DEVELOPMENT OF AN ENERGETICALLY SELF-SUFFICIENT BUILDING: THEORETICAL MODEL AND EXPERIMENTAL RESULTS

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Abstract

The research in renewable energy applications is becoming more and more important due to environment pollution and traditional sources costs. This paper present an innovative system of a building heating plant based on solar thermal technology and geothermic energy storage. This system combines the possibility to reach an almost total energy coverage with limited costs. The results of the mathematical model, developed to properly dimension the plant, are in accordance with the experimental results obtained by the measurement on the real applications. This correspondence encourages the continuation of the research in order to optimize the system.

keywords: solar thermal, thermo-well, heat-pump

1. INTRODUCTION

The environment pollution and the increase of the energy consumptions, together with the reduction of the fossil fuel reserves, make the search and the use of renewable energy sources a problem of great topical interest. In 2007, the Ue Commission has presented the integrated program on energy and climate changes, aiming at the XXI century emission reduction. The program consists of a considerable whole of measures finalized at a new European energy policy, able to assure the restriction of the CO2 emissions and to strengthen the energy security and the competitiveness. The Commission's commitment is to reduce the CO2 emissions at least of the 20% within 2020, operating on energy saving and efficiency. The target is to join a contribution of the renewable energy sources equal to the 20% of the European energy mix within 2020.

This target will require a considerable increase in the fields using renewable energy sources: the generation of electric energy, the bio-fuel and the buildings heating.

The present paper propose a building model energetically nearly self-sufficient.

The concept is to exploit the energy that collide with the buildings from the environment, using the energy transfer physical laws, aiming at a considerable reduction of the electric energy costs and joining the almost complete energetic self-sufficiency.

Another goal has been the limitation of the plant's realization costs, using common materials and components that the technologies in the van of energy saving and renewable sources usually don't use.

Even a small thermal difference is able to hold in useful energy and to make possible winter heating, warm water production and summer refreshment. It is estimated an incidence of 1,48 kWh/m^{2}day of solar radiation on a horizontal surface during the coldest month in Milan. This assures, respecting the transmissive coefficients indicated in the laws, the possibility of an almost total energy coverage.

2. THE PLANT SYSTEM

The plant is formed by the following fundamental systems: the thermo-surface, the thermo-well, the heat-pump, the heating/refreshing plant (Fig. 1).

2.1 The energetic collect

The first important element, to collect the heat necessary for the plant operating, is the thermo-surface, that is the surface able to catch the solar radiation. A catching surface of 65 m^2, receives a quantity of energy equal to 10 m^3 of gas per day, even in the worst climatic conditions in January. The innovation consists in the low cost and in the large availability of the material used for the thermo-surface: the alveolate poly-carbonate, able to create an ideal greenhouse effect for the solar radiation utilization. The thermo-carrier fluid (water and glycol) pass through a coil (made of resin pipes), costing 1 €/m and resting on a black sheet .The modularity of the scheme allows the combination with the photovoltaic technology, by the introduction of a panel under the poly-carbonate that doesn't modify the photovoltaic cell performances. In this way, the surface needed is the half. It is not necessary that the thermo-surface is placed on the roof, but also on a vertical external surface: it becomes a well ventilated front that reverse its operating during the winter season, in which the air is kept still, assuring a good thermal insulation. Another mineral-wool layer, inserted between the wall and the thermo-surface, combines the properties of the wall thermal insulating with the energy absorption by the poly-carbonate element: the whole thickness it's only 90 mm (even less, about 40 mm, considering the high insulating level of the air contained, that is almost still).

2.2 The storage and the autonomous distribution

Winter operation: during the day, the hot water from the roof warms up the water for sanitary use, while the remaining heat is used by the heat-pumps, to serve the heating plants of each flat, that is thermally autonomous without the traditional hot water boiler.

The remaining warm water from the roof goes inside the thermo-well, realized in reinforced concrete and filled up with gravel and water, that assures an higher heat transfer capacity.

During the night the process is inverted: the water is warmed by the ground, that is at an higher temperature, feeding the heat pumps.

Summer operation: the heat is extracted by the flat and given up to the fresh thermo-carrier fluid passing through the fan-coils.

An heat pump for each flat allows a better use even in the middle seasons: it is possible to switch on or to switch off its own heating plant, related to the specific needs, even by a remote control.

The ideal terminals are fan-coils, but good results are possible also with aluminium or cast iron radiators, using them at a continuous operation state and offering, in this way, important performances to the existing real estate.

3. THE MATHEMATICAL MODEL

It has been developed a mathematical model, based on the heat transfer equations, in order to dimension correctly the system's components and to evaluate theoretically the system's behaviour.

3.1 Radiation of heat on the thermo-surface

The irradiation power on the ground, for surface unit is given by:

$$\dot{E} = \int_0^\infty \dot{e}_\lambda \, d\lambda$$

As known, it is not an integral analytically solvable, but it is necessary to use data-base indicating the solar radiation filtered by the atmosphere (distinguishing the radiation on an horizontal surface and on a vertical surface, depending on the panel arrangement). Then, it is necessary to calculate the energy actually snared by the panels:

$$\dot{E} = \int_0^\infty \dot{e}_\lambda \tau_\lambda \alpha_\lambda \, d\lambda = \dot{Q}$$

The heat snared by the thermo-surface won't be the whole radiation, but the radiation filtered by the poly-carbonate and absorbed by the sheet at the various wave-lengths of the solar spectrum.

3.2 Heat carried away by the coil

We have considered the heat transfer conditions in the steady state, when the thermo-carrier fluid removes the same heat quantity snared by the thermo-surface (the thermo-carrier fluid will have to maintain an input temperature lower than the atmospherical temperature). Given the thermo-carrier fluid, it is possible to obtain the Reynolds and Prandtl numbers, dependent upon its thermo-physics properties.

$$Re = \frac{\rho v D}{\mu}$$

$$Pr = \frac{C_P \mu}{k}$$

By the Dittus-Boelter relation, it is possible to obtain the Nusselt number value:

$$Nu = C_1 Re^{C_2} Pr^{C_3}$$

the coefficients that appears in the relation have to be evaluated related to the fluid movement and to the thermal exchange type. Obtained the Nusselt number, from its expression it is possible to get the convective coefficient for the fluid:

$$h = \frac{Nu \cdot k}{D}$$

Known the conductive coefficient of the tube, it is possible to express the thermal power exchanged by a coil of length L

$$\dot{Q} = \frac{\Delta T_\infty}{R_{conductive} + R_{convective}}$$

Where:

ΔT_∞ is the temperature difference joined by the sheet in balance conditions and the temperature of the undisturbed fluid (fluid input temperature)

$$R_{conductive} = \frac{1}{kL2\pi} \ln \frac{R_{ext}}{R_{int}}$$

$$R_{convettiva} = \frac{1}{hL2\pi R_{int}}$$

The thermal power exchanged, considering the thermo-carrier fluid, is also equal to:

$$\dot{Q} = \dot{m} C_P (T_{output} - T_{input})$$

3.3 Heat pump work

The heat pump differs its function according to the plant's target: winter heating or summer refreshment. In the case of winter operating:

$$COP = \frac{\dot{Q}_H}{\dot{L}} = \frac{\dot{Q}_H}{\dot{Q}_H - \dot{Q}_C}$$

While, in the case of the summer refreshment, the refrigeration cycle efficiency is:

$$\varepsilon = \frac{\dot{Q}_C}{\dot{L}} = \frac{\dot{Q}_C}{\dot{Q}_H - \dot{Q}_C}$$

The heat pump COP and the refrigeration cycle efficiency are linked by the following relation:

$$COP = \varepsilon + 1$$

Whatever is the configuration, to find the heat exchanged by the heat pump's exchangers, it is possible to use the formulas for the heat exchangers at parallel flow:

$$\dot{Q} = US \frac{\Delta T_{out} - \Delta T_{in}}{\ln \frac{\Delta T_{out}}{\Delta T_{in}}}$$

where the ΔT are the temperature differences between a fluid and the other one in input and output of the exchanger. Besides, the heat exchanged on each side (in absence of phase transitions) can be obtained by:

$$\dot{Q}_H = \dot{m} C_P (T_{out} - T_{in})$$

$$\dot{Q}_C = \dot{m} C_P (T_{out} - T_{in})$$

These are the ideal operating conditions for the machine; in reality, there are some thermal losses, and the machine's work can be influenced by thermal efficiencies, as well as current efficiencies (of course, the electric power is not entirely transformed in useful work).

3.4 The thermo-well

The thermo-well is schematized by a cylinder of reinforced concrete, containing gravel balls of known dimension. We have supposed a ball disposition similar to the metal crystalline grid; in this way, the balls volume is the 70% of the total. Considering the thermo-well as an heat exchanger, the exchange surface is equal to:

$$S_{exchange} = \frac{0.7 \cdot V_{well}}{V_{gravel}} S_{gravel} = \frac{0.7 \cdot \pi R^2{}_{well} H_{well}}{(4/3) \cdot \pi R^3{}_{gravel}} \cdot \pi 4 R^2{}_{gravel}$$

As for the thermal flows, the well acts as an exchanger, but it doesn't use a continual flow, but a mass. It can be considered the steady state exchange for an infinitesimal vertical height dh of the well, for which the water and the gravel inside has joined the thermal balance:

$$\dot{Q} = \frac{T_{ext} - T_{int}}{R_{conductive}}$$

where

$$R_{conductive} = \frac{1}{\pi 2 k dh} \ln \frac{R_{ext}}{R_{int}}$$

The well works properly only in transitory conditions and it is possible to calculate the quantity of energy that it can accumulate (within the gravel and not considering the surrounding ground):

$$Q = m_{gravel} C_p (T_{max} - T_{min})$$

where the ΔT is between the maximum gravel temperature (temperature of the hot water in input) and the minimum reachable temperature (temperature of the cold water in input).

4. RESULTS

The mathematical model put in evidence that the heat flows are marked by extremely low power levels and temperature differences of few degrees. For example, in a winter day in Milan, it is possible to join a radiation power peak of 250 W/m2; about 200 W/m2 are effectively snared in the thermo-surface. Using these data it's possible to calculate that, in a steady state, the thermo-carrier fluid is able to carry away the power of 200 W/m2 using a temperature difference of less than 20 °C. Besides, the water in output presents a temperature difference, with respect to the input, of 3 °C arriving at 10 °C.

As said, the power is slow, but the integral of this power flow during the day results an energy enough to meet the requirements. The thermal power necessary for the sanitary and heating requirements, is supplied by the heat-pump, able to maintain the water in the heating plant at the temperature of 50 °C, with a power absorption of about 2 kW .

The thermo-well model is based on the possibility to store energy instead of the thermal power exchanged. As a matter of fact, the exchanger is particularly efficient and the temperature differences are limited; therefore the water in output has joined the thermal balance with the ground. The energy stored by 1 m^3 of the thermo-well is about 0.8 kWh for each degree of temperature increase. That value is acquired considering only the volume of the thermo-well; if it is also considered the possibility to exchange heat with the surrounding ground, it is possible to consider a stored heat of 1 kWh/mc*k.

In winter days in Milan, the heating system has to face a power flow due to a difference of temperature of 20 °C. If we suppose a typical flat of 100 m^2 with walls' thermal conductivity of 0.37 W/m^2*k, there is a flow of 600 W towards the external. This means a requirement of 14.5 kWh per day. Besides, a family (of 3 members) needs about 6.5 kWh per day to heat sanitary water. In the coldest months the lowest radiation in Milan on horizontal surface is 1.48 kWh/day (source: NASA). So, theoretically, it will be needed a 14 m^2 collecting surface to obtain the whole energy requirement (in practice, the system will be oversized, of course).

At present, there are already self-sufficient buildings used to test different kind of solutions. Data taken from this buildings show that a collecting surface of 65 m^2 is enough to make the system work in a 4 floors building of about 400 m^2. In winter months the temperature of the solar collector never reaches 20 °C according to the results of the theoretical mathematical model and the temperature of the output water is about 10°C. In this conditions the power absorbed by the heat pumps is less than 2 kW for each one. The thermo-well volume used is equal to 8 m^3, according to the theoretical model of 2 m^3 for a 100 m^2 flat.

In the following table 1, there is a comparison between the mathematical model and the data taken from the system working in the above-stated building.

Table 1

		Model	House	Unit
Collecting surface (1)	Thermal suface	58.17	65	m2
	Output water avg. temp.	11.86	10	°C
Heat pump (2)	Thermal Power	10.76	12.2	kW
	Electric Power	2.69	4.4	kW
Thermo-well (3)	Volume	8.61	8	m3

Notes:

Every data used in the mathematical model refers to the most critical month of the year (January).

(1): Thermal surface must be oversized in practice (as shown). The temperatures are heavily influenced by the weather. Output water can reach much higher temperatures in particular sunny days, as it may happen that the output water has no significant temperature variation in particular cloudy or rainy days.

(2): The thermal power of the heat pump is the power required to guarantee the water heating in the heating plant right in the period when it's needed.

The electric power absorbed by the heat pump is oversized to make the pump work with higher temperature differences (fewer COP). Besides, in the house, the electric power includes the power required to make the hot water circulate in the heating plant.

(3):The thermo well volume in the model is the volume needed to stock the whole thermal energy by insolation during a day (using a temperature difference of 10 °C). So the well is already oversized in the model.

The geometric dimensions (diameter and height) of the well will be chosen on the base of the purpose the well has mostly to reach (exchanger or storage).

5. ADVANTAGES AND INNOVATIVE ASPECTS

At present, almost the whole of the sanitary water and heating plants, based on the thermal solar technology, are not able to provide entirely to the energetic requirements of a flat in the coldest months of the year. Usually it is proposed a solution based on the simultaneous use of the thermal solar panels with a traditional boiler during the winter season, despite of the average solar radiation is enough to meet the energy requirements in any month of the year. This because of the impossibility to receive a power adequate to the human necessities in any moment in which it should be necessary. For example, it should be impossible to switch off the heating plant for 3 consecutive rainy days. Therefore, it can be stated that the most innovative component is the thermo-well, that has the possibility to store the energy in surplus during sunny days and to recover it afterwards, in case the primary source is lacking. It should be noted that the gravel has a specific heat that is about the half of the specific heat of the water, but its density is almost double. The result is the possibility to store the same heat quantity of an equal water volume. It should also be noted that the thermo-well is contained in a reinforced concrete structure, a heat conductor that allows the interactions with the surrounding ground, that becomes an energy stock.

In summer, when the target is the heat dispersion the well becomes a cold source, as the subsoil has a lower temperature with reference to the external environment. It has also another advantage in its capacity to be an excellent heat exchanger of limited dimensions. The gravel pebbles have a thermal conductivity double respect the conductivity of the water and the well configuration allows an high exchange surface. Besides, the water filters in the gravel, in order to cross the well slowly. In this way, the water in output from the well has joined the thermal balance with the subsoil.

The little dimensions of the well are an advantage in respect of the traditional geothermic drills. As a matter of fact, the geothermic drills with horizontal development requires an extended surface (not always available) and there are limitations for its use (for example it is not possible to plant trees); there are also high costs for the earth moving. The vertical drills have not this problem but requires a deeper excavation, that implies high costs.

In conclusion, we believe that the system, presented in this paper, shows several advantages respect to the traditional ones and, therefore, it is worth to continue the research in order to optimize it.

6. ACKNOWLEDGMENTS

The authors would like to thank Ing. Angelo Zuliani and Dr. Luigi Andreoli for their effective support.

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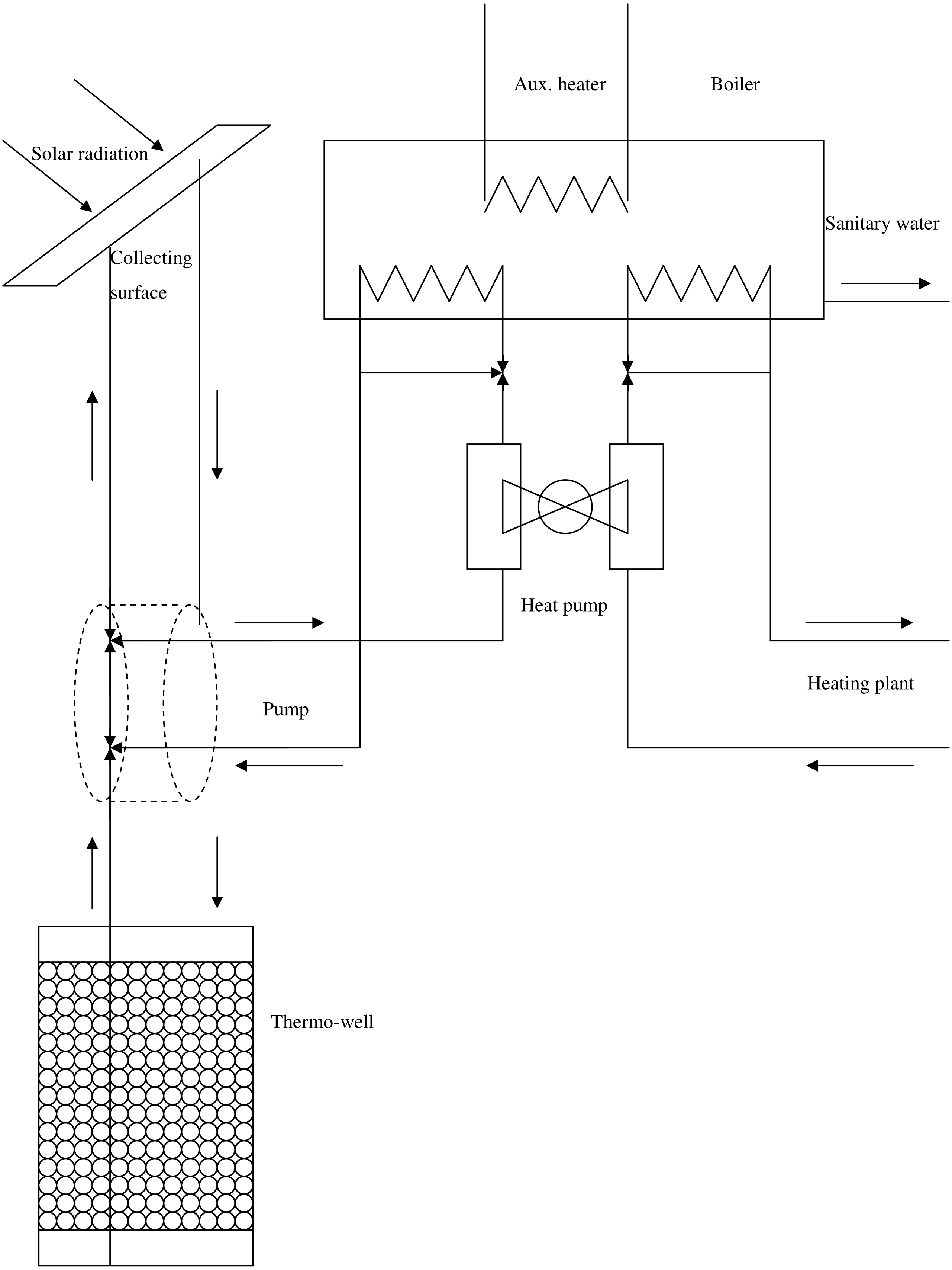
Figure 1


Aux. heater
Boiler
Solar radiation
Sanitary water
Collecting surface
Heat pump
Heating plant
Pump
Thermo-well