Simulation Based Assessment of Heat Pumping Potential in Non-Residential Buildings – Part 1: Modeling

Stephane Bertagnolio[1], Pascal Stabat[2], Benjamin Soccal[1], Samuel Gendebien[1] and Philippe André[3]

[1]Thermodynamics Laboratory, University of Liège, Liège, Belgium
[2]Centre Énergétique et Procédés - Mines Paristech, Paris, France
[3]Departments of Environmental Sciences and Management, University of Liège, Belgium

Corresponding email: stephane.bertagnolio@ulg.ac.be

SUMMARY

This paper is the first one in a series of three papers presenting the assessment methodology of heat pump systems developed in the frame of the IEA-ECBCS Annex 48 project. A package of simulation tools is developed in order to assess the energy and environmental performances of the reversibility and heat recovery solutions dedicated to space heating and cooling of non-residential buildings. This paper presents the development of such tools and their implementation in an equation solver.

INTRODUCTION

Environmental concerns and the recent increase of energy costs open the door to innovative techniques to reduce energy consumptions. Buildings represent between 20% and 40% of the total final energy consumption in developed countries [1]. Non-residential buildings are part of the main energy consumers and improvement of their energy performance is a major challenge of the 21th century.

A solution to reduce the energy consumption in residential and non-residential buildings consists in better exploiting the potential of the heat pump technology. The heat pump market was, till now, concentrated on residential buildings. Now, attention is given to (new and existing) non-residential buildings, where heating and cooling demands co-exist. The possible applications of heat pumps in non-residential buildings consist in recovering heat at the condenser when the chiller is used to produce chilled water (simultaneous heating and cooling demands) or in using the chiller in heat pump mode (non-simultaneous heating and cooling demands). Both strategies appear particularly feasible when cooling and heating needs and the heat pump technology are, at least partly, present in the building, which is often the case in the tertiary sector. The analysis of these reversibility and recovery potentials is one of the subjects of the IEA-ECBCS Annex 48 project [2].

A package of simulation tools is developed in order to assess the energy and environmental performances and costs of such solutions. A first tool allows a quick estimation of the potential of recovery and reversibility options. It consists in comparing computed or measured hourly values of heating and cooling system loads and to compute theoretical reversibility and recovery potentials (Figure 1). Hourly heating and cooling system loads can be generated by means of a calibrated building energy simulation model or obtained through in-situ measurements. This first evaluation allows the user to make a first selection between the available reversible and recovery systems.

A second tool allows to simulate the behavior of the selected heat pump system and to compute its performances using the previously computed hot water and chilled water demand profiles (at distribution network boundaries) as inputs (Figure 1). Only a few parameters are asked to the user (HVAC components rating performance, CO2 emissions per kWh of electricity, weather data…). The considered heat pump configuration is then compared to a classical primary HVAC system (composed of a boiler and a chiller) in terms of final and primary energy consumption, CO2 emissions and costs.

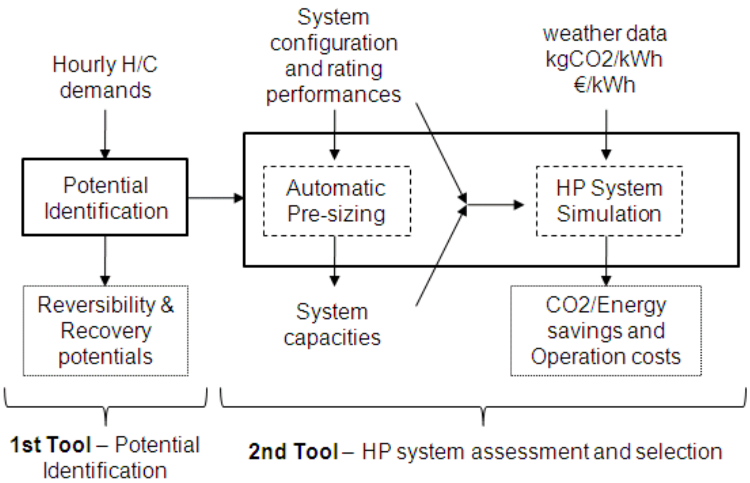


Figure 1. HP system assessment methodology

In this first paper, the development of such models and their implementation in an equation-based solver are described. The considered heat pump configurations are presented and the models of the main components (heat pump, boiler, thermal storage system, cooling tower and ground heat exchanger) are presented. Five general configurations are considered for now: (1) reversible air-to-water heat pump with back up boiler, (2) exhaust air heat pump with back up boiler, (3) dual condenser heat pump with back up boiler, (4) water loop systems and (5) ground coupled heat pump systems.

A parametric study on the European building stock and the application of such tools to a case study buildings are presented in both companion papers.

REVERSIBILITY AND RECOVERY POTENTIALS

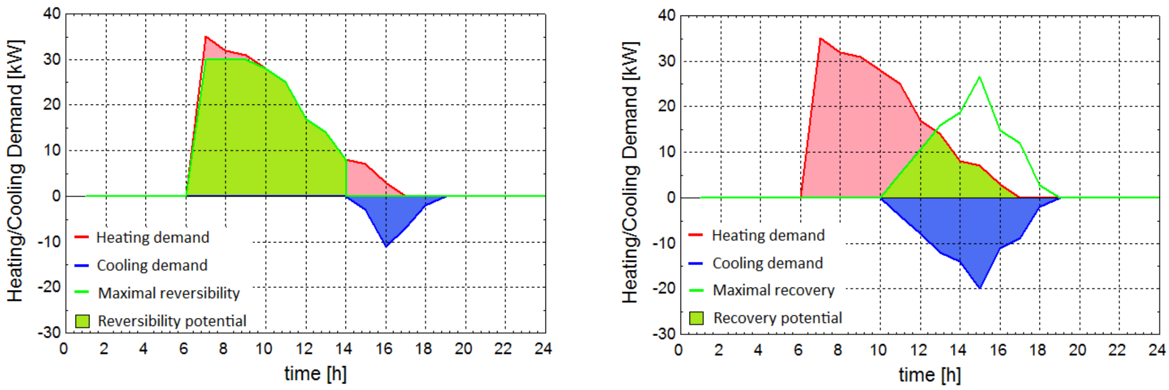
The reversibility potential (Figure 2) is defined as the percentage of heating demand which could be provided by a chiller operating in heat pump mode in the following conditions:

- Priority is given to "cooling" at every moment and the heat pump can operate in heating mode only if there is no cooling demand.
- The chiller/heat pump is sized to meet the peak cooling load
- The heating capacity of the heat pump in actual operating conditions is approximately 80% of the cooling capacity in rating conditions.

The recovery potential (Figure 2) is defined as the percentage of heating demand which could be provided by a chiller condenser in the following conditions:

- The chiller is in operation to provide the cooling demand
- The chiller is sized to meet the peak cooling load

- The maximal heating power available on the condenser is defined as : (EER+1)/EER * Cooling Power
- The remaining demand is assumed to be covered by back up boiler.



a) b)

Figure 2. a) Reversibility potential and b) Recovery potentials

CONSIDERED HEAT PUMP SYSTEMS

System 0: Classical separated heat and cold production system

This system will be used later as a reference for the other ones as it represents the simplest way to satisfy cooling and heating demands. The two hot water and chilled water networks are completely separated; they are respectively supplied by the boiler and the air-cooled or water-cooled chiller.

System 1: Reversible air-to-water heat pump system

This system is composed of a reversible air-to-water heat pump, a backup boiler (not represented in Figure 3) and circulation pumps. The heat pump can be reversed by means of a refrigerant change-over (4 ways valve) which inverses the flow in the refrigerant circuit.
The reversible unit is installed in combination with a backup boiler, for the following reasons:

- To supply heat when heating and cooling loads are simultaneous.
- To complete the heating load when the capacity of the heat pump is limited due to the limited capacity of the unit caused by an under-sizing of the unit or a too low outdoor temperature.

System 2: Exhaust air heat pump system

Exhaust air represents a very interesting heat source because of availability, good coincidence with needs and its very constant temperature. Condensing the water contained in extracted air allows recovering part of the latent energy and increases the heat source capacity.

This system includes a water-to-water heat pump, a cooling tower, a backup boiler and circulation pumps and uses the exhaust ventilation air as a heat source for the heat pump (Figure 3). This type of heat pump can achieve a good performance level as the temperature of the source is quite constant. Because non residential building demand could be quite large, the exhaust air flow could be an insufficient heat source. In that case an additional heat source (backup boiler) is required. The heat pump is not reversible and each water network is independent.

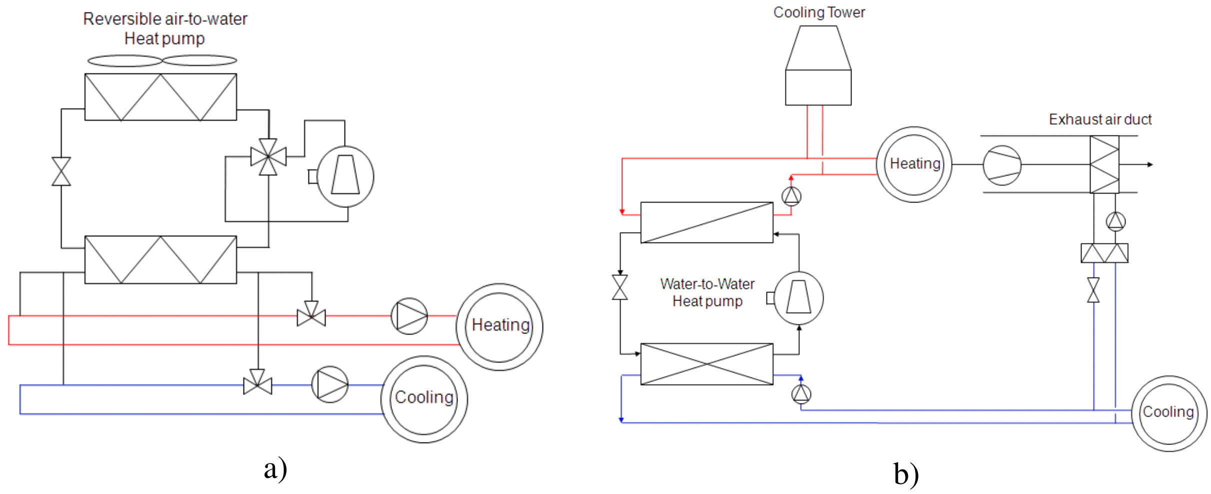


Figure 3. a) Configuration 1: Reversible air-to-water heat pump. b) Configuration 2: Exhaust ventilation air heat pump (backup boiler is not represented)

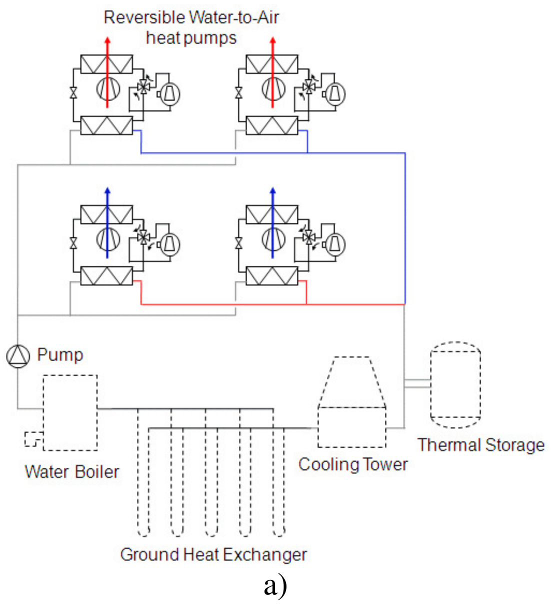
System 3: Dual condenser heat pump system

There are many configurations of dual condenser systems [3], only double-bundle condenser system is considered in the present work. The double-bundle heat pump includes two individual condensers: one air-cooled condenser and one other one water-cooled condenser installed in parallel. This type of heat pump system allows heat recovery, since it can provide simultaneous heating and cooling demands but does not allow reversibility (no auxiliary heat source for heat pumping). Refrigerant gas from the compressor flows into condenser shells, allowing heat rejection to one or both condensers. Usually each condenser is sized for full heat output of the heat pump.

System 4: Water loop heat pump system

A water loop heat pump system is made of several reversible water-to-air heat pump units, each serving a zone, connected to a closed water loop circulating throughout the building (Figure 4). Each heat pump unit uses the water loop as heat source/sink rejecting or absorbing heat to/from it. The main advantage of this system is that balanced simultaneous heating and cooling demands, and corresponding absorbed and rejected heat flows, can keep the temperature of the loop in a certain range (usually between 16°C and 32°C, [4]) without requiring need for an additional heat source/sink system. If the temperature exceeds the upper limit, a heat rejector (e.g. a cooling tower) must be switched on. In the opposite case, a heat source is used (e.g. a gas condensing boiler or an electrical boiler) even if it results in production of heat at low temperature.

Hybrid configurations combining ground heat exchangers with a standard heat source (boiler) or a heat rejector (cooling tower or dry fluid cooler) are also considered. Three configurations are considered in the present work: (1) water boiler and heat rejector; (2) water boiler and ground heat exchanger (heating dominated case); (3) heat rejector and ground heat exchanger (cooling dominated case). When ground heat exchangers are not used, adding a thermal storage allows a better use of the water loop: the water loop temperature remains longer in the appropriate range without operating the cooling tower or the boiler. A thermal storage of 50 to 100 kg of water per installed kW of cooling capacity is generally advised to perform the maximal energy savings [4].



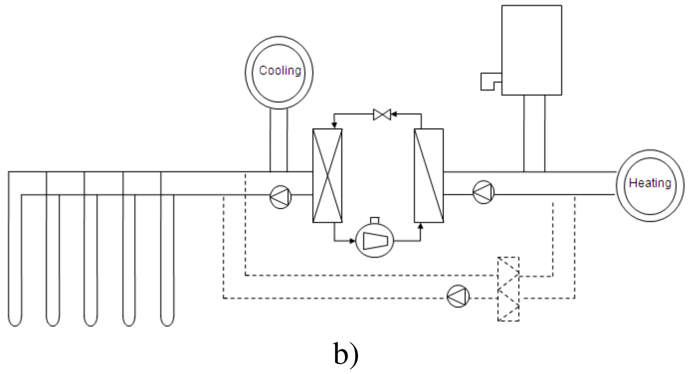


Figure 4. a) Configuration 4: Water loop heat pump system. b) Configuration 5b: Ground coupled heat pump for heating and cooling.

System 5: Ground coupled heat pump system

Two configurations are considered in the present work: (a) reversible ground coupled heat pump for alternate heating and cooling and (b) ground coupled heat pump for heating and cooling

The first system includes a geothermal borefield, a reversible water-to-water heat pump, a backup boiler and circulation pumps. The operation of the system can be reversed by means of a refrigerant change over (4 ways valve) which inverses the refrigerant flow in the two heat exchangers:

- Cooling mode: heat of the condenser is rejected to the ground and the evaporator transfers cold to the chilled water network.
- Heating mode: the evaporator absorbs heat from the ground heat exchanger and the condenser transfers heat to the hot water network.

A backup boiler is needed to supply heat when heating and cooling loads are simultaneous and to complete the heating load when the capacity of the heat pump is too limited.

The second system includes a geothermal borefield, a water-to-water heat pump, a heat exchanger, a backup boiler and circulation pumps (Figure 4). This configuration allows operation in both heat recovery (simultaneous heat and cold production) and reversibility modes (alternate heat and cold production). An additional glycol-to-water heat exchanger allows also direct "ground cooling" (without operating the heat pump, also called "passive cooling") if the ground-loop exhaust temperature is sufficiently low.

MODELING

The main hypothesis of the present methodology concerns the secondary HVAC system: secondary equipments are supposed to be adapted to operate with low temperature hot water (typically between 45 and 55°C). In the case of a building retrofit, the performances of the existing (or retrofitted) secondary HVAC system (AHU and terminal units) operating with low temperature hot water are not computed.

Heat pump/Chiller model

The chiller model uses performance curves identified based on manufacturer data [5]. The model uses three basic functions usable to predict the chiller consumption over a range of operating conditions (secondary fluids temperatures and percentage of load):

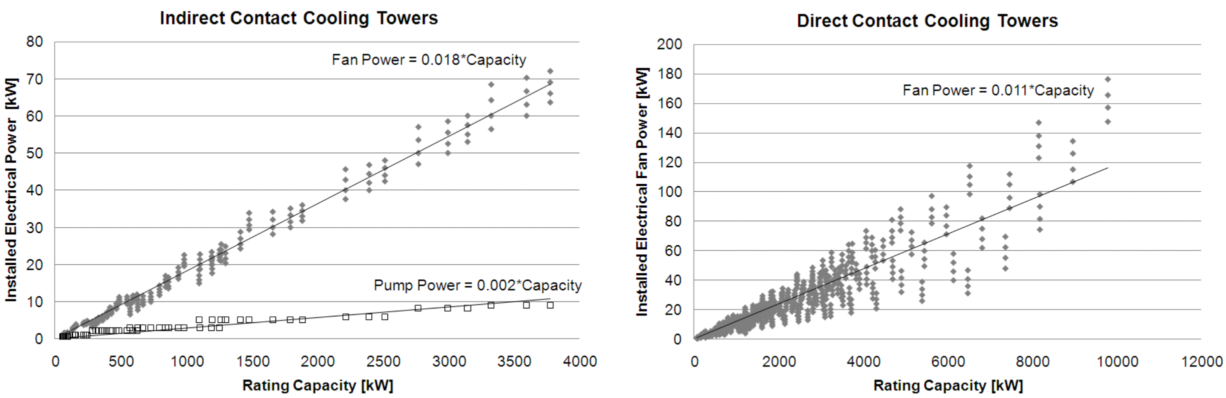
- Chiller capacity as a function of the operating conditions at full load;
- Electric power demand as function of the operating conditions at full load;
- Electric power ratio as function of part-load ratio.

Boiler model

The water boiler model uses part load regression laws generated by means of a reference heat exchanger based model adapted from [6]. Three types of water boilers are available: On-Off burners, High-Low-Off burners and Modulating burners. A condensing boiler model is currently under development.

Cooling tower model

Two semi-empirical models are used to simulate the behavior of the direct [6] and indirect contact cooling towers [7]. Both models rely on the Merkel's theory and epsilon-NTU method and aggregate the heat and mass transfers by using enthalpy [7] or wetbulb [6] temperature gradients to represent the temperature and humidity gradients. The indirect contact cooling tower model uses only two parameters: air-side and water-side thermal resistances. The direct contact cooling tower model uses a unique global heat transfer coefficient.



a) b)

Figure 5. a) ICCT catalog data. b) DCCT catalog data

The parameters of both models can be identified based on one or two rating points. If actual data are not available, regression laws based on catalog data can be used to estimate the rating fans and pumps powers as a function of the unit capacity (Figure 5). During the simulation, the values of the heat transfer coefficients identified in rating conditions are corrected to take into account of the actual operation of the unit (actual air and water flow rates) [6] [7].

Pump model

At the moment, pump power consumption is constant and equal to the rating value. Only the specific pump power (in W/kg/s) is asked to the user. Default values of specific pump power are given in Table 1.

Table 1. Specific Pump Power values

	W/kg/s	Source
Chilled water pump	350	[8]
Hot water pump	300	[8]
Water loop central pump	600 - 800	[9]

Water loop model

Thermal inertia of the water networks is generally neglected when simulating classical primary HVAC systems. In the case of water loop heat pump systems ("system 4"), the thermal inertia of the loop cannot be neglected because of the large amount of water present in the circuit. Once generally considers 11 to 14 kg of water per installed kW of cooling capacity [4]. The associated flow rate is generally between 0.027 and 0.054 kg/s/kW of cooling [10].

The inertia of the water loop is represented by an equivalent thermal capacity ($C_{w,loop}$) placed on the return side of the loop ($t_{w,return,loop}$), at the supply of the heat production/rejection plant ($t_{w,su,plant}$). The first order differential problem is represented by the following equations:

$$\frac{dU}{d\tau} = \dot{M}_w * c_w * \left(t_{w,return,loop} - t_{w,su,plant}\right) \quad (1)$$

$$\Delta U = \int \frac{dU}{d\tau} * d\tau \quad (2)$$

$$\Delta U = C_{w,loop} * (t_{w,cap} - t_{w,cap,0}) \quad (3)$$

$$t_{w,su,plant} = t_{w,cap} \quad (4)$$

Ground heat exchanger model

The analytical solution of the cylindrical heat source (CHS) problem is used to simulate the behavior of the ground surrounding the borehole and to compute the mean borehole wall temperature [11]. The superposition principle is used to apply the CHS model to variable heat transfer rate. A load aggregation algorithm is used to reduce the number of values stored and to decrease the computation time [12]. Heat transfer from the bore wall to the fluid is simulated by solving the equation system associated to three thermal resistances connected in series: grout thermal resistance, pipe wall thermal resistance and fluid convective thermal resistance. Supply and exhaust borefield temperatures are computed at each time. Since this model is used for only one-year simulations, no correction related to long-term effects (like interferences between boreholes or 3D effects) are taken into account at the moment.

Implementation

All the HVAC components simulation models are implemented in an equation solver [12]. Sizing rule-of-thumb values are used to identify the main parameters of the models (heat pump capacity, installed pumping power, ground heat exchanger length…) and to reduce the number of input values asked to the user to a minimum.

DISCUSSION

A series of simple simulation tools has been developed in order to allow quick and easy assessment of various heat pump systems adapted to non-residential buildings. More detailed simulation tools and longer simulation periods should be considered for advanced design issues (accurate sizing of the ground heat exchangers…). A selection of simple semi-empirical HVAC components simulation models have been done according to the following criteria: validated, robust, easy to parameterize and accurate. These simulation models have been implemented in an equation solver and connected to allow quick and robust simulations of heat pump systems. Default values of the considered parameters are proposed to the user when data is missing. Other heat pump systems, as variable refrigerant flow systems and templifier systems, are currently studied and will be modeled in a similar way.

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