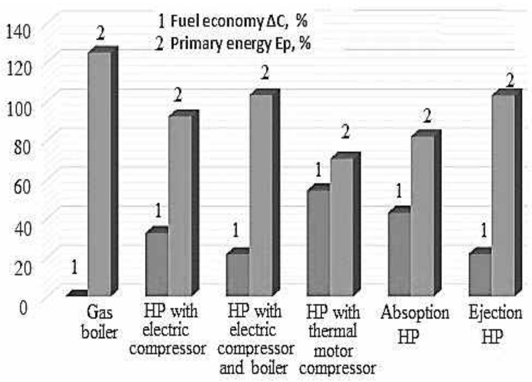


Fig. 9. Primary energy and fuel economy for different types of heat pumps.

Recently, the ground-source heat pump system has attracted more and more attention due to its superiority of high energy-efficiency and environmental friendliness [26].

Renewable forms of energy produce low or no GHG emissions.

The temperature of the ground is fairly constant below the frost line. The ground is warmer in the middle of winter and cooler in the middle of summer than the outdoor air. Thus, the ground is an efficient heat source.

The GSHP system, which utilizes groundwater as a heat source or sink, has some marked advantages including a low initial cost and minimal requirement for ground surface area [27].

The calculated values for the COP of GSHP systems, operating as a water-to-water heat pump are summarized in Figure 10.

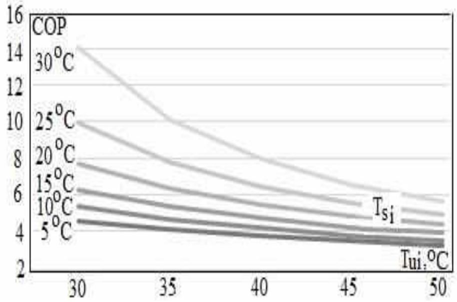


Fig.10. COP of GSHP.

3. ANALYSIS OF THE TEMPERATURE GRADIENT AROUND THE GROUND PIPES OF GSHP

For determination of thermophysical properties of working fluid of GSHP, the CoolPack 1.46 software package was used [29]. The CoolPack is a collection of easy-to-use programs for modeling and design of various HP systems. To carry out calculations, it is necessary to specify only units of measurement and key points, and there is no need to describe the operating diagram of the device.

Using the CoolPack 1.46 for numerical modeling, the heat pump cycle (Figure 11) was calculated for the new parameters with a temperature in the hot spot of 60 ºC; working substance of cycle is ammonia. Italics show the process in which the temperature of the working carrier at the outlet of the GP was 10 °C. For this cycle:

$$COP = COP'\cdot\eta_i\cdot\eta_{\partial o} ,$$

where $COP' = (h_B - h_C)/(h_B - h_A)$ – coefficient of performance without taking into account of compressor and isentropic influence;

$h_B - h_C$ – difference of enthalpies in points B, C;

$h_B - h_A$ – difference of enthalpies in points B, A;

$\eta_i = 0.7$ – isentropic efficiency;

$\eta_k = 0.92$ – isentropic efficiency of the compressor.

Coefficient of performance is equal:

$$COP' = (1720-480)/(1720-1480) = 5.2;$$
$$COP = 5.2\cdot0.9\cdot0.92 = 4.3.$$

This value of the COP is significantly higher than the typical values given in [30, 31], which indicates the high efficiency of this cycle.

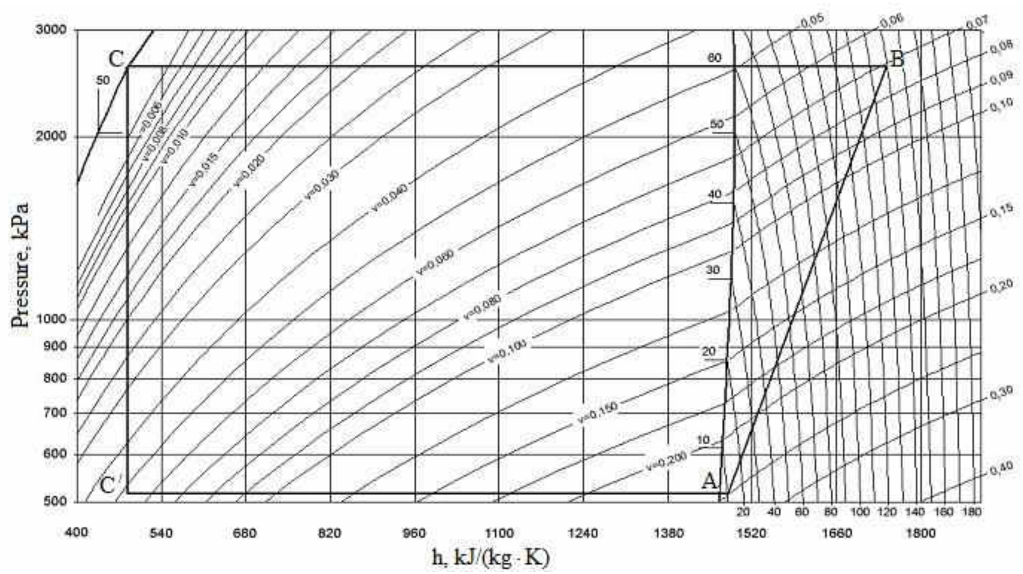
Analysis of experimental data made it possible to establish the dependence of thermophysical properties of the soil from temperature (Figure 12).

It is determined that the proposed GSHP are perspective for Ukraine which has the deficit of own energy resources, as enables to increase the replacement factor of organic fuel and reduce the amount of thermal effluent to the environment.

A large number of GSHP works in the residential, commercial and public buildings throughout the world due to advantages of high energy and environmental performances.

These buildings represent the biggest potential for energy saving technologies.

As a next stage of our investigations the changes of temperature gradient in the soil around GP as a source of energy for the GSHP are analyzed.



A – start of compression; B – output of compressor; C – condensation point of the working fluid.

Fig. 11. GSHP cycle with ground pipes using CoolPack.

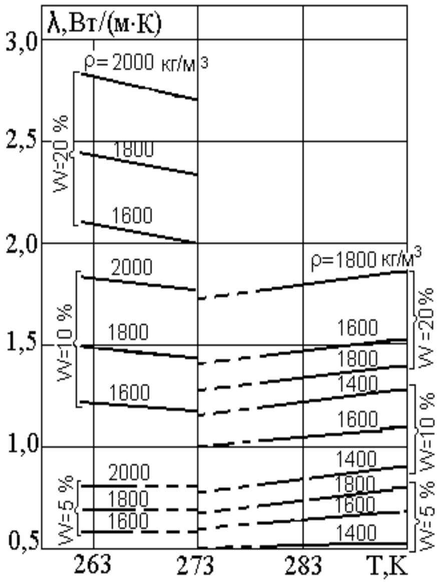


Fig. 12. Thermophysical properties of the soil.

The temperature gradient depends on the depth and the temperature gradient of the soil changes most dynamically at a depth of 4…8 m. At a depth of 8…12 m, the soil temperature decreases from 9 ºC to 8ºC.

The isotherms in the soil run parallel to the ground's surface. According to the results of our research, during some periods of time after start of operation of the HP, the temperature gradient changes significantly at a distance of 0.1 m near the grounds surface (Figure 13).

The temperature around the buried ground tube does not rise more than for 9.0 ºC. Although before the ground pipes (GP) are buried, the temperature at the corresponding depth reached by 12ºC.

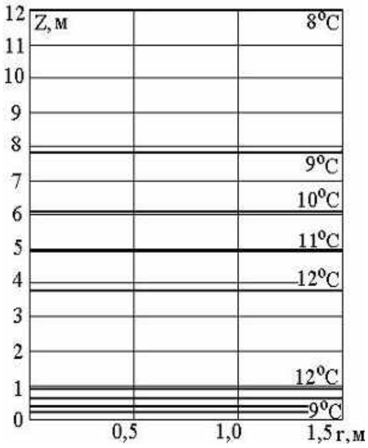


Fig. 13. Distribution of ground temperatures at the beginning of GSHP operation.

At a distance of 1 m under soil, temperatures almost don't change comparably to isolines at Figure 14. Therefore, for the normal operation of the GP for GSHP, it is necessary according to results of calculation to reduce the temperature at the inlet to the compressor to 7 °C. Overheating of the working fluid by 2 °C must be ensured in order to prevent drops of fluid from entering the compressor.

As it can be seen from Figures 14 and 15 after the start of operation of the GSHP with vertical pipes, distribution of temperature in the soil around GP changes sharply. And the highest effect is observed at distance 1.5 m.

Therefore, in case of several closely located GP, the distance between them should be 2 m.

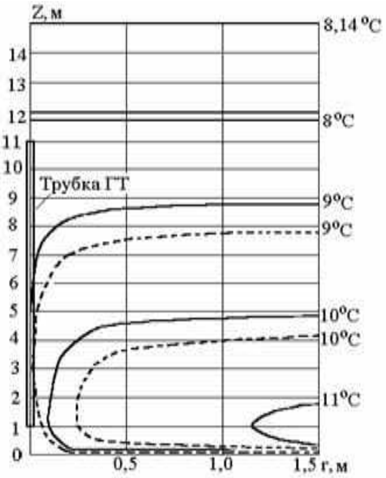


Fig. 14. Distribution of ground temperatures during the operation of GSHP.

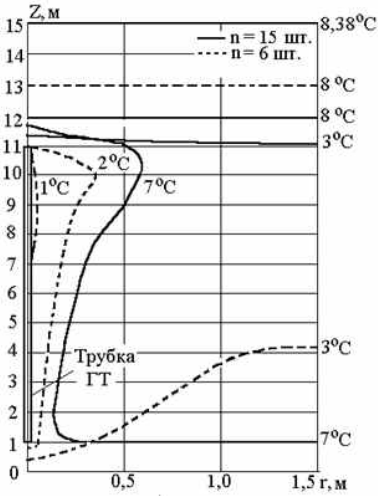


Fig 15. Field of temperature at the end of heating season.

4. RESULTS OF NUMERICAL SIMULATION OF THE THERMAL PARAMETERS IN GROUND HEAT EXCHANGER AND DISCUSSION

Using object-oriented programming facilities numerical modelling of amount of heat Q can be provided by one ground pipe (GP). For 8 points of section C`–A (Figure 11) the input data for further calculations were determined, and these indicators were averaged for each section. Results of numeric simulation obtained using refined calculation based at new data that are shown in Figure 16. Analysis of specified results of numerical simulation shows that the total amount of utilised heat by one ground pipe is equal to: Q = 67.4 W. Preliminary calculations by simplified methodology give an overestimated value Q = 90 W.

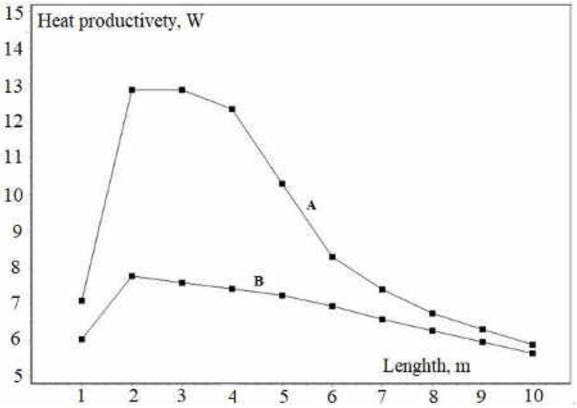


Fig. 16. Dependence of heat on lengths of the GP:
A - at the beginning of operation;
B – during the operation

For the GSHP using low-potential heat of soil, the distance between GP must be no less than 2 m in order to prevent their mutual negative influence on the soil. This solution prevents freezing of the ground during long term of exploitation GSHP.

At the end of the heating season, when the number of GP n < 6, the temperature of the soil around GP drops to 0ºC, which is a threat of freezing to the surrounding soil (Figure 16).

As a result of numerical modelling during a long-term operation of GSHP it is necessary to predict the features of thermal processes in the soil around the ground pipes (GP).

The changes in the temperature field in the soil around GP leads to the thermal relaxation of soil.

But after shutdown of GSHP the field of temperature in the soil around GP can be restored.

The changes of temperature field in the soil during operation and after the GSHP shutdown are shown in Figures 17–18.

The analysis of graphs shows that during the extraction of heat using GP there is an intense temperature drop in the soil layers around GP, i.e. at a distance of 0.1 m. At a distance of more than 0.5 m, the influence of heat exchange processes on the temperature field in the soil becomes much less noticeable. When the GSHP is shut down, i.e. in case of the absence of heat exchange in the soil during 48 hours, the temperature in the soil layers surrounding the GP increases. During the first 12 hours, the heat exchange process occurs most intensively (bottom curve), but over time the curves they approach each other, and then asymptotically approach to the natural temperature of the soil at the given depth.

The analysis of temperature curves in the soil around the ground pipe shows that after 48-hours of shutdown the system leaves the state of thermal relaxation of soil due to the natural ability of the soil to accumulate energy.

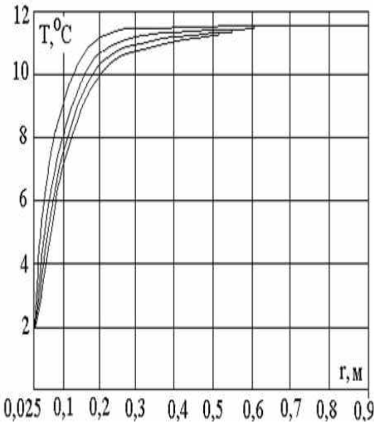


Fig. 17. Non-stationary temperature field in the soil around ground pipe.

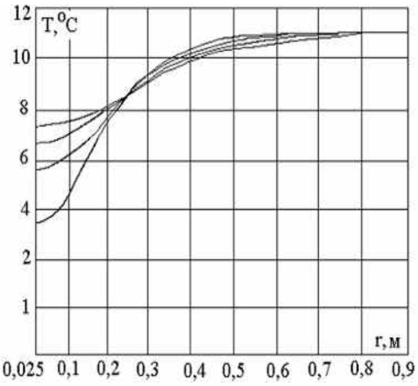


Fig. 18. Temperatures in the soil around GP for every 12 hours during 48-hour shutdown of GSHP.

5. CONCLUSIONS

The widespread implementation of the GSHP with the ground heat exchangers is hampered by rational design of the evaporation part and preparation of wells for them. For example, near Odessa region, evaporation zone of the coolant in ground popes should be at the depth of 5 m. That is, the height of the buried part of the GP must be about 7…10 m, depending on the thermal load, the coolant and operating pressure. This plays a significant role in the cost of GSHP heating system.

In addition, during a long-term operation of the GSHP, there can be a noticeable decrease in the temperature field around the ground pipe is observed until a column of frozen soil appears, and the radius of this column and the rate of its increase directly depend on the amount of heat removed by the HP, i.e. on the amount of heat given off by the soil. This is dangerous not only because of the disruption of vegetation, but also because of a possible decrease in the strength of the foundations of the nearby buildings.

However, such negative impacts can be mitigated by installing heat accumulators and using comprehensive alternative heat supply systems.

Another impact factor is that the heat transfer capacity of the soil at the point of the planned installation of GSHP can be determined only by experimental research and numerical simulation. Because the soil moisture, temperature, composition and thermal conductivity can change significantly during the heating season. Therefore, the ground pipes, even closely located ones, can have completely different performance indicators. Our research is carried out to optimize the design of ground pipes of the GSHP.

Modelling of heat exchange processes in the soil around the GP shows that in order to avoid soil freezing, the minimum permissible number of evaporators is equal 6. Installation of 8…15 heat exchangers of the GSHP allows us to avoid seasonal temperature fluctuations near the ground pipe.

However, even without improving ground heat exchangers, it is clear that they have an advantage compared to solar collectors because:

– ground heat exchangers don’t require significant areas for installation;

– performance ground heat exchangers is practically independent of weather conditions and is characterized by high stability;

– ground heat exchangers are more reliable.

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