Endothermic Technology for Energy Efficient Housing

Francesco Piccininni*, Gurvinder S. Virk†,

* Department of Environmental Engineering and Sustainable Development
Politecnico di Bari
Viale del Turismo, 8 74100 Taranto  Italy

† Institute of Technology and Engineering
Massey University
Wellington, New Zealand

Abstract: - This paper presents a new solar-assisted heat pump technology for domestic houses based on endothermic panels that integrate within the fabric of the building to provide effective space heating and cooling. The main components in the system are described and the setting up of the demonstration system built at Thermal Sciences Laboratory of the second Engineering Faculty of the Technical University of Bari in Taranto is presented. Initial operational results from the system are presented to show that the technology is effective in collecting and dissipating large quantities of energy so that high coefficients of performances are achieved.

Keywords: solar assisted heat pump, energy saving, unglazed solar collectors, thermal plant simulation, TRNSYS

1. Introduction

The project introduced in this paper investigates new endothermic space and water heating systems which collect freely available energy from the surrounding environment. These systems have been developed as particularly promising additions to the generic set of devices known as active solar heaters, or solar-assisted heat pumps. It is expected that the widespread application to a variety of sectors over broad geographical areas would considerably alleviate the greenhouse effect while simultaneously providing economical space and water heating as well as summer cooling.

Endothermic systems consist of three essential components: an energy collector (roof mounted water-bearing cladding absorbing solar energy, i.e., an energy roof), an energy converter (heat-pump) and a heat store (normally a hot water storage unit). The unique feature of the endothermic heating system is the combination of an integrated energy collection system (that doubles as the roof as well) with a heat pump to provide a high efficiency for the overall system.

This work investigates the potential of using innovative thermal energy panels that can be used to collect and dissipate heat in order that the operation of heat pump based systems can be enhanced. It is well known that the coefficient of performance of a heat pump is governed by the Carnot cycle Law and so it is beneficial to ensure that the temperature difference between the heat source and heat sink is as small as possible.

This paper presents a novel solar-assisted heat pump system technology that is capable of ensuring that the minimum temperature difference is maintained thus leading to the highest COP. The technology is being developed under an EC funded project Endohousing where the technology is being investigated at the EU level. The technology uses unglazed solar collectors for not only collecting thermal energy when needed for space heating but also to dissipate excessive heat when used in space cooling situations. The Endohousing project is investigating the potential of this technology to provide space heating and cooling and hot water in domestic houses throughout different parts of Europe.

The technology has potential to reduce the energy consumption in domestic houses and its widespread adoption in housing throughout the EU as well as other sectors could have would considerably alleviate the greenhouse effect providing at the same time economical space and water heating.

2. Overall system and methodology

The project investigates the potential of using solar assisted endothermic systems (solar assisted heat pumps) with high COP to make major savings in the consumption of primary forms of energy while providing...
full space heating and cooling and the hot water requirements for domestic houses in different regions of the EU throughout the year. The approach is to use a novel integral solar collector that forms the entire roof of the house so as to blend into the surroundings. The objectives are to formulate a linkage between the energy requirements and the design parameters for selecting and sizing the components of the endothermic system, to design, set up and demonstrate six test endohouses in different climatic regions by detailed monitoring over long periods covering the heating and cooling seasons and to assess and generalise the performances of the technology for widespread use in the EU.

The endothermic system has five main components. These are as follows:
1. Integrated solar panels
2. Thermal energy stores
3. Heat pump
4. Controller
5. Energy distribution system

It is useful to describe each of these components in order to obtain a full appreciation of the technology.

2.1 Integrated solar panels

The system uses unglazed solar panels with profiles shapes that can be integrated into the building to form the entire the roof; in this way the panels blend into the surrounding and do not appear as ugly after thought add-ons. The panels are manufactured from hollow aluminium extrusions through which heat transfer fluid is circulated.

Figure 1 - Endothermic system schematic

These solar panels are used in both heating and cooling situations to optimise the operation of the overall systems and for this purpose they are called collvectors to highlight their dual functionality of collecting energy (collectors) and dissipating energy (convectors).

The roof balance is:

\[ Q_{\text{roof}} = A \alpha S_{\text{rad}} - Ah(T_{\text{roof}} - T_{\text{air}}) - Ah_{\text{HTF}}(T_{\text{roof}} - T_{\text{HTF}}) - A\sigma\varepsilon(T_{\text{roof}}^4 - T_{\text{rad}}^4) \]  

Figure 2 - The special plank designed and constructed for the experimental plant.
conducted to the heat transfer fluid (HTF). The $T_{rad}$ value is function of air temperature and of the clouds.

### 2.2 Energy stores
The system comprises two energy stores, namely low and high temperature stores. Energy is normally collected via the collvectors and stores in the low temperature store (cold store) but it can be passed directly to the high temperature store (hot store) if the water temperature is high enough. The size of the thermal energy stores has to be designed to allow sufficient energy to cover the needs of the house for some period.

The availability of solar energy, the thermal energy requirements for space and domestic hot water heating are variable along the day. The system accumulates thermal energy generated by heat pump through he condenser, hot tank, and the evaporator, cold tank, in order to compensate the temporal phase-difference between the availability of energy and the moment in which the heat must be supplied to users. The amount of the volume of the tanks assigned to accumulate responds to contrasting requirements.

In order to acquire the right thermal level quickly both when the solar radiation is available and/or when the heat pump is operating, the mass of reservoir water must be relatively small; vice versa, in order to maintain the thermal level during the supply of energy to the heating system it requests the thermal mass must be relatively high. The assessment of the correct dimension can be evaluated as result of the measure of the thermo-physical characteristics of the components of the thermal system.

The temperature variation of the cold tank ($\Delta T_S$) depends on the thermal global transmittance of the house ($U_H$), the amount of the surfaces of the walls ($S_W$), the temperature difference between internal ($\Delta T_{int}$), and the external one ($\Delta T_{air}$). The amount of this power, through the value of the COP, influences the amount of the heat rejected from the cold tank whose thermal level depends by the water mass (M). Also the thermal energy from the solar radiation, if available, is taken into account. The mass flow (mf) collects thermal energy crossing the solar collector from inlet temperature ($T_{inSC}$) to output temperature ($T_{outSC}$). The COP value depends on the temperature of the cold tank ($T_{CT}$), by means of the following relationship:

$$\Delta T_S = U_W \cdot S_W \cdot (T_{in} - T_{out}) \cdot \left(1 - \frac{1}{\text{COP}_{TCT}} \right) m_{sc} \cdot c_{sc} \cdot (T_{outSC} - T_{inSC}) \cdot \Delta r$$

### 2.3 Heat pump
The heat pump is connected between the cold and hot stores and operates with these as the heat source and sink respectively.

The Endohousing system consists of several components such as hot and cold stores, the Endoplanks, the heat pump, the distribution system, the control system and the building itself; in addition the effects of the climate is very important. The most important parameters coming out of a heat pump model is the heat pump’s performance. In this respect, the two most important parameters are the COP (coefficient of performance) and the heat capacity, HC. The driving energy is here denoted EE and the COP is given with the following simple equation $COP = HC/EE$

Heat pumps are strongly favoured by a low operating temperature lift. A rule of thumb is that an increase of the heat source temperature by 1K leads to a performance benefit of 3%. The similar “gain” from lower heat sink temperature is 2% for 1K. The performance limit is rather given by the second law of thermodynamics that give the limit for efficiency from the temperature lift of the cycle.

The heat pump exchanges heat with the external in order to obtain high values of the coefficient of system performance (COP) and to supply the complete energetic requirement for air conditioning of the domestic rooms and for the domestic hot water all year round.

### 2.4 Controller
A system efficiency depends on the temperature of the two tanks that are the heat source and the sink one. In this way the temperature of the hot tank is influenced by the availability of solar energy (input) and by the energetic needs for the house conditioning and the domestic hot water (output). All these energetic exchanges are variable around the day independently one to another. So only an electronic controller may be able to control and drive all the active components like water pump and three/two way valves following an appropriate control strategy.

The controller is used to operate the overall system to transfer the thermal energy during the three main modes, namely heat collection/dissipation, heat upgrading and energy delivery.

The controller uses Ethernet and TCP/IP networking technologies. It incorporates a web server which can deliver user-specific web pages to a PC or mobile device running internet browser software. If a system is set up with the correct connections, a user with the appropriate
security codes can monitor or adjust the controller from any Internet access point in the world. It is also compatible with the traditional Trend protocol. A local PC or display (SDU-xcite) can be connected via the RS232 port.

2.5 Energy distribution system
The endohousing system can be used for space heating and cooling and for hot water. The cooling is provided by using the cold store whereas the hot store provide the heating and the domestic hot water.

The low temperature heat source for the heat pump in the standard ENDOHOUSING circuit layout is the solar heat collected by the Endoplanks, and provided via the collector fluid to the low temperature storage tank. The heat pump is then intended to use the thermal storage tank’s medium as heat source for its own low temperature side. So, in case of the solar irradiation being inadequate a complementing heat source for the heat pump may be provided.

Floor heating is an attractive choice of heat distribution method in conjunction with domestic heat pumps. Floor heating operates almost exclusively with free convection, as the temperature difference between floor surface and ambient air is small and the surface area is, comparatively, huge. Suitable energy delivery units can be used for this. For example, space heating can be provided by circulating the hot water through under floor heating coils and cooling through ceiling mounted chilled water pipe work.

3. Heat pump optimized operation
Figure 1 shows a schematic of the full system showing the main hardware components and the controller will be discussed here to show how the three modes of collection/dissipation, heat upgrading and energy delivery are carried out.

The system essentially comprises 3 main components, namely:
1. An energy collection system: this harvests freely available thermal and solar energy from the environment and transfers the collected energy to either the domestic hot water cylinder, the hot store or the cold store.
2. An energy upgrading system: this part of the system uses a heat pump to upgrade the low grade thermal energy to useful temperatures for space heating and cooling and for hot water. The heat pump also has a back up energy system in severe cases when insufficient thermal energy is collected from the environment.
3. An energy delivery system: this delivers the useful thermal energy where it is needed in the house using the most appropriate method. The energy for the space heating and hot water is provided from the hot store or directly from the heat pump which takes it from the cold store (or the back up). The cooling is provided by using the chilled water from the cold store.

The parameter normally used to compare heat pumps efficiency is the coefficient of performance (COP$_{HP}$) that measures the ratio between the heat output and the energy used to drive the machine.

In this configuration account also of the heat supplied from the solar collector to the hot tank is possible to define the heating system effectiveness using the classic relation of the COP of the heat pump linking and/or the increment of efficiency whit the increase of temperature of the evaporator due to the heating of the cold tank.

With the same electric power and mass flow of the fluid, an increased temperature difference is had that it is equivalent to increase the thermal flow. Indicated with $Q_c$, the supplied nominal thermal flow from the condenser, $Q_E$ the flow which had to the increment of efficiency and $Q_s$ the flow picked up from the solar collector we can express the following system effectiveness endohousing with relation: Through the
system they experiments is possible to estimate directly the heat picked up from the solar collector and sum \((Q_E\) and \(Q_S\)) that it is the energy supplied from the condenser. The system uses unglazed solar panels with profiles shapes that can be integrated into the building to form the entire the roof; in this way the panels blend into the surrounding and do not appear as ugly after thought add-ons. The panels are manufactured from hollow aluminium extrusions through which heat transfer fluid is circulated. Figure 1 shows a flat and bold roll profile that has been designed.

The proposed system uses a solar-assisted heat pump system to provide an efficient method for supplying the thermal energy for space heating and hot water production in buildings. When only the heat pump works the COP expressed by (1) coincides with the typical heat pump COP:

\[
COP_{HP} = \frac{Q_C}{EE_{HP}} \quad (4)
\]

When the unglazed solar collector works, the denominator is added of the harvested heat, \(Q_S\), and the denominator is added of the electrical power for circulation water pump.

\[
COP_{heating} = \frac{Q_C + Q_S}{EE_{HP} + EE_{WP}} \quad (5)
\]

The third component come from the efficiency increase due to the higher temperature of the cold tank. The heat pump efficiency is higher as lower the temperature difference between the sink and the source. This is easy to see with the Carnot heat pump efficiency expression:

\[
COP_{Carnot, HP} = \frac{T_H}{T_H - T_L} \quad (6)
\]

Heat pumps work by extracting thermal energy from a low temperature \((T_L)\) source and upgrading it to a higher temperature \((T_H)\) sink. Fixed the higher temperature \(T_H\), higher the low temperature \(T_L\) higher the efficiency. The same way is for real machinery. In the figure 4 is shown the relations between the temperatures of the source and the sink.

For real machines, the relevant technical I/O curves characteristic curves, factory provided, show the relationship among the evaporator inlet temperature, the condenser inlet temperature and the value of \(COP\), as reported in Fig.4.

To the aim to take advantage of, from a thermodynamic point of view, the energy available, the system endohousing previews to use also the energy picked up from the collector even if has not sufficient a thermal level to heat the warm tank. In this case the collected thermal flow from the collector oriented to south comes supplied to the cold tank, that one connected with the evaporator of the heat pump. The consequent thermal elevation provokes an increment of the efficiency of the heat pump, like indicated from the COP of pump of operating heat second an inverse cycle of Carnot. The Endohousing system from the possibility to use energy to low thermal level in order to increase the performances of the system. This involves an increment of the performances of the system because the energy
supplied to the cold tank is free energy. The energy is defined free when, if not used at the moment of its availability, it is however lost; that is does not involve some production of entropy.

In the cooling configuration, the useful thermal energy is available in the cold tank that exchanges heat with the evaporator.

\[
EndoCOP_{\text{cooling}} = \frac{Q_{E,F} + (Q_E + Q_{S,DHW})}{EE_{HP} + EE_{WP}}
\]  

4. TARANTO ENDOSITE

4.1 The house

The endosite, in Taranto, is the home of the caretaker who occupies the house with his wife and his son. The house is situated inside of the property of the Faculty of Engineering and has been constructed with the same characteristics as the buildings of the university. It is occupied all year round and it contains a heating system and an air conditioning system.

A 120 m² of pitched roof was built on the house of the caretaker of the Engineering Faculty. The power station is located close in order to reduce the length of the pipeline connecting the planks to the rig of the tanks and the heat pump controlled by a controller. On the top of the roof are assembled the weather station and the pyranometer. By chance the two parts of the pitched roof are oriented to north and to south. In this way shall be easier to use the first half roof for the cooling and the second for heating. In Fig. 6b is shown the whole pipelines of the thermal plant in Taranto, the manifolds for regulating and the connections from and to the hot store and the cold one.

4.2 Design

The performances of the energy supply plant have been investigated by means of dynamic simulation code, TRNSYS [8]. It simulates the hourly performances by means of several FORTRAN subroutines, called types, which are linked together in order to model a thermal system. Each subroutine calculates the heat and the mass flow interactions. In Fig. 6 is shown the TRNSYS scheme of studied thermal plant.

Simulations performed using average climatic data relevant to Taranto area. The hourly weather data, as solar radiation, dry bulb temperature, humidity ratio and wind speed, are generated by type 54. This type generates hourly weather data given values of radiation, humidity and temperature of the specified location, [7]. The monthly average weather data are taken from an external data file, called “wadata.dat”, in which the user can add data for his specific location to the end of the file. The data are generated in a manner such that their associated statistics are approximately equal to the long-term statistics at the specified location.
An other important component used in the system simulation is the type 668. This component models a liquid-to-liquid heat pump (typically water to water). The model relies on user-supplied data files containing the heating and cooling capacity and power requirements at different source and load temperatures. The type 668 was linked with two types 60, representing the cold and the hot storage tank. The cold storage tank is linked with the evaporator of water-water heat pump, while hot tank is linked with the condenser of heat pump. Type 60 models the thermal performance of a water-filled sensible energy storage tank, subject to thermal stratification.

4.3 First results

The first campaign of measures carried out with the experimental system has allowed to estimate the performances of new conception components. The determination of the operational parameters has the aim to assess the values in order to set up the simulation program so have greater accuracy their behaviour. The same had been made for the heat pump. Observing numerous operational cycles they have been estimated the values of COP in function of the temperature difference between of the source and the sink. First results are shown in Figure 7. The choice of the heating system, as fan coil, radiator or radiant panels, determines the temperature of water supplied by heat pump. The amount of energy consumption can be evaluated through the values of the COP established by the evaporator inlet temperature, $T_L$, as below reported:

$$ COP_{HP} = 0.92 \cdot \ln(T_L) + 2.3 $$  

(8)

The logarithmic equation (8) of heat pump’s COP was determined by the real machines’ characteristic curve, factory provided, with a condenser outlet temperature of 45 °C.

In order to increase the effectiveness of the heat pump, the thermal system under study uses the south oriented pitched roof as unglazed solar collector to supply thermal energy to cold the tank of the plant cooled by the evaporator of the heat pump. In this way, the inlet temperature of evaporator and the heating power increases and so the system effectiveness (COP) improves.
Fig. 7 – Result of the simulation of the temperatures distribution, upper draw. Below, the start up of the experimental plant for assessment the thermal performances of the alloy planks.

5. Conclusions

The development and the characterization of an innovative heating system with high performances in terms of efficiency, has been proposed implemented in order to manage and control all quantities relevant to the plant. The main parameters influencing the efficiency of the system have been identified. An opportune control strategy allows to take advantage of dynamics of the thermal system, of the solar energy and of energetic needs in order to take advantage from the available solar energy to use the energy, if not directly usable, to increase the efficiency of the heat pump. The opportunity to use an unglazed solar collector that looks like a roof with tiles allows to insert the solar collector harmonizing it also in the refurbishing of buildings.

Fig. 8 – The average temperature of the hot tank and the cold one (a) and the HP’s efficiency (b).

The carrying out of several measurements allowed quantifying the thermal characteristics of the whole components of the thermal plant in order to set up a validated simulation code for designing.

References

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Nomenclature

- A: Area of roof, [m²];
- ADW: Actual Domestic hot Water flow mass, [kg/s];
- cHTF: Specific heat capacity of HTF, [J/kg°C];
- EEHP: Electrical energy supplied to heat pump, [W];
- EEWP: Electrical energy supplied to water pumps, [W];
- h_air: Convective heat transfer coefficient, [W/m²°C];
- HC: Heating Capacity [kWh];
- hHTF: Heat transfer coefficient of HTF, [W/m²°C];
- HTDW: Hot tank to Domestic Hot Water;
- MCT: Cold tank fluid mass, [kg];
- MISC: Solar collector mass flow, [kg/s];
- MHT: Hot tank fluid mass, [kg];
- Qc: Heat power supplied by heat pump’s condenser, [W];
- QE: Heat power due to COP increase, [W];
- QEVA: Thermal power exchanged at evaporator of the refrigerator, [W];
- QS: Heat power harvested by unglazed solar collector, [W];
- Qs_DHW: Solar energy for domestic hot water, [W].

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