Numerical simulations of ground–coupled heat pumps combined with thermal solar collectors

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ABSTRACT: This paper presents the numerical study of a solar-assisted ground-source heat pump system for building heating and the production of domestic hot water. An experimental study has been carried out and has allowed to validate the numerical model of the process. Two variants of the process are studied. These two variants use the solar energy for the domestic hot water (DHW) heating and for the injection of heat into the ground. In addition, the first variant also uses solar energy to heat the building thanks to a direct solar floor (DSF) and has a solar collector's surface more important. While taking into account the electric consumption of the circulation pumps, results show that the global electric consumptions of these two variants are identical and have a value equal to 31 kWh per square meter of building surface. Nevertheless, with heat injected into the ground which represents 54% of the heat extracted, the first variant can be a solution to better balance the thermal ground loads.

Keywords: ground coupled heat pump, solar collector, energy savings, numerical simulations

1. INTRODUCTION

In one century, the greenhouse gas effect concentration has increased by 30 % [1]. In addition, building sector is responsible for the half of the greenhouse gas emission, principally due to the heating [2]. In this context, geothermal heat pumps (GHP) with borehole heat exchangers (BHE), also called ground coupled heat pump (GCHP) are a good solution to decrease the consumption of energy thanks to their high energy efficiency. Low-temperature geothermics are based on the use of the heat contained in the soil via embedded heat exchangers and heat pumps. Heat pumps make usage of this low-temperature energy possible by increasing the outgoing fluid temperature of BHE to values of the order of 35°C, which can be used to heat building directly in a low delivery temperature system such as a heating floor. In these conditions, because the low difference of temperature between the heating floor and the ground, the average value of the performance coefficient (COP of the heat pump) is expected to be above 3. They can also be reversible (heating mode or cooling mode) and thus be used for cooling in the summer. The majority of existing studies concerning ground heat pumps concern commercial or institutional buildings, which require an important number of boreholes. Studies concerning small GHP systems are scarcer in spite of the important number of individual houses, especially in France. Indeed, in 2000 in France, according to the INSEE (Institut National de la Statistique et des Etudes Economiques), the proportion of individual houses represent more than half of residential buildings (56 % exactly) [3].

On other side, the use of solar energy is a simple solution to save energy for the heating of domestic hot water, but that asks only a little surface of solar collector, especially in individual houses. As a consequence, it would be interesting to find solutions that exploit better solar energy. Exactly, when GCHP are used, a solution consists to oversize solar collectors with respect to the domestic hot water requirement alone so that the excess solar energy is routed to the boreholes to favour thermal ground recovery and the heat pump COP in heating mode. In addition, ground coupled heat pumps are generally combined with heating floors. As a consequence, another simple solution can be the coupling of solar collectors with heating floors to heat building directly with solar energy. This working can decrease the operating time of the heat pump and consequently the global electric consumption of the process.

This paper presents a numerical study about a process called GEOSOL which is used in an individual house and for which a GCHP is combined with thermal solar collectors.

First, a description of the process will be presented. Then, we'll talk about the model used to simulate the process. It has been validated thanks to the experimental study of the system in an individual house. Third, we'll present the yearly energy balance of the system. Simulation will be carried out for two variants of the process. For the two variants, the solar energy is used to heat domestic hot water (DHW) and to inject energy into the ground. In addition, for the first version, the solar collector's surface is more important and the solar energy is also used to heat the building thanks to the direct solar floor.

1. DESCRIPTION OF THE PROCESS

1.1 Schematic diagram and behaviour of the process

The schematic diagram of the GEOSOL process is presented on figure 1.

Solar heat is used in priority to product DHW and is injected into the boreholes only when the DHW temperature setting is reached. The advantage of this system is that it contributes to balance the ground loads, optimizes operating time of solar collectors and avoids its overheating problems.

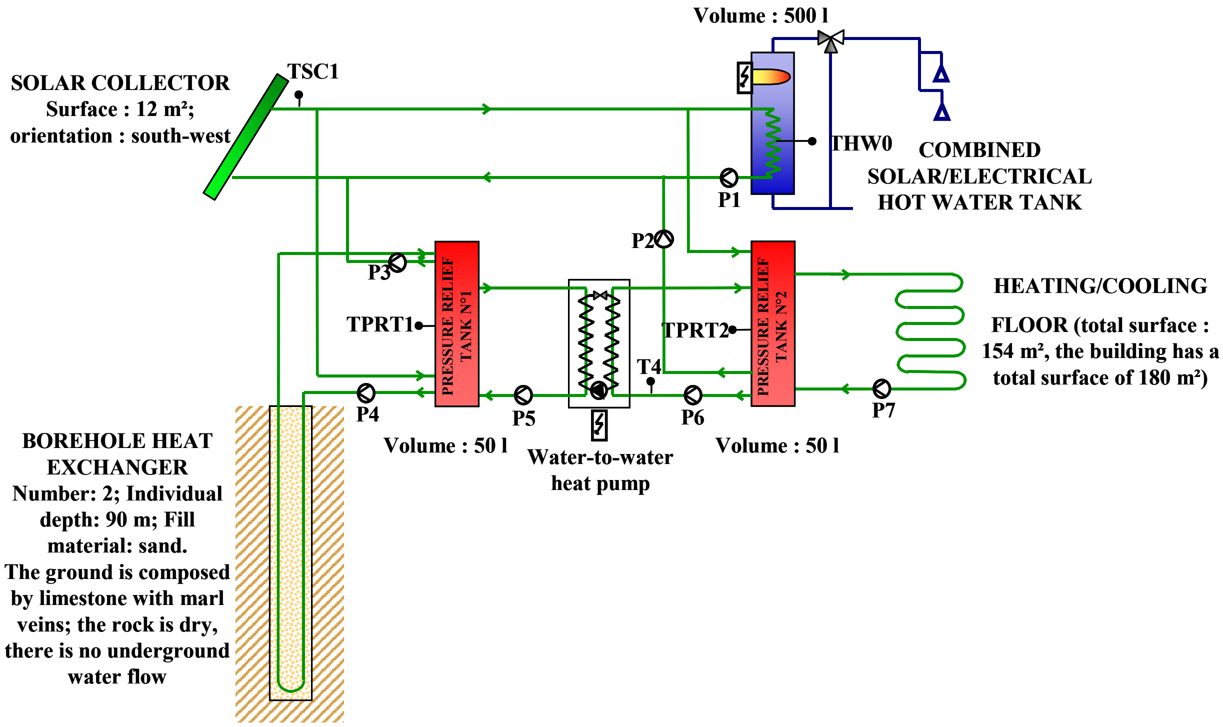

Figure 1 : Schematic diagram of the process installed in a single family house

The solar energy can also be used to heat directly the building instead of the heat pump. For this working, the inside setting temperature is increased of 3°C in order to storage solar energy into the building and as consequence to decrease the heat pump's operating time. That allows to minimize its electric consumption which represents an important part of the process's global electric consumption.

To optimize the use of electricity, circulation pumps operate sequentially. We do not use three-way valves, as they generate higher maintenance costs and complicate the control system.

1.2 Control system of the solar collectors

Compared to classical systems of heating or cooling, the control of this installation is relatively complex. The power provided by geothermal energy is nearly the same throughout the year, as opposed to solar energy for which the power provided depends on solar radiations. To ensure proper operation of the installation, it is simpler to use two existing control systems: one adapted for ground-coupled heat pump systems and another adapted for solar heating systems. However, these two control systems must have good operational flexibility in order to ensure that the GCHP system combines well with the solar collector system and also to ensure that all circulation pumps turn off if all preset temperatures are respected.

For the process, the operating mode of the solar collectors in DHW heating (DHW mode) is a function of the DHW tank temperature (THW0) and the outlet solar collector temperature (TSC1). The circulation pump P1 is activated if (TSC1-THW0) > 6°C and is turned off if (TSC1-THW0) < 2°C or if THW0 > 60°C.

Thanks to the direct solar floor, the solar energy can also be used to heat the building if Tindoor < (Tsetting + 3°C) and if (TSC1 – TPRT2) > 6°C. This operating mode is turned off if Tindoor > (Tsetting + 3°C) or if (TSC1 – TPRT2) < 2°C, where Tsetting is the indoor temperature setting. The DHW mode and the DSF mode can operate simultaneously.

If THW0 > 60°C, the DHW setting temperature is reached and the excess solar heat is injected into the ground by operating the circulation pumps P3 and P4, if (TSC1-TPRT1) > 6°C. This operating mode is also activated if solar heat is not sufficient for the DHW heating and it is turned of if (TSC1-TPRT1) < 2°C.

1.3 Control system of the heat pump

The heat pump and the P4, P5, P6 and P7 circulation pumps are activated in accordance with the indoor temperature and the outlet heating floor temperature (T4). If the indoor temperature (19°C) is not respected, the P6 and P7 circulation pumps are activated and, in heating mode, the heat pump and the P4 and P5 circulation pumps are turned on if T4 < 26°C. In heating mode, the P4 and P5 circulation pumps and the heat pump are turned off if T4 > 30°C, which ensures a low difference in temperature between the heating floor and the ground. Circulation pumps P6 and P7 are turned off if the indoor temperature is respected.

1.4 Installation and experimental study of the GEOSOL process

The process has been installed and tested in a 180 m² single family house constructed in 2004.

The solar collector area is oversized with respect to the domestic hot water requirements alone so that the excess solar energy is routed to the boreholes to favor thermal ground recovery. Rooftop thermal solar collectors covering 12 m² were installed, although 6 m² would have been sufficient in relation to the DHW needs.

The heating power of the heat pump has a value of 15.8 kW (for an inlet temperature to the condenser of 40°C and an inlet temperature to the evaporator of 5°C) and two 90 m depth boreholes were installed.

The DHW tank has a volume of 500 l and the two pressure relief tanks volumes of 50 l.

A water–antifreeze mixture – 35% propylene glycol solution (antifreeze to –18°C) – circulates throughout the installation because the solar collectors are subject to the risk of freezing.

A measurement system set-up provides precise tracking of the energy flows and of the behaviour in each circuit using temperature PT1000 sensors and volumetric water meters. These data are also used to validate the numerical model of the process.

Papers [4][5] present interesting experimental results and show that the combination of renewable energies such as thermal solar energy and geothermal energy in a single system should make it possible to meet a residence's heating and hot water requirements, while guaranteeing a satisfactory level of comfort. In addition, these papers show that to optimize the system's COP, choosing the best circulation pump control system is essential. In our system, if only one circulation pump worked continuously, the average system's COP would have a value of 2.6 versus 3.35 if all circulation pumps worked only when the heat pump is activated. Consequently, operating circulation pumps non stop must be avoided to preserve the main advantage of GCHP: to low energy consumption. At least, the experimental study has shown that the surface of solar collector (12 m²) is not sufficient for the building's heating by solar energy.

2. NUMERICAL MODELING

The GEOSOL process has been implemented into the TRNSYS [6] modelling environment using standard and non-standard component models.

The model consists of 7 major components which correspond to the schematic diagram of the process (figure 1) : the boreholes heat exchangers, the heat pump, the heating floor, the two pressure relief tanks, the solar collectors and the combined solar/electrical hot water tank.

2.1 Borehole heat exchanger

Inputs and outputs of the vertical ground loop heat exchanger model (TRNSYS component type 557) include entering and exiting temperatures and fluid mass flow rates. This type uses the duct storage model (DST model) developed at Lund Institute of Technology (LTH) in Sweden [7] which has been incorporated into TRNSYS by Pahud and Hellström [8]. It can be used for the simulation of thermal processes that involve heat and/or cold storage in the ground. The storage volume has the shape of cylinder with rotational symmetry.

2.2 Heat pump

Inputs to the heat pump model (TRNSYS component type 668: water to water heat pump) include entering fluid temperatures, fluid mass flow rates and cooling/heating control signal. The model relies on manufacturer's catalog data files containing the heating and cooling capacity and power requirements at different source and load temperatures. Outputs of the model are the outgoing fluid temperatures, the heat pump powers (produced by the condenser, absorbed by the evaporator and absorbed by the compressor) and heat transfers to load and from source.

2.3 Building and heating floor

The building is modeled in the TRNSYS environment using the TYPE 56 (multi-zone building). It allows to take into account the loads of the building in function of the climatic conditions and the indoor setting temperature whatever time step chosen. In this way, the outlet and inlet temperatures of the heating floor are more precise and as consequence, the evolution of the heat pump performances, which depend on these temperatures, is more accurate.

2.4 Pressure relief tank

The two pressure relief tanks are modelled by using the component type 60. This component is used to simulate water storage tank by taking into account thermal losses and thermal stratification. This is necessary to simulate the process as the operation mode of the solar collectors depends on the temperature of the fluid stored in these two tanks.

2.5 Solar collector

The component type used to model the solar collectors is a non-standard component model. It is based on a simplified approach of mass and heat transfers using a three-nodes electrical analogy: cover, absorber and fluid. This new TRNSYS 'TYPE' is different from the other solar collector TYPEs, as it takes three important aspects into account: the transient behaviour of the collector, infrared radiation exchanges between cover and surrounding (ground and sky separately), and thermo physical collector characteristics. An experimental validation has been carried out. Using this new model allows to obtain a detailed energy balance of this component in different working conditions [9].

2.6 Combined solar/electrical water tank

Like for the pressure relief tanks, we use the component type 60 but in addition we use the option of an electric resistance heating element subject to a temperature and time control. We also use the option of an internal heat exchanger which allows to heat DHW with the solar energy.

2.7 Controller

The control system of the process is modelled using several equations while respecting the principles of the real control system presented in the previously.

Each of these components have been validated thanks to the data provided by the experimental study of the process. For each component, the validation has been carried out for its behaviour (evolution of the temperatures) and for its energy balance.

The numerical model of the GEOSOL process consists of two parts: the solar domestic hot water system and the ground coupled heat pump. Each of these parts has been validated using their energy balances. For example, for the GCHP, the comparison of experimental energy balances with those calculated by the numerical model by using the same climatic conditions has allowed to validate the model [10].

3. RESULTS AND DISCUSSION

In this part, we present the annual energy balance calculated by the numerical model of two versions of the GEOSOL process with the weather data of Chambéry, in France. The indoor building temperature is set to 19°C with a deadband of 0.3°C.

The parameters of the version n°2 (V2) of the model correspond to the ones of the installation used for the experimental study (figure 1). For this version, the solar energy is used in priority to heat the DHW and the excess solar heat is injected into the ground.

With the version n°1 of the numerical model (V1), the solar energy is also used to heat the building with the direct solar floor. That's why the surface of the solar collectors is increased to 18 m².

Table 1 presents the yearly energy balance of the two variants of the GEOSOL process and figure 2 presents the repartition of the energy between the different parts for the first variant.

3.1 Study of the variant n°1

First of all, we can study the figure 2 which allows to clearly understand the behaviour of the variant n°1 of the process. Concerning the ground, 9138 kWh are extracted by the GCHP, which represents 51 kWh per meter of boreholes. This value is low and shows that the geothermic potential of the site is underexploited. Indeed, for a ground with good thermal conductivity (2.8 W/m.K), like limestone, the energy yield is comprised between 75 and 90 kWh/m [11]. That shows that the GCHP is oversized in relation to the energy needs. This is due to the fact that the ground coupled heat pump is oversized with respect to the building's energy needs which are reduced when the direct solar floor operates. By decreasing the borehole length and the heat pump power, it is possible to reach an energy yield extracted per meter of boreholes comprised in classical values. Like this, the model has shown that only the operating time of the heat pump and the energy extracted per meter of boreholes increase. In parallel, the annual energy extracted from the ground and the heat pump's electric consumption stay constant.

In the boiler room, 112 kWh are added to the heat extracted from the ground. This energy is transferred from the ambient air to the fluid of the pressure relief tank n°1 and represents only 1% of the energy extracted from the ground. As consequence, this supply is insignificant.

Then, the heat pump adds to this energy 3171 kWh, which corresponds approximately to its electric consumption, and provides 12421 kWh of heat. These values allow to calculate the heat pump's coefficient of performance (COP) which is equal to 3.9.

At last, 2191 kWh of energy provided by the solar collectors is added to the heat products by the heat pump. The sum of these two energies corresponds to the heat provided to the building by the heating floor. Fewer than 1% of this energy is loosed from the pressure relief tank n°2 to the ambient air of the boiler room. As consequence, 14520 kWh are used to heat the building, which represents 80 kWh per square meter of the building surface. 15% of this energy comes from the solar energy, and 85% from the heat pump. For this variant, the heat pump has an operating time of 988 h and the operating time of the solar collectors in direct solar floor is equal to 500 h.

Concerning the use of solar energy, figure 2

Part of the installation	Energy (kWh)		Δ (%)
	V1	V2	
Heat extracted from the ground	9138	10450	+ 14%
Heat pump's electric consumption	3171	3576	+ 12.7%
Heat provided by the heat pump to the building	12421	13985	+ 12.6%
Solar energy injected into the DHW tank	2506	2738	+ 9%
Solar energy injected into the ground	4929	3362	- 32%
Solar energy injected into the heating floor	2191	/	/
Total energy injected into the heating floor	14520	13985	- 3.7 %
Electric consumption of electric resistance of DWH tank	1472	1269	- 13.8%
Electric consumption of circulation pumps	893	725	- 18.8%
Total electric consumption (heat pump, electric heater, circulation pumps)	5536	5570	+ 0,6 %

Table 1: Yearly energy balance of two variants of the GEOSOL process

shows that only its half is exploited by the solar collectors. On the remaining energy, 13% are loosed along the pipes which connect the solar collectors to the boiler room. Then, 52% of the remaining solar energy are injected into the ground, 25% into the DHW tank and 23% into the direct solar floor. It is important to remember that solar energy is used in priority to heat DHW or building, only excess of the solar energy is injected into the ground. That allows to re-inject into the ground about 54% of the energy extracted by the heat pump.

For the variant n°1, the solar fraction for the production of DHW is equal to 63%.

3.2 Comparison with the variant n°2

With table 1, we study the evolution of the yearly energy balance if no solar energy is used for space heating and if the solar collectors surface decreases to 12 m². For this version (n°2), operating time of the heat pump is more important. The increase is about 127 h (11,4%). The energy extracted from the ground and the heat pump's electric consumption increase respectively of 14% and of 12.6%. For this variant, the heat injected into the ground represents 32% of the heat extracted instead of 54% for the variant n°2. That clearly shows that the variant n°1 allows to balance the thermal ground loads. So, it can be an interesting solution for bigger buildings which require a larger number of boreholes and where a thermal recharge of the ground is necessary.

For the variant n°2, the solar fraction for the production of DHW is equal to 68% instead of 63% for the variant n°1. Yet, the solar collector's surface is more important for the variant n°1. This is due to the running in direct solar floor which decreases the level temperature of the solar collectors under the THW0 temperature (figure 1).

An important point of the energy balance is the electric consumption of the circulations pumps. For the version n°1, this consumption is significantly higher than for the version n°2 due to the operation in direct solar floor which requires two pumps and due to a higher solar collectors surface which requires an operation time of injection of excess solar energy into

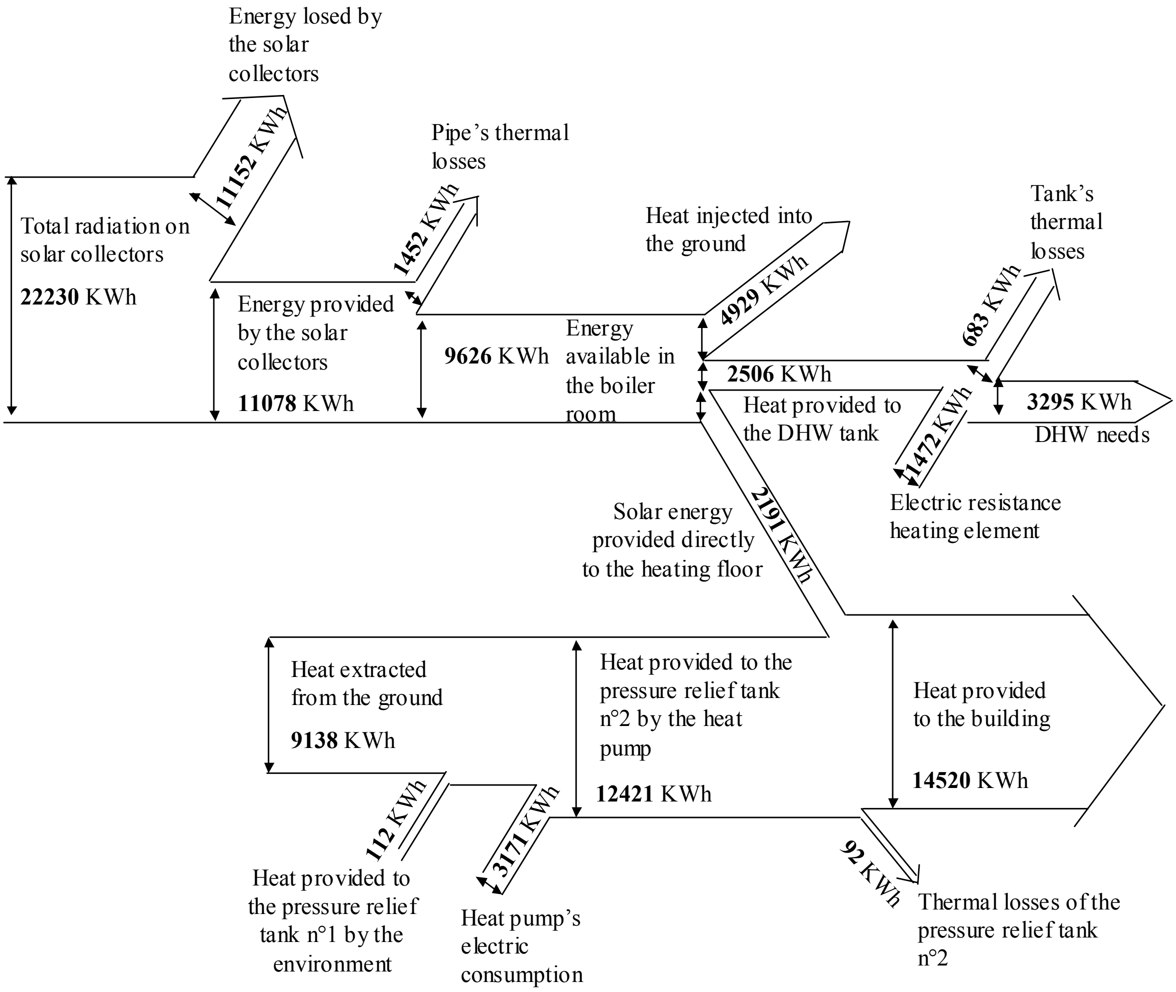

Figure 2 : Yearly energy balance of version 1 of the GEOSOL process

the ground more important. This additional electric consumption penalizes the energy balance of the version n°1 (893 kWh versus 725 kWh).

So, for the two variants, the global electric consumption is the same with a value of 31 kWh per square meter of building surface.

4. CONCLUSION

This paper presents the GEOSOL project which concerns the combination of ground–coupled heat pumps combined with thermal solar collectors.

The installation and the experimental study of the process in a single family house have allowed to validate the numerical model carried out under the TRNSYS software. We have presented the yearly energy balances of two variants of the process. For the first variant, solar energy is used in priority for the heating of the DHW and of the building and the excess solar energy is injected into the ground. With 18 m² of solar collectors, that allows to inject into the ground 54% of the heat yearly extracted from the ground which may assure better performances of the heat pump after several years of operation by balancing the ground loads. In addition, the use of solar energy to heat building allows to decrease the operating time of the heat pump of about 12% compared with the second variant for which solar energy is only used for the DHW heating and the injection of heat into the ground. Consequently, the yearly energy yield extracted from the ground is lower which can be interesting for bigger building where a thermal recharge of the ground is required.

Nevertheless, the use of solar energy to heat building decreases the level temperature of the solar collectors, which decreases the probability to heat DHW with solar energy and consequently the solar fraction for the heating of DHW. In addition, the increasing of the solar collector's surface increases the amount of excess solar energy that must be injected into the ground if we want to avoid overheating problems. Moreover, the electric consumption of the circulation pumps used to inject the solar energy into he heating floor is significant. Consequently, in relation to the second variant of the process, the total electric consumption of the circulation pumps is more important, which penalize the global electric consumption of the process. That's why the global electric consumptions of the two variants are approximately identical with a value of 31 kWh per square meter of building surface.

To conclude, these results show that the combination of ground coupled heat pump with thermal solar collectors is a good way to save energy in building. If solar energy is already used to for the DHW heating and for the injection of heat into the ground, its use to heat directly the building thanks to the heating floors doesn't really allow to save energy, but can be a solution to better balance thermal ground loads of bigger buildings.

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