U.P.B. Sci. Bull., Series C, Vol. 84, Iss. 3, 2022 ISSN 2286-3540

CORRELATION BETWEEN THE FUNCTIONING OF A DISTRICT HEATING SYSTEM COUPLED WITH A HEAT PUMP AND THE CHANGING OF WEATHER CONDITIONS

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This paper is a continuation of previous works in which the authors analysed the way in which the geothermal water from the Olt Valley aquifer is used in the district heating system of Călimănești. To increase the energy efficiency of the system, the authors analysed the possibility of connecting the geothermal station with a heat pump that recovers the thermal energy from the hot water discharged from the heat exchangers that prepare the primary thermal agent. Optimal operating conditions and the most suitable working agent were established, as well as energy performance indicators. In this paper, the authors analyse how the geothermal station coupled with the heat pump covers the thermal load required by the district heating system in relation to the evolution of climatic conditions in the area, during the cold season. The thermal load coverage limits and the thermal agent and geothermal water flows, respectively, have been established. It was pointed out that in the current climate conditions, caused by the phenomenon of global warming, the use of a heat pump in the system eliminates the use of gas-fired hot water boilers.

Keywords: geothermal heat pump, district heating system, geothermal station

1. Introduction

Olt Valley is one of those places in Romania where the beauty of the landscape has always delighted the eyes of those who cross it. But not only the beauty of nature made these places famous and important. Even at the exit of the Olt Gorges, on the right bank, the mineral springs with various therapeutic properties determined the development of a large complex of spas and hotels, the area Căciulata - Călimănești being very sought after for treating different types of diseases [1]. However, the real richness of the area is the huge deposit of hot geothermal water from underground. It is located at a depth of approx. 3000 m and is exploited artesian, the water having at the head of the wells the temperature of 93...98 °C [2,3,4]. The hydrological and geological characteristics of the deposit make the pressure and drilling flow constant, without the need for the used

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water to be reinjected into aquifer, the waste geothermal water being discharged into the Olt River. The exploitation of these resources began in 1983-1984, when the first drillings were commissioned. Initially, the thermal energy of geothermal water was used directly by hotels and spa treatment units for heating, the domestic hot water preparation, and thermal baths. Since 2001, geothermal water, from drilling 1009, has been used as a heat source for the district heating system of the city of Călimănești [5,6,7]. The action of modernizing this system consisted of the construction of a geothermal station equipped with two plate heat exchangers: a heat exchanger with a thermal power of 500 kW that works continuously, preparing the thermal agent necessary to produce domestic hot water, and a second with a thermal power of 1320 kW that operates seasonally, preparing the necessary thermal agent for the heating system [8,9,10]. The three thermal power plants of the city have been transformed into thermal distribution points, keeping the old hot water boilers as backup systems for cases of damage, or coverage of peak loads. From the available drilling flow, which is 18 l/s, the geothermal station can use only 10 l/s, the rest being used by nearby hotels [11,12,13]. Geothermal water from the Călimănești aquifer, having a high gas content, must be degassed before being introduced into the heat exchangers. To ensure the necessary temperature for the heat supply, the temperature of the agent, in the return of the district heating system, cannot be lower than 40 ... 45 ^{o}C, which means that the hot water in the primary circuit of the heat exchangers cannot be cooled below about of 50 ^{o}C. For reasons of aquatic environmental protection, the water from the outlet of the geothermal station heat exchangers cannot be discharged directly into the Olt River, being necessary an atmospheric cooling, up to the permitted discharging temperature about of 30 ^{o}C. In this way, a significant amount of heat is lost in the environment, being used practically only 2/3 of the available thermal potential. To recover this heat loss and increase the capacity of the district heating system, several solutions have been proposed, including the implementation of a heat pump [14, 15, 16]. This, using as heat source the hot water discharged from the heat exchangers of the geothermal station and operating in parallel with them, can add a supplementary flow of thermal agent sent into the heating system, increasing its full thermal power with up about 60%.

In a previous article [17,18,19], the authors analysed the solution of implementing a heat pump in the district heating system of Călimănești, establishing the optimal operating conditions and the efficiency of the system consisting of the geothermal station and the heat pump. In this paper, the authors aim to analyse how the geothermal station coupled with the heat pump can cover the thermal load required during the heating season, in relation to changing weather conditions.

2. Thermal load of the district heating system.

The town of Călimănești, in addition to the tourists who come to the spa and stay in the hotels that have treatment units, also has a number about of 8600 permanent inhabitants of which almost 15% live in apartments connected to the district heating system. In the cold season 2019-2020, 466 apartments and residential houses, 9 public institutions and 47 economic operators were connected to this system [20,21,22]. The city of Călimănești is part of the climate zone III of Romania, for which the conventional outdoor temperature for the cold season is $t_{ec} = -18$ ℃. For residential and tertiary buildings, a conventional interior design temperature $t_{ic} = 20$ ℃ can be considered [23,24,25].

Under these conditions, considering the thermal characteristics of the constructions connected to the district heating system, the maximum thermal load of the system is evaluated as follows [26,27]:

- maximum thermal load for heating: $\dot{Q}_{heat}^{max} = 3500$ kW
- maximum thermal load for DHW preparation: $\dot{Q}_{dhw}^{max} = 500$ kW

Taking in account that the heat transfer characteristics are unchanged, the thermal load of the district heating system, which must be realised by geothermal station (GTS), varies linearly with the temperature of the external environment t_e, according to the relation:

$$\dot{Q}_{GTS} = \dot{Q}_{heat}^{max} \frac{t_{ic} - t_e}{t_{ic} - t_{ec}} + \dot{Q}_{dhw}^{max} \text{ [KW]} \quad (1)$$

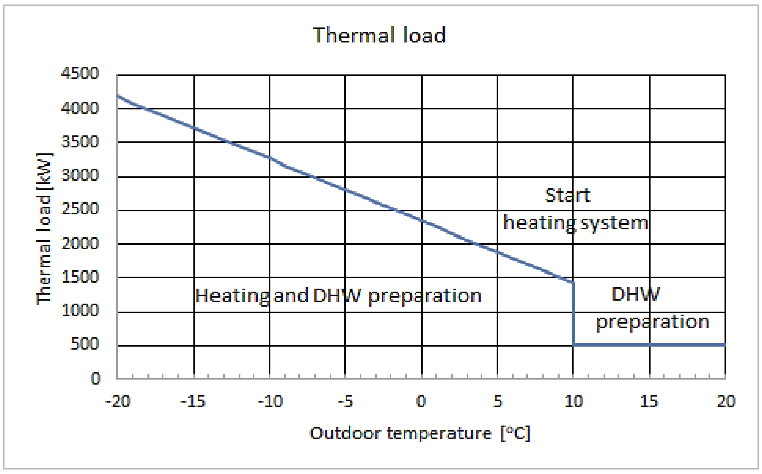

Fig. 1. Variation of thermal load in relation with outdoor temperature.

The variation of the thermal load in relation to the outdoor temperature is shown in Fig. 1. It is considered that the district heating system is put into operation when the mean daily temperature of the external environment is lower than 10 °C, producing thermal agent both for the preparation of domestic hot water and for heating. For mean daily outdoor temperatures above 10 °C, the system prepares agent only for domestic hot water.

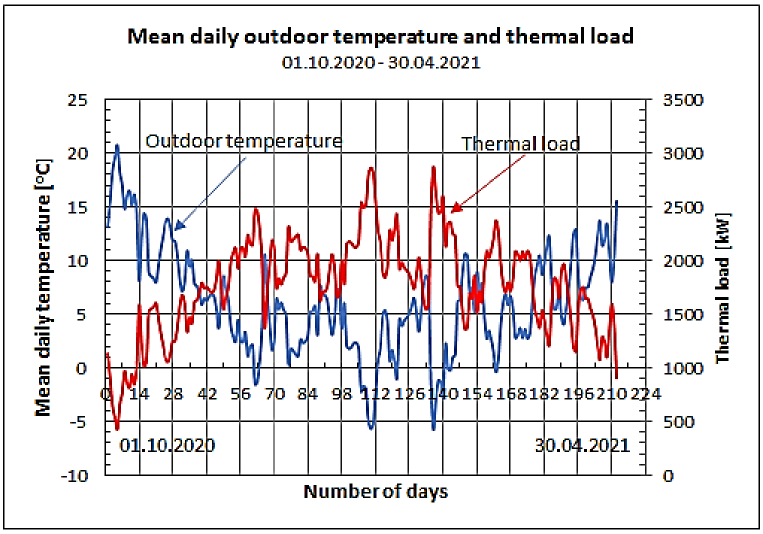

Fig.2. Variation of mean daily outdoor temperature and thermal load, in the cold season of 2020-2021.

In the cold season 2020-2021, the variation of the mean daily outdoor temperature and necessary thermal load for heating system in the Calimanesti zone, is shown in Fig. 2 [28]. In recent years, due to global warming, mean temperatures during the cold season have been higher than usual. It can be noted that mean outdoor temperatures below 0 °C was recorded in the area for a few days, only in the second half of January and in February, the thermal load during this period being about 70% of the maximum load calculated, based on conventional temperatures. The system was started on Octomber 01, 2020 and was stopped on April 30, 2021.

3. Correlation between required thermal load and characteristic of the geothermal station coupled with a heat pump

The operation diagram of the geothermal station coupled with the heat pump is shown in Fig. 3.

By cooling the geothermal water with $\Delta t_1 = 45°C$ (from 95 °C to 50 °C) the heat flow introduced in the heating system is:

$$\dot{Q}_{he} = \dot{m}_{gw} c_w \Delta t_1 = \dot{m}_{he} c_w \Delta t \qquad (2)$$

and by recovering the residual heat from the geothermal water, the heat flow introduced by the heat pump into the system is:

$$\dot{Q}_{hp} = \dot{m}_{gw} c_w \Delta t_2 \frac{COP}{COP-1} = \dot{m}_{hp} c_w \Delta t \tag{3}$$

where, $\Delta t_2 = 20°C$ (from 50 °C to 30 °C) is the degree of geothermal water cooling in the heat pump evaporator, *COP* its energy efficiency, and $\Delta t = 40°C$ (from 85 °C to 45 °C) the temperature difference between the outlet and the inlet of the thermal agent sent into the district heating system.

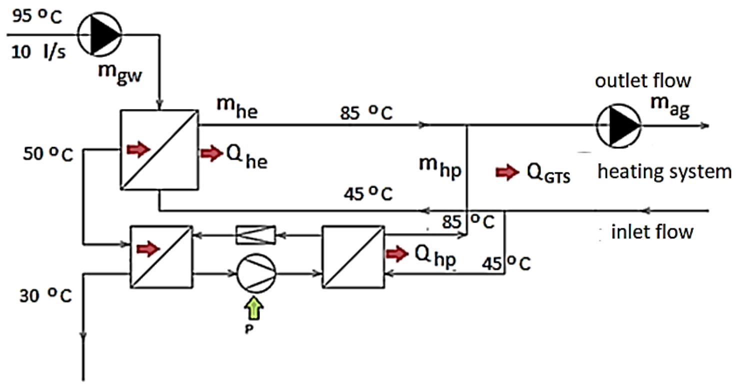

Fig. 3. Operation diagram of the geothermal station coupled with a heat pump

The two expressions determine the total heat flow that the geothermal station (GTS), coupled with the heat pump, introduces into the district heating system:

$$\dot{Q}_{GTS} = \dot{m}_{gw} c_w \left(\Delta t_1 + \Delta t_2 \frac{COP}{COP-1}\right) = (\dot{m}_{he} + \dot{m}_{hp}) c_w \Delta t \tag{4}$$

For the maximum available flow of geothermal water, the maximum heat flow delivered to the district heating system, according to relation (4), is $\dot{Q}_{GTS}^{max} = 3000$ kW, of which 1890 kW directly from the geothermal water and 1110 kW from the heat recovered by means of the heat pump. For the operating conditions of the heating system, the energy efficiency of the heat pump was considered $COP = 4{,}1$ [17]. The external limit temperature up to which the system can operate only with the thermal energy produced in the geothermal water heat exchanger is:

$$t_e^{gw} = t_{ic} - \frac{\dot{Q}_{he}^{max} - \dot{Q}_{dhw}^{max}}{\dot{Q}_{heat}^{max}} (t_{ic} - t_{ec})\ °C \tag{5}$$

and the external limit temperature up to which the system can operate coupled with heat pump is:

$$t_e^{gw+hp} = t_{ic} - \frac{\dot{Q}_{he}^{max} + \dot{Q}_{hp}^{max} - \dot{Q}_{dhw}^{max}}{\dot{Q}_{heat}^{max}}(t_{ic} - t_{ec})\ ^\circ C \quad (6)$$

For the operating conditions of the heating system $t_e^{gw} = +4{,}9\ ^\circ C$ and $t_e^{gw+hp} = -7{,}1\ ^\circ C$. For outdoor temperatures lower than t_e^{gw+hp}, gas-fired hot water boilers must also be started. Fig. 4 shows how the geothermal station can cover the thermal load of the district heating system, depending on the level of the outdoor temperature.

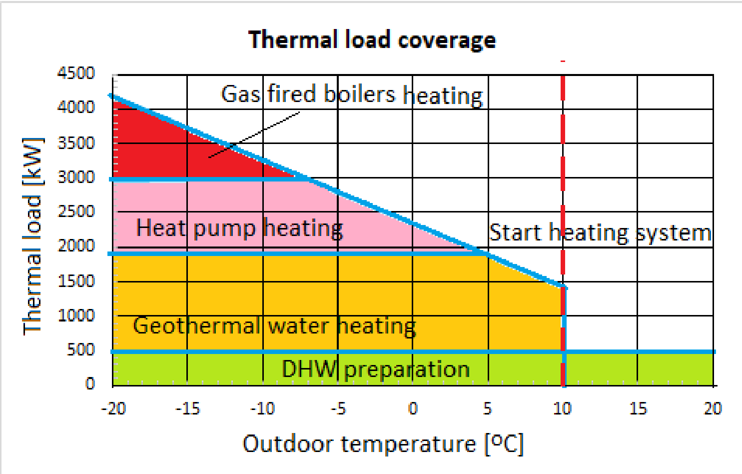

Fig. 4. The thermal load coverage in relation with outdoor temperature.

4. System adjustment when changing external conditions

The adjustment of the geothermal station functioning, so that the heat flow produced can cover the thermal load determined by the outdoor temperature, can be done by changing the flow of the thermal agent sent in the network, with the constant maintenance of its temperature (quantitative regulation) or with the constant maintenance of the flow of the agent sent in the network and the change of its temperature (qualitative regulation). Only quantitative adjustment has been considered in this paper. The heat flow required for the district heating system can be expressed as (1) and requires the flow to be taken from the geothermal water well:

$$\dot{m}_{gw} = \frac{\dot{Q}_{heat}^{max}\frac{t_{ic} - t_e}{t_{ic} - t_{ec}} + \dot{Q}_{dhw}^{max}}{c_w\left(\Delta t_1 + \Delta t_2 \frac{COP}{COP - 1}\right)}\ [\mathrm{KG/S}] \quad (7)$$

in which the external limit temperature is $t_e^{gw+hp} = -7{,}1\ ^\circ C$, the temperature at which the water flow taken from the well reaches the maximum value of $\dot{m}_{gw}^{max} = 10$ kg/s. If the temperature of the thermal agent sent to the district heating system is kept constant, its flow rate depending on the temperature of the external environment is expressed:

$$\dot{m}_{ta} = \dot{m}_{he} + \dot{m}_{hp} = \frac{Q_{heat}^{max}\frac{t_{ic}-t_e}{t_{ic}-t_{ec}} + Q_{dhw}^{max}}{c_w \Delta t} \quad [\text{KG/S}] \tag{8}$$

The variation of these flows in relation to the external temperature is presented in Fig. 5.

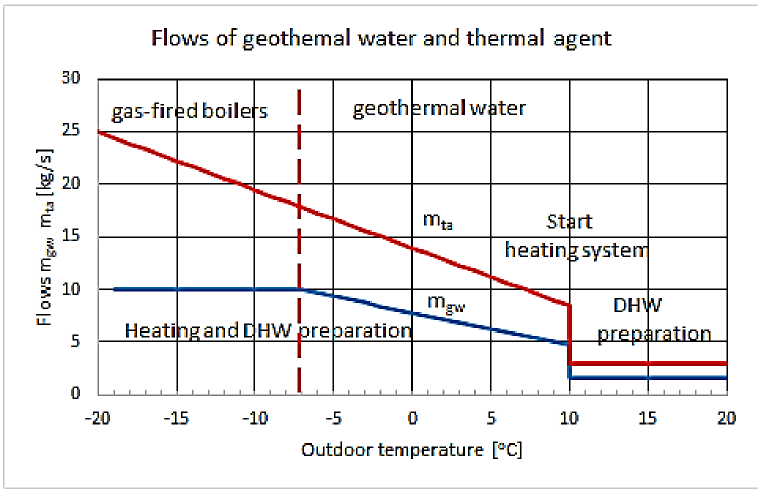

Fig. 5. Variation of geothermal water flow and thermal agent flow in relation with outdoor temperature.

Coupling the geothermal station with a heat pump to recover the thermal energy of the wastewater discharged from the geothermal heat exchangers, allows to increase the flow of thermal agent introduced into the district heating system and cover about 70% of its maximum thermal load. Under these conditions, the district heating system can ensure the thermal comfort of consumers only up to an outside temperature of around -7 ^{o}C (Fig. 5).

Examining the way in which the climatic conditions in the area have manifested in recent years, by coupling the geothermal station with a heat pump, the maximum available flow of geothermal water can ensure the coverage of the entire thermal load of the heating system, without the use of water boilers hot on gas. Due to the global warming phenomenon, the average daily temperatures during the cold season were higher than the usual temperatures for this period. As can be seen in Fig. 6, according to the weather archive in the area, during the cold period of the 2020-2021 season [28], in just a few days the average outdoor temperature dropped below -5 ^{o}C, the temperatures in the rest of this period being in the range 0 ... + 5 ^{o}C. Under these conditions, the thermal load of the system can be covered throughout the heating season without the need to come into operation the hot water boilers with gaseous fuel.

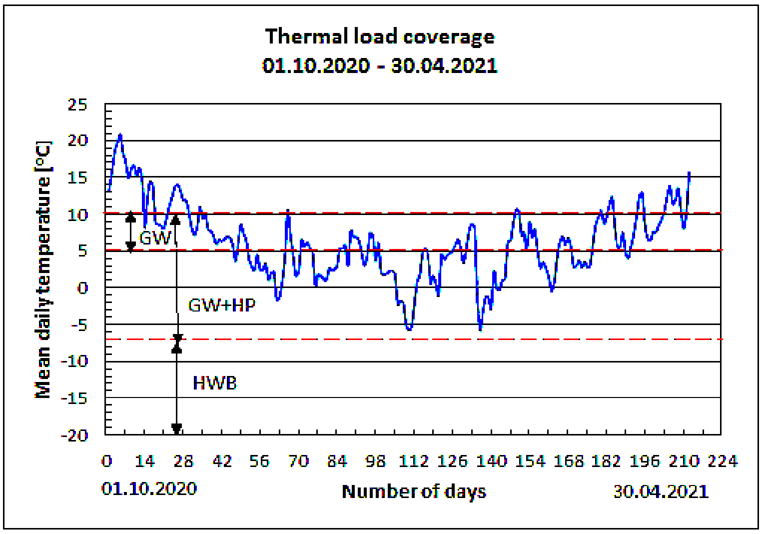

Fig. 6. Thermal load coverage in relation with outdoor temperature

The primary energy ratio of the current heating system, which uses only hot water boilers with gaseous fuel to cover the load peaks, can be determined with the expression [26]:

$$PER = \frac{\dot{Q}_{GTS}^{max}}{\dot{Q}_{HWB}^{max}} \cdot \eta_{HWB} \tag{9}$$

where:

- $\dot{Q}_{GTS}^{max}$ [kW] is the maximum thermal load under the calculation conditions;
- $\dot{Q}_{HWB}^{max}$ [kW] is the supplementary energy needs for heating, provided by the gas-fired hot water boilers;
- η_{HWB} is the hot water boilers efficiency ($\eta_{HWB} = 0.88 \ldots 0.92$).

For the climatic calculation conditions of the area, the value of this indicator is about of 1.6. When the heating system is connected to the heat pump, the primary energy consumption is determined by the consumption of gaseous fuel and the electricity required to operate the heat pump. The primary energy ratio is expressed in this case [26]:

$$PER = \frac{\dot{Q}_{GTS}^{max}}{\frac{\dot{Q}_{HWB}^{max}}{\eta_{HWB}} + \frac{\dot{Q}_{HP}^{max}}{\eta_{EE} \cdot COP}} \tag{10}$$

where:
- $\dot{Q}_{HP}^{max}$ [kW] is the supplementary energy needs for heating, provided by the heat pump;
- η_{EE} is the electricity production efficiency ($\eta_{EE} = 0.33 \ldots 0.35$);
- COP is the heat pump efficiency ($COP = 4.1$).

For the climatic calculation conditions of the area, the value of this indicator is about of 2.1, which highlights an increase of about 30% in the energy efficiency of the district heating system.

5. Conclusions

- The available flow of geothermal drilling water can continuously provide the necessary thermal energy for the preparation of domestic hot water. The geothermal water flow required for this purpose represents about 25% of the available well flow. During the period when the district heating system is not working, the thermal energy necessary for the preparation of domestic water can be provided entirely from geothermal water.
- During the cold season, when the district heating system comes into operation, the maximum available geothermal water flow can only provide the thermal energy needed to prepare the domestic water and about 40% of the thermal energy needed to cover the maximum heating load of the system. Under these conditions, the district heating system can ensure the thermal comfort of consumers only up to an outside temperature of around +5 ^{o}C. If the outside temperature drops below this limit, it is necessary to start the gas-fired hot water boilers
- The heat pump coupled with the geothermal station is a very good solution to increase the efficiency of the heating system of Calimănești. Firstly, the heat pump allows the full use of the thermal potential of geothermal water, which can be discharged at a temperature close to the environment, and secondly, increases the flow of heat sent to the district heating system, allowing either its expansion or the connection of new consumers to the network.
- The water extracted from the aquifer of the area contains a large amount of combustible gases, with a content of over 90% methane. This feature is favourable for the implementation of a gas cogeneration system, which would also provide the electricity needed for the operation of the heat pump.

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