Calculation and Design of the Heat Pumps

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***Abstract*—Paper deals with calculation and design of the heat pumps that are used for purposes of heating and cooling. Heat pumps are systems that draw heat from one source (earth, water, air or ambient) and transfer it to another. Their operation is described by Carnot circular process, in which thermal energy is taken from one body to working medium and then from a working medium to the heated body. Energy put in the process is equal to the energy needed for moving and compression of the working medium. Authors have calculated that average energy input is equal to ¼ of useful thermal energy (output). Further on in the paper the working principle of the heat pumps and their main parts are described.**

***Index Terms*-- Compressors, Geothermal Energy, Geothermal power generation, Heating, Heat pumps, Temperature Control, Thermodynamics, Thermomechanical Processes**

I. Introduction

The time of cheap fossil fuels as the main drivers of civilization is nearing its end. The limited reserves of fossil fuel and they high price give the opportunity for introducing new technologies into commercial applications. Changes that took place on the planet's energy systems is not only affecting the type of energy sources, but also the centralized energy systems, in which the consumer is merely the last link. It is now possible to produce energy at the point where it is needed and thus avoid costly transmission. This option not only changes the structure of the energy system but also the social structure of society, from collective to individual.

Heat pumps are systems that are characterized by the high output/input ratio. Average input energy is equal to ¼ of the output energy. This mean that for 1 W of electric energy heat pump transfer from the ground additional 3 W of geothermal energy which if we neglect loses is equal to the 4 W of thermal energy. Heat pumps for primary source of energy uses thermal energy from air, soil or ground water. The most reliable source is the soil and groundwater due to their (approximately) constant temperature throughout the year [1]. Soil temperature at depths greater than 10 meters can be considered constant and it depends on the geographical location is on average 6 degrees Celsius (Fig. 1).

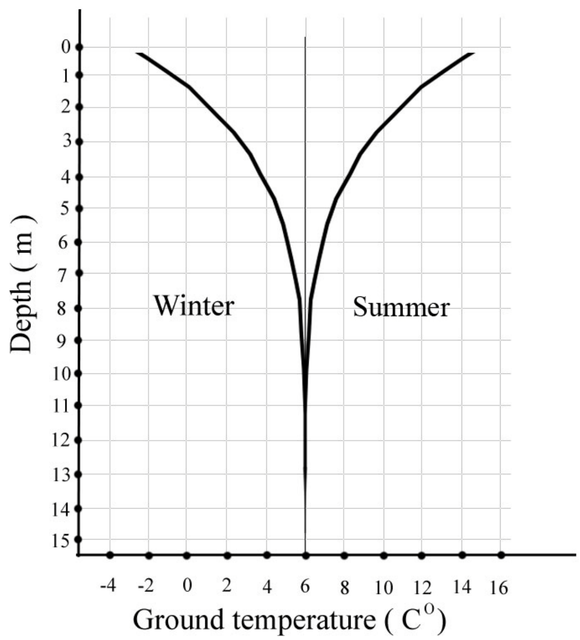

Fig. 1. Dependence of ground temperature on depth

II. The Principle Of Heat Pump

Ground energy is used in summer for cooling and in winter for heating purposes. Thermodynamic principle of the heat pump is described by Carnot circular process [2].

For heating purposes thermal energy of soil is collected in water - antifreeze solution that is then pump to the heat exchanger (evaporator), in which it transfer heat to working medium (like HFC-134a). Fig. 2. describes process by line between points 1 and point 2. When working medium gets to about 12 ºC it goes to compressor there his pressure and temperature rises from 1.71 bar to 8 bar and 12 ºC to 60 ºC [6]. This is shown on Fig. 2. on line from point 2 to point 3. Now the working medium goes through second heat exchanger (condenser), where it transfer his heat to working fluid (water) that is used for heating the building. Passing through the expansion valve (point 4 to point 1, Fig. 2.), the pressure of the working media fall to starting 1.71 bar and process starts again.

Working media is a sort of refrigeration gas. In past Freon

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gas was used, but because its reactivity with ozone Freon (R-22) is no longer in used and is substituted with hydro fluorocarbons like HFC-134a.

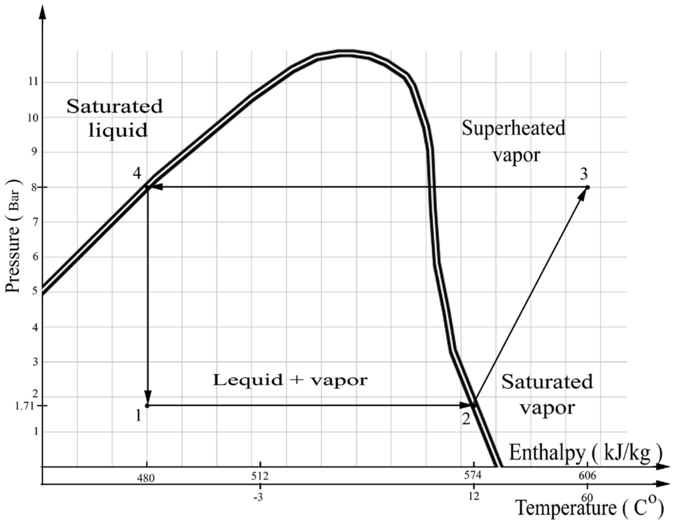

Fig. 2. Carnot cycle of HFC-134a

Heat pump systems operate exclusively on the basis of temperature differences. For high temperature differences the transfer of the energy is faster.

In point 1 (Fig. 3.) working medium leaves the evaporator in which it took power from the ground; its temperature is around 12 ºC. This temperature is not sufficient to heat the room, so we have to compress the working medium in the compressor to raise his temperature to 55 ºC.

In point 2 the working media leaves the compressor and now the fever goes to the condenser. In the condenser the working medium transfers its heat to working fluid (water) that is used to heat the building. Heated water can be used for floor heating (35 ºC), radiator heating (40 ºC – 50 °C) or with additional heating up in the boiler as hot water or steam. After the working fluid delivered its heat on medium it exits from the condenser (point 3) and enters the liquid container.

The purpose of this tank is to balance pressure and volume of media in the entire line of heat pumps. After the liquid container, working fluid which is still under high pressure pass through thermal expansion valve where his pressure and the temperature is reduced to 1 bar and -6 ºC [6]. After that, the working medium is ready to re-take heat from the soil in the evaporator and thus continues to cycle.

III. Heat Pumps Exploitation System

There are two basic systems of heat pumps. Closed circuit system uses a buried heat exchanger so that the working fluid is never in direct contact with the ground. Open system uses geothermal fluid as the working fluid (groundwater) from production well and after a process returns it to injection well [5].

Horizontal system with closed circuit (Fig. 4.) is used in places where there is sufficient space and suitable soil for construction works. The bundle of pipe is taken parallel to the soil to a depth greater than the depth of freezing (about 2 m). The disadvantage of this system is large fluctuations in soil temperature at such shallow depths.

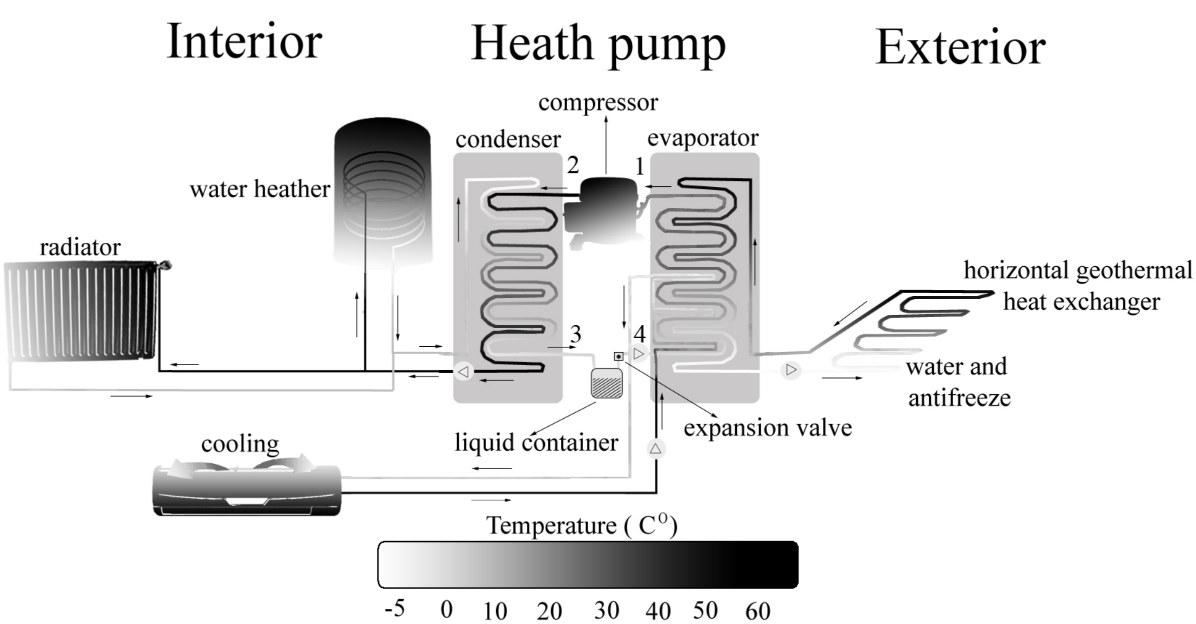

Fig. 3. The principle of heat pump

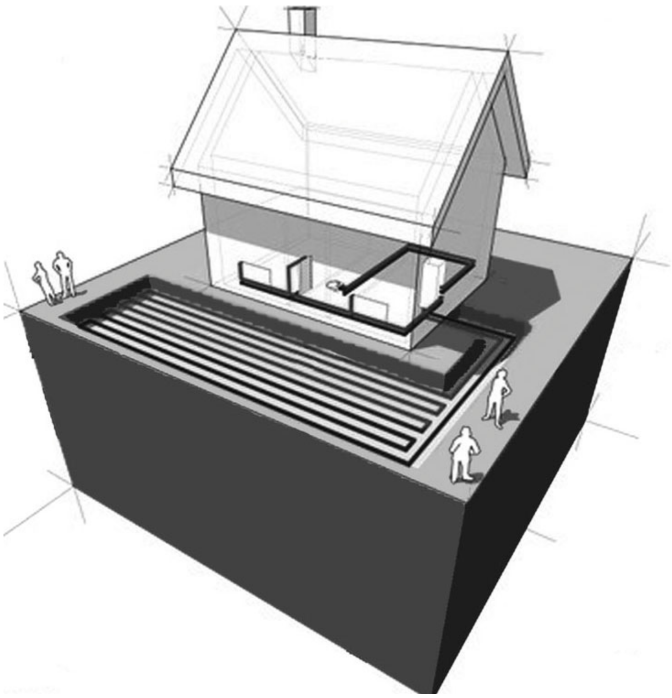

Fig. 4. Horizontal system with closed circuit

Vertical system with closed circuit (Fig. 5.) is applied to objects that have a need for greater amounts of heat energy, in areas where the soil type is not suitable for horizontal system.

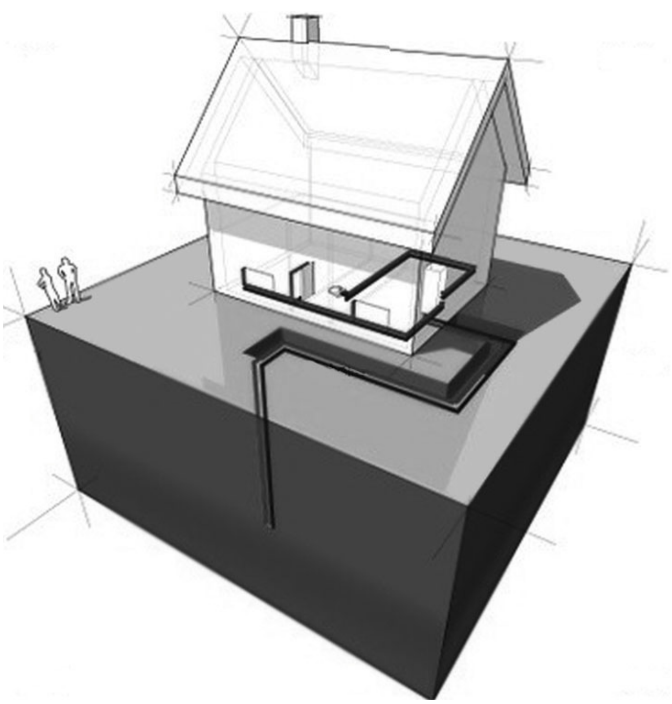

Fig. 5. Vertical system with closed circuit

For this system it is necessary to drill a deeper hole (100m to 200m) or more smaller (20m, 30m, 50m) ones. Polyethylene-based pipes were placed in a U-shaped with a strong coupling at the bottom.

Vertical system with open circuit (Fig. 6.) is effective in the case of abundant groundwater.

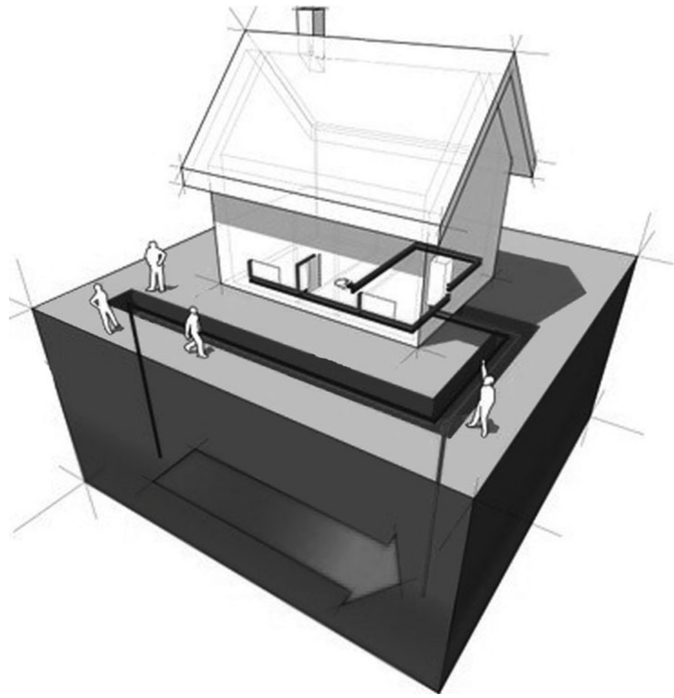

Fig. 6. Vertical system with open circuit

Underground water is directly pumped from a production well, and after passing through the heat pump system returns in the injection well that is at least 15m away. The advantages of this system are low initial investment and good thermal properties of groundwater.

IV. CALCULATION OF THE HEAT PUMP SYSTEM

An example of calculation is performed for heat pump systems of exploitation of geothermal energy with the following rules:

1) For average-sized objects (186 – 223 m^2) necessary thermal power is 10,6 kW to 11,4 kW, depending on climate conditions
2) Length of the pipe for vertical heat exchanger is 13 m/kW to 17 m/kW, and for the horizontal approximately 30% to 50% longer
3) Installation depth of the horizontal heat exchanger is from 1,2 m to 1,8 m

In the following example, calculation will be performed for heating the object area of 180 m^2 and a height of the walls of 2,8 m.

A. Sizing a drill hole of heat exchanger

From previously selected first rule, worst case scenario is chosen (P_0=11,4 kW for A_0=186 m^2), which means that for heating space of 186 m^2 thermal power of 11,4 kW is required.

Unit area which requires 1 kW of thermal power will be calculated by the ratio of surface area that is heated and with required thermal power:

$$a = \frac{A_0}{P_0} = \frac{186}{11,4} = 16,32 \frac{m^2}{kW} \tag{1}$$

where:
a – unit area
A_0 – surface area in the worst case
P_0 – thermal power required in the worst case

Calculation of condenser power is reduced to determining the necessary thermal power from these rules for the given object area:

$$Q_{con} = \frac{A}{a} = \frac{180}{16,32} = 11,03kW \approx 11kW \tag{2}$$

where:
Q_{con} – power of condenser
A – Area of a given object

Thermal power required for heating the object of 180 m^2 is 11 kW. Coefficient of performance of the selected compressor is:

$$COP = \frac{heat\ capacity}{needed\ electrical\ energy} = 3,5 \tag{3}$$

where:
COP – coefficient of performance

This coefficient says that for 1 kW of input power compressor gives 3,5 kW output power.

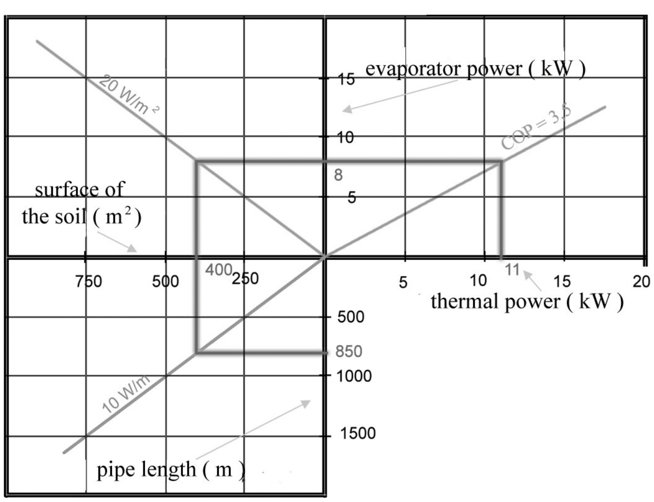

Fig. 7. Nomogram for sizing geothermal exchanger [14]

From the nomogram (Fig. 7.) required parameters for the needed heat power of Q_{con}=11 kW were determined.

The process of determining the parameters of the nomogram is shown in several steps:

1) As an input parameter in the nomogram the value of capacitors thermal power is entered (Q_{con}=11 kW)
2) Bold line on Fig. 7. is withdrawn vertically to the value of the compressors coefficient of performance (COP=3,5)
3) The horizontal bold line on Fig. 7. retreats to the selected heat that takes off from the ground (in this case it is taken as 20 W/m^2 for the soil of medium conductivity)
4) At the intersection of the ordinate and the horizontal bold line the value of the evaporator was read (Q_{evap}=8 kW)
5) Bold line descends vertically to the value of 10 W/m which is for soil of medium conductivity and good exposure
6) At the intersection of abscissa and the bold line require soil surface to put the geothermal exchanger was read
7) The bold line leads to the horizontal axis, where the required length of the tube exchanger was read (l=850 m)

TABLE I
INPUT AND OUTPUT DATA FROM THE NOMOGRAM

Input data		**Output data**	
Q_{con}	**11 kW**	**Q_{evap}**	**8 kW**
COP	**3,5**	**A_{soil}**	**400 m^2**
The heat that takes from the ground	**20 W/m^2**	**Length of the heat exchanger pipes**	**850 m**

To check the accuracy of the parameters of the chart the following equality will be used:

$$Q_{evap} + P_{comp} = Q_{con} \tag{4}$$

where:
Q_{evap} – the power of the evaporator
P_{komp} – compressor power
Q_{con} – capacitors power

Compressor power can be calculated from the relation:

$$P_{comp} = \frac{Q_{con}}{COP} = \frac{11}{3,5} = 3,14kW \tag{5}$$

Substituting into the formula we get:

$$8 + 3,14 = 11,14 \approx 11kW$$

B. Calculation of the heat pump cycle

Object area is 180 m^2 and the height of the wall is 2,8 m. From the known facts, the volume of the object can be calculated:

$$V = A \cdot h = 180 \cdot 2,8 = 504m^3 \tag{6}$$

where:
V – volume of the object
h – height of the walls

Analog to the previous cases (P_0=11,4 kW and A_0=186 m2) it follows:

$$V_0 = A_0 \cdot h = 186 \cdot 2,8 = 520,8m^3 \tag{7}$$

where:
V_0 – volume of the object in the worst case

Heating factor is obtained:

$$f = \frac{P_0}{V_0} = \frac{11,4}{520,8} = 0,022kW / m^3 \tag{8}$$

where:
f – heat factor

Because of the availability of the phase diagram for the required reading of the enthalpy Freon gas 12 (CF2Cl2) is used in calculation [8], although in recent times medias less harmful to the environment was used. In the process of heating, the temperature of the condenser is 60°C and of the evaporator -3°C. From the phase diagram for Freon gas 12 (Fig. 8.) the values of enthalpy were read:

$$i_1 = 574\frac{kJ}{kg}$$

$$i_2 = 606\frac{kJ}{kg}$$

$$i_3 = i_4 = 480\frac{kJ}{kg}$$

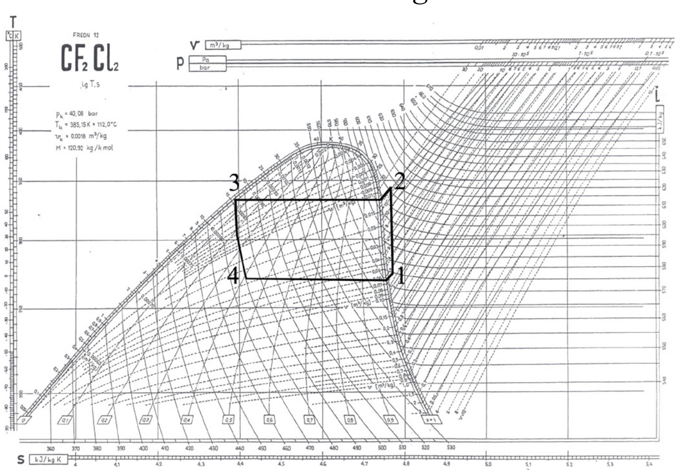

Fig. 8. Phase diagram for Freon 12

Heat release in the condenser is:

$$q^{\bullet} = i_2 - i_3 = 606 - 480 = 126\frac{kJ}{kg} \tag{9}$$

where:
$q^{\bullet}$ – heat release in the condenser

Evaporator cooling capacity is:

$$q_0 = i_1 - i_4 = 574 - 480 = 94\frac{kJ}{kg} \tag{10}$$

where:
q_0 – evaporator cooling capacity

Spent compressor work equals:

$$je = i_2 - i_1 = 606 - 574 = 32\frac{kJ}{kg} \tag{11}$$

where:
je – spent compressor work

It has been checked:

$$q_0 + je = q^{\bullet} \tag{12}$$

$$94 + 32 = 126$$

Heating power is calculated by multiplying the volume of heated space and heat factor:

$$Q^{\bullet} = V \cdot f = 504 \cdot 0,022 = 11,09kW \tag{13}$$

where:
$Q^{\bullet}$ – heating power

Supply of Freon gas equals:

$$D_f = \frac{Q^{\bullet}}{q^{\bullet}} = \frac{11,09}{126} = 0,088\frac{kg}{s} \tag{14}$$

$$0,088\frac{kg}{s} = 0,088 \cdot 3600 = 316,8\frac{kg}{h}$$

where:
D_f – supply of Freon gas

Compressor power is obtained as the input energy per unit of time:

$$P_{comp} = je \cdot D_f = 32 \cdot 316,8 = 10137,6\frac{kJ}{h} \tag{15}$$

$$10137,6\frac{kJ}{h} = \frac{10137,6}{3600} = 2,82kW$$

Heat of vaporization is obtained by acting cooling effect of evaporator per unit time:

$$Q_0 = q_0 \cdot D_f = 94 \cdot 316,8 = 8,27kW \tag{16}$$

Efficiency of the heat pump is obtained from the equation:

$$\eta = \frac{\dot{Q}}{P_{comp}} = \frac{11,09}{2,82} = 3,93 \qquad (17)$$

where:
η – Efficiency

Another way to calculate efficiency of heat pump using the Freon gas phase diagram is:

$$\eta = \frac{i_2 - i_3}{i_2 - i_1} = \frac{606-480}{606-574} = 3,93 \qquad (18)$$

V. Cost Comparison Of Natural Gas And Heat Pump Heating

Without specific calculation it is very difficult to specify the costs for installation of heat pumps because their costs are more individual, depending on the length and the depth of underground pipe, the soil conditions, installation and other factors. As an orientation, it can be stated that the cost for installation of heat pumps range from 1500,00 to 2500,00 Euro per 1 kW of thermal output. This price includes drilling, heat pumps, installation of equipment and hydraulic adjustment carried out by the installer. Installation of gas heating for the same usable space would amount to of 3500,00 Euro to 6,500 Euro [3,9,10].

Figure 9. shows the cost comparison of gas heating and heat pump heating for the same object. In calculation of gas heating average efficiency of cauldron 75%, heat power of cauldron 7,5 kWh/m^3 and gas prices for Croatia of 0,3644 €/m^3 is used. For heat pump cost calculation average COP 3,5 and electrical energy prices required for running heat pump 0,102€/kWh for higher tariffs and 0,052€ for lower tariffs is used.

For investment costs of 2000,00 Euro per 1 kW for heat pumps and investment cost for gas heating of 5000,00 Euro payback period is 28 years. The main reason for that is high investment cost for heat pumps and relatively low price for gas in Croatia (gas price in Croatia 0,3644€/m^3 and in EU average price for gas is 0,84708€/m^3 – lowest:0,28677€/m^3; highest: 1,192€/m^3)[15].

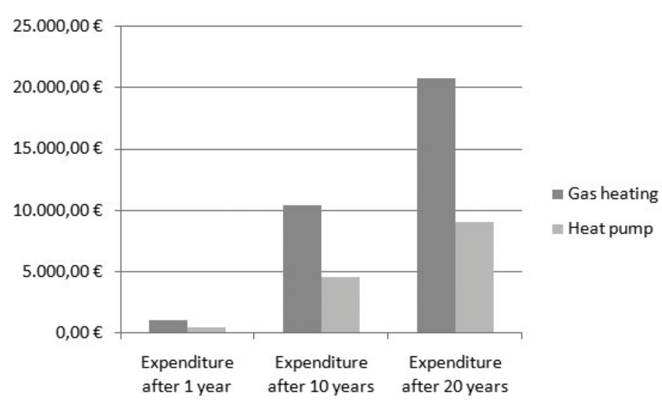

Fig. 9. Cost comparison of gas heating and heat pump heating

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VII. Biographies

Jurica Perko was born in Djakovo, Croatia, on July 13, 1988. He graduated from the high school A.G.Matos Djakovo, under graduated from the Faculty of Electrical Engineering Osijek and currently attending graduate studies from the Faculty of Electrical Engineering Osijek.

He is founder and first president of association for the promotion of arts and culture youth "Street" in Djakovo. Organized seven manifestations with cultural activities for young people and one humanitarian action. Actively participate in sports. Head of the "break dance" workshop for youth in Djakovo. Received a state scholarship award 2009. Year.

Vjekoslav Dugec was born in Djakovo, Croatia, on May 8, 1988. He graduated from the Electrical and Traffic School, Osijek, and currently enrolled in the College of Electrical Engineering in Osijek.

He began to gather experience on professional practice in the Croatian Utility Company (HEP) during the high school. While attending he worked in T-HT (Telecommunication company).

His special fields of interest included renewable energy sources. In his spare time, she enjoys web design, parkour, drawing and reading.

Danijel Topic was born in Orahovica, Bosnia and Herzegovina, on July 22th 1985. He graduated from the Technical High school Zepce, Bosnia and Herzegovina. He obtained his MEng degree in 2008 from the Faculty of Electrical Engineering, Osijek.

Currently he is an assistant at the Power System Engineering Department of Electrical Engineering Osijek, Croatia.

His main interest is in renewable energy sources.

Damir Sljivac was born in Osijek, Croatia, on February 4, 1974. He obtained his BSc degree in 1997 from the Faculty of Electrical Engineering, Osijek, MSc degree in 2000 and PhD degree in 2005 from the Faculty of Electrical Engineering and Computing Zagreb, Croatia in the field of the Power System Engineering. Currently he is an Associate Professor at the Power System Engineering Department and vice-dean at Faculty of Electrical Engineering Osijek, Croatia. His main interest is in power system reliability, economics and renewable energy sources. He has published over 50 papers in those fields. He is a member of IEEE Power Engineering Society, IEEE Reliability Society, IEEE Croatia Section, Executive Board of National Council for Energy Of Croatian Academy for Science and Art and Croatian National Committee of CIGRE and CIRED.

Zoran Kovac was born in Orahovica, Croatia, on April 17, 1969. He obtained his BSc degree in 1994 from the Faculty of Electrical Engineering, Osijek and MSc degree in 2004 from the Faculty of Electrical Engineering and Computing Zagreb, Croatia in the field of the Power System Engineering. Currently he is a technical manager at Transmission System Operator – Transmission Area of Osijek at Croatian National Grid Company HEP, and a Senior Lecturer at the Power System Engineering Department, at Faculty of Electrical Engineering Osijek, Croatia. His main interest is in power system reliability and optimization. He is a member of Croatian National Committee of CIGRE.