DESIGN, MODELING AND PERFORMANCE OPTIMISATION OF A REVERSIBLE HP-ORC PROTOTYPE

Sylvain Quoilin, Olivier Dumont and Vincent Lemort
University of Liege
Chemin des chevreuils 7, 4000 Liege
Belgium
e-mail: olivier.dumont@ulg.ac.be
Web page: http://www.labothap.ulg.ac.be

EXTENDED ABSTRACT

INTRODUCTION

Building is one of the economical sectors where solutions are available to significantly reduce energy consumption and greenhouse gases emissions. Among other, heat pumps offer promising perspectives to provide energy-efficient space and sanitary hot water heating in many applications. This paper presents an innovative system comprising a heat pump connected to a solar roof and a geothermal heat exchanger. This heat pump is also able to invert its cycle and operate as an ORC. By using the whole rooftop (hereunder called “absorber”) as a heat source, a large amount of heat is generated throughout the year. This heat is used in priority to cover the building annual heating needs and the surplus heat generated during the summer is utilized to generate electricity in the so-called HP/ORC module. The same module can be used during winter as an efficient heat pump which radically reduces the complexity of the total system. The main advantage of the proposed technology is due to the reversibility of scroll machines, which have proven to operate efficiently both as compressor and as an expander in lab testing.

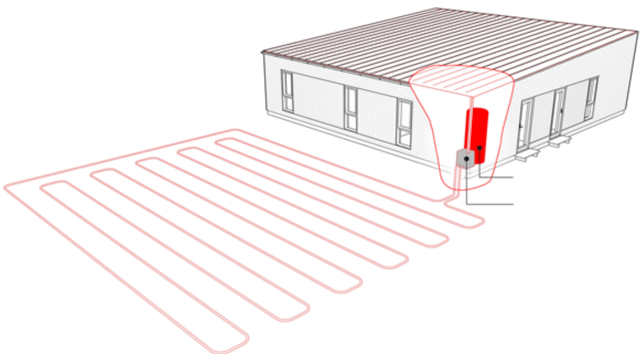

Figure 1: Illustration of the Innogie concept: the reversible HP-ORC module is inserted in a building between a solar roof and a geothermal heat exchanger

OPERATING MODES

Three different operating modes are considered depending on the weather conditions. The system is assumed to be controlled in such a way that the transition is performed smoothly between these different modes using ambient temperature sensors, state of charge of the storage (a stratified water tank), solar insolation, day of the year, etc.

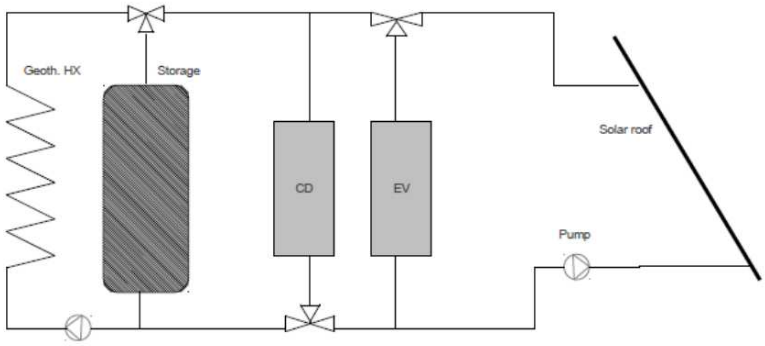

Figure 2 Integration of the HP-ORC into the overall system (NB: for the sake of clarity, only the condenser and the evaporator of the HP-ORC unit are shown).

Direct heating
The heat flows from the absorber to the storage/consumption via an intermediate exchanger.

ORC mode
Whenever thermal energy is available in the absorber, the ORC is activated as long as the storage can cover space and DHW heating requirements. In the case where heating requirement are not met, the direct heating mode is activated in place of the ORC (in priority during low irradiation hours) until those requirements are satisfied. In this mode, the heat source (for the evaporator) is the solar roof and the heat sink is the geothermal heat exchanger (for the condenser).

HP mode
During winter months, when heating requirements exceed heat production by direct heating, the heat pump mode is activated. In this case the heat source (at the evaporator) of the cycle is the solar roof or the geothermal heat exchanger (if it is at a higher temperature) and the heat sink (at the condenser) is the building heating loop.

MODELING

In ORC mode, the model is the one proposed in [1], slightly modified to take into account a different heat exchanger configuration. The expander model is the one proposed by Lemort et al. [2], and validated with experimental data on a hermetic, lubricated scroll machine operating with R245fa. In this experimental campaign, the reversibility of the scroll compressor was demonstrated with a very promising maximum expander isentropic efficiency of 71% (including generator losses).

In heat pump mode, the heat exchanger models remain unchanged, but the pump is replaced by an adiabatic expansion valve model. The compressor is modeled using the EN 12900:2005 (E) European standard [3] with the empirical coefficients provided by the manufacturer.

DEFINITION OF THE NOMINAL CONDITIONS

ORC mode
Since the ORC mode is the one involving the highest heat flow through the cycle, it is the one selected to size the system components. A nominal sizing point is defined as follows:

- The evaporating temperature is set to 90°C, which approximately corresponds to the maximum pressure at the inlet of the expander.

- On the cooling water side, an inlet temperature of 15°C and an outlet temperature of 20°C are assumed.
- The heat source temperature glide, i.e. the difference between the inlet and outlet glycol water temperature on the absorber, is set to 25K in order to maintain a reasonable glycol water flow rate.
- The nominal pinch points are set to 5K for the evaporator and 7.5K for the condenser.
- The nominal superheating and sub cooling of the evaporator and the condenser are set to 10K and 2K respectively.

HP mode

For the heat pump mode, the following operating conditions are imposed:

- The evaporating temperature is selected as the equilibrium temperature when the heat pump thermal power is 8 kWth and when the solar insolation is 90 W/m² (representative of winter conditions in Denmark).
- The condensing temperature is fixed to 60°C in order to get a water temperature around 55°C at the inlet of the heat storage.
- For hot water production, a temperature difference of 5K is assumed between the inlet and the outlet of the condenser.
- The superheating and sub cooling of the evaporator and the condenser are set to 3 and 2K.

The heat exchangers, the pump and the expansion valve are sized using the nominal conditions. However, the size of the scroll machine (which defines the net power of the system, both in HP and ORC mode) results of a tradeoff between winter and summer conditions. This can only be optimized using yearly simulations, as proposed in the next section. The results presented in Table 1 for the nominal conditions have been obtained with the optimal expander size resulting from this optimization.

Table 1: *Main simulated nominal values for winter and summer conditions*

		ORC	**Heat pump**
Heat transfer fluid temperature in the absorber	[°C]	85.2/107.5	-6.7/-8.5
Thermal power through the absorber	[kW]	62.3	10.9
Condensing temperature	[°C]	27.2	60
Efficiency/COP	[-]	0.076	2.4
Net electrical power consumption/generation	[kW]	4.7	-3.2
Pump power consumption	[kW]	1.25	0
Required solar irradiations	[W/m²]	660.5	47

EVALUATION OF THE SEASONAL PERFORMANCE OF THE HP/ORC SYSTEM

In the previous section, the performance of the system has been evaluated on a nominal sizing point, allowing to select and to define the geometry of some components. However, as already mentioned, it is important to account for the performance of the system over a whole year when optimizing its design. In this section the system is modeled over the year by taking into account the average climatic conditions and the average building heat demand for each month. These simulations allow optimizing discrete variables such as the choice of the working fluid, the use of a recuperator, the size of the scroll machine (available sizes are taken from the manufacturer catalog). The following methodology is applied:

1. For a given configuration (fluid, expander size, recuperator or not), the system performance (in terms of thermal and electrical powers) is evaluated over a wide range of evaporation/condensation temperatures, both for the ORC mode and the HP mode.
2. Performance curves are derived from these simulations as a function of the system configuration and of the temperature levels.
3. These curves are implemented in the yearly simulation model, which optimally switches between the three operating modes depending on the weather and of the heat demand for the given month.

SIMULATION RESULTS AND CONCLUSIONS

This study proposes an innovative reversible domestic heat pump/ORC system, allowing for both heat and electricity production depending on the weather conditions. The proposed system is based on an experimental study carried out at the Thermodynamics Laboratory of the University of Liège and demonstrating the reversibility of scroll machines. This study furthermore allowed modeling those machines with realistic efficiency curves based on lab measurements.

A model of the system has been developed to assess the power consumption/generation of the prototype over different operating points. A second model has then taken profit of these simulation results to evaluate the system performance over one year and to optimize its design in terms of component sizing, working fluid and architecture.

Simulations of the HP/ORC system, with the components optimally sized, indicate that, in ORC mode, the electrical energy produced over one year reaches 4030 kWh and the monthly efficiency of the cycle varies between 4.3 and 6.4%. The monthly COP of the heat pump varies from 2.6 to 3.3, for a yearly electrical energy consumption of 527.3 kWh. The direct heating mode provides 62.3 kWh of heat throughout the year.

The second phase of the project consists in the practical experimentation of the system. A prototype has been built and will be tested in the coming months, allowing validating the above models and confirm the performance prediction.

ACKNOWLEDGEMENTS

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