COMPARATIVE ANALYSIS OF AIR-TO-AIR HEAT PUMP MODELS FOR BUILDING ENERGY SIMULATION

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ABSTRACT

The decrease of heat demands in the low energy buildings requires to reexamine modeling approaches in the building simulation, particularly the dynamic response of the building and its equipments lead to re-examine modeling rules. From a review of air-to-air heat pump models, three types are compared in order to evaluate the ability of each one to predict the energy consumption and power demands. These air-to-air heat pump models coupled to a single zone building are simulated on Modelica. The aim is to underline the advantages and the drawbacks of the different modeling approaches for dynamic simulation in respect of the different phenomena to represent.

KEYWORDS: Low energy building, building system performance simulation, dynamic simulation rules, air-to-air heat pump, Modelica

INTRODUCTION

Modeling of primary and secondary HVAC systems in low energy buildings should pay extra attention to the sizing of facilities causing over-consumption of up to 40% when operating at part load (Bouia, Kaemmerlen, and Filfli 2010), and increasing the number of cycles in one hour by the sensitivity of the building to internal and solar gains. A more accurate sizing requires an accurate approach of heating demands of the buildings. If the building envelope simulation tends to adopt sub-hourly dynamic simulation for control study, heating systems are often represented by hourly time step models with a static parameterization. This study aims to observe if the move to sub-hourly time step is necessary to improve HVAC systems modeling and what are the impacts of the interaction between the building envelope and heating systems, especially about the control unit. A first part presents a short review of heat pump models in order to simulate in a second part three typical models which are representative of the different approaches of the air-to-air heat pump modeling. Based on the simulation results, the last part presents modeling rules for dynamic simulation of heat pump integrated in low energy buildings in terms of “what type of model for what type of searched phenomenon”.

HEAT PUMP MODELS OVERVIEW

Heat pump models are often categorized depending on the physical approach:

- thermodynamic/physical approach, based on the geometry of the heat pump and general physics laws (heat and mass transfer)
- black box approach, in which empirical correlations determine heat pump performances as a function of the conditions of use (exterior and interior temperatures, power demands, etc.)
- grey box approach, which is at the intersection of the two above-mentioned approaches.

As discussed in the introduction, low energy buildings require a more accurate dynamic modeling. Hence, another classification is used in this state of the art, following the dynamic representation of the system:

Rated performances These models, not suitable for low energy building simulation, calculate the performances of the system for points rated on temperatures and for full-load and steady-state operating. Design oriented heat pump models and labeling certifications are the two subfamilies of the rated performances models.

Quasi-static This approach considers time as a sequence of steady states. During a sequence, the dynamics of the system response must be faster than the dynamics of the disturbances. For instance, hourly time step simulation considers that the operating conditions (like the outside temperature) does not change a lot compared to the heat pump performances during the hourly cycle. The heat demands are averaged on one hour and the performances are adjusted in function of sink temperature and load factor. The behavior of the heat pump is assimilated to steady-state snapshots.
These models calculate heat rate and electric power at any instant of the simulation, so that the transient phases and the steady states are both simulated in a closed loop.

Figure 1 represents the measured start and stop operation of an heat pump. This real operation can be simulated considering a semi-static model (Figure 2) or a dynamic model (Figure 3). The superscript $ss$ refers to steady state operating (see nomenclature at the end of the paper).

On figure 2, the on/off behavior is equivalent in energy to average operation. It means that the model calculates an equivalent “on” period to respect perfectly the temperature set point.

In this section, an overview firstly shows a short review of heat pump models of the literature organized depending on the above-presented categorization. Then, models adapted to building simulation and representative of a family according to its dynamic and its complexity are chosen. This aspect will be detailed in the next part.

Short review

The following review aims to present some models from literature organized depending on the kind of dynamic modeling.

Rated performances modeling

Two approaches can be found for the rated performances models:

- models to design heat pumps,
- models to ascertain standards.

The static physic-based models are used for improving the design of the heat pumps. The laboratory of Oak Ridge (ORNL - Oak Ridge National Laboratory) has been working since the middle of the 70s on such a model (Rice 2011). A very detailed description of the heat pump (hot or cold mode, type of refrigerant, characteristics of overheating, type of heat exchangers and compressor, geometries of the internal and external units, etc.) is required. Some models used for standards make it possible to compare the performances between various products or references by standardization of the tests and of the calculative procedures. For instance, in North America, standard ANSI/AHRI 210/240-2008 defines the conditions of measurement and the method of calculation of the seasonal performance in summer (SEER, Seasonal Energy Efficiency Ratio) and in winter (HSPF, Heating Seasonal Performance Factor). In Europe, the proposal standard prEN 14825:2010 aims at setting up seasonal coefficients of performance: SEER and SCOP (Afjei and Dott 2011).

Quasi-static modeling

By considering the running operation as a sequence of steady states, the quasi-static models make it possible to calculate the performance of the heat pump independently of the state of the system at the last time step. These models are very appropriate to black box or grey box approaches. The approach of this family of model - already used in 1980 in DOE-2 (York and Tucker 1980) - is the determination of the full load rate performances in steady-state that are degraded according to the temperatures of the sources, the needs (cycling and level of load) and the operating conditions of the heat pump (variable speed, frost and defrost phases, etc). Many models propose correlations of degradation according to the phenomena taken into account:
• frosting and defrosting of the evaporator of air-source heat pump (Miller 1982) (Kaygusuz 1994) (Argaud 2001),
• integration of the standby power in the part load rate (Henderson, Parker, and Huang 2000) (Marchio and Filfli 2003),
• cycle losses of single-speed compressor (Parken, Beausoleil, and Kelly 1977) (O’Neal and Katipamula 1991) (Garde 2001),
• cycle losses of variable speed compressor by the rotational frequency of compressor (Rice and Fischer 1984) (Shao, Shi, and Li 2004) or by a correlation connecting partial load factor (PLF) according to the part load rate (PLR) (Marchio and Filfli 2003) (Bory, Dupont, and Riviere 2006).

Dynamic modeling
Two approaches can cohabitate in dynamic models:

• empirical, based on equations with one or several time constants to represent the transient phases,
• physical, based on differential physic laws (heat and mass transfer).

These approaches require the use of a control system similar to a real temperature regulation system. An indoor temperature based control system loop matches the heat demands with the heat supplied by the system, typically indoor temperature to setpoint scenarios.

The empirical approach of the transitional stages led to various models with one or several time-constants, in the general form presented on figure 4.

![Figure 4: Emitted heat representation of time constant model of a dual-stage heat pump $\tau_{on1}$ et $\tau_{on2}$ for the start-up at each stage of compression and $\tau_{off}$ for the stop of the system](image)

In 1985, Mulroy and Didion (1982) proposed a two-time constants to take into account two components of inertia of the system: the mass of the components (like the evaporator) and the mass of the refrigerant which does not circulate. Wang and Wu (1990) found values of 2.45 and 0.34 minutes for a model with two-time constants. Goldschmidt and Hart (1980), Rosell, Morgan, and McMullan (1983), Garde (2001) proposed only one time constant to model the transient phase. This approach is validated by Murphy and Goldsmith (1979). Garde (2001) found a time-constant of 2 minutes. Murphy and Goldsmith (1979) found time-constants from 0.32 to 0.47 minutes respectively for heating mode pump and cooling mode. O’Neal and Katipamula (1993) found a time-constant of more than 2 minutes for a heat pump functioning in cooling mode. The electric power is considered without time-constant because its value is equivalent in steady state and transient phases (O’Neal and Katipamula 1991) (Henderson and Rengarajan 1996).

The dynamic physical models are based on the equations of the mass, the momentum and energy governing the system. Chi and Didion (1982), Mulroy (1986), MacArthur and Grald (1987), developed extremely precise dynamic models having the disadvantage of a complex parameter setting and long computing times. The components of the system can be modeled separately and then combined to simulate the whole system. For instance, Pettit, Willatzen, and Ploug-Srensen (1998) and Morales-Ruiz et al. (2009) presented results on the simulation of the transient phases of exchangers. Castaing-Lasvignottes and Gibout (2010) developed specific models of compressors. The validated work of Li and Alleyne (2010) about the transient state of the refrigerant during on/off phases could also be cited. The dynamic physical approach is very suitable for object oriented modeling because these research works described above could be modeled in a box in order to simulate a whole heat pump system by combining different component boxes.

Choice of models
From the above-presented state of art, we have determined 3 kinds of approaches to model and simulate:

• empirical (or semi-empirical) quasi-static modeling,
• empirical (or semi empirical) dynamic modeling,
• physical dynamic modeling.

The representative models of each approach were selected for their reliability and the feasibility of their parameterization.
SIMULATION

The three approaches were implemented and simulated in the same modeling environment in order to use the same resolution method for each simulation as we operate for an “ASHRAE 140” test, excepted that the aim is not to validate a model from others ones but to observe their adequacy for low energy building simulation. Modelica was chosen for its building simulation, especially for control system (Wetter 2009) and for physical dynamic modeling (Pfafferott and Schmitz 2004). The simulations are achieved in Dymola environment.

General description

A low energy building was modeled considering Paris weather data: temperature and solar flux. The 100 m² monozone single family residence is coupled to an air-to-air heat pump by a control system. The temperature setpoint is fixed at 20°C and the control unit operates to maintain internal air temperature within a +/-0.5°C band. In order to focus the study on the impacts of the dynamic modeling of the heat generator, the air-to-air heat pump was chosen for the absence of associated emission system and was configured in all or nothing functioning. So an on/off heat pump product is sized to fit heating demands of the low energy building. The rated performances at 7°C outside and at 20°C inside are 330 W for electric power and 1380 W for emitted power (COP = 4.2). The physic-based model being the more difficult to configure, the two empirical models were parametrized from this one.

Physical dynamic model

The physical dynamic approach is a complex model initially built to observe transient phases in heat pump design (Barbouchi et al. 2012). It consists of components from the TLK/IfT Library (TIL): two air/refrigerant heat exchangers, a compressor and an expansion valve. They are connected in temperature, pressure and mass flow. A regulator on the expansion valve controls the superheat temperature.

A similar control unit of the empirical dynamic model is used to force the heat pump to operate on on/off, despite its possible multi-speed operating. The input variables are the indoor and outdoor temperatures. The outputs are the emitted heat and the electric consumption (only from the compressor consumption).

From the air-to-air heat pump characteristics of the study of Barbouchi et al. (2012), the temperatures were modified to determine the rated performances and the parameters \( \tau \) and \( \alpha \) used in the two others models.

Figure 5 shows the emitted heat and the electric demands to maintain the interior temperature to the chosen setpoint.

Empirical quasi-static model

The representative model of an empirical or semi-empirical quasi-static approach is based on the split air conditioner model of Marchio and Filli (2003). It uses only three operating points from manufacturer data to determine the performances following the operating temperatures during the simulation.

The part load losses (cycling (1) and stand-by (2)) are based on Henderson, Parker, and Huang (2000) model:

\[
PLF_{cyl} = 1 - 4 \times \tau \times N_{max} \times (1 - \frac{PLR}{PLF_{cyl}}) \\
\times (1 - \exp(-\frac{1}{4 \times \tau \times N_{max} \times (1 - \frac{PLR}{PLF_{cyl}})}))
\]

(1)

\[
PLF_{sb} = \frac{PLR}{\frac{1}{1 - \alpha} \times PLR + \alpha}
\]

(2)

where \( PLF = \frac{COP_{operating}}{COP_{rated}} \) and \( PLR = \frac{Operating \ load}{Full \ load} \).

The parameters defined from the physical model are a start-up time constant, \( \tau \), of 13 seconds, a maximum cycling rate, \( N_{max} \), of 3 per hour, and a stand-by fraction, \( \alpha \), of 3%.

This quasi-static model must operate for time frame superior at a cycling period. We have typically chosen an hourly time step. The regulation is made via a calculation of hourly needs from an ideal regulation of a fixed temperature at 20°C. The power called to the heat pump is the hourly average power. The figure 6 shows the results of the simulation of the above-presented model.

Empirical dynamic model

The empirical dynamic approach is simulated from a one time constant model. The emitted heat, \( P_{th} \), is cal-
MODELING RULES FOR LOW ENERGY BUILDING

This part aims to elaborate the strengths and weaknesses of each models on the optic of integration of these air-to-air heat pump models in low energy building simulation. These observations may lead prospective actions to complement and extend the modeling rules defined from this study.

Power demands

On figures 6, 7 and 5 presenting the power demands of each model on the same three hours period of simulation: from 9 AM to midday at the beginning of January. In the case of empirical semi-static, the emitted heat and the corresponding electric power are considered as constant during the period. In the case of both dynamic models, cycling phenomenon can be observed, the decrease of the building heat demands leads to shorter “on” periods, thus more cycling. Both models made it possible to respect the subhourly time frame building simulation because the performances of the heat pump are calculated each time step.

Regulation

The empirical semi-static model need a perfect control unit which determine the hourly average heating demands. The building and the heating system could be simulated individually. For the both dynamic models, the regulation is made with a closed loop control. At any instant, a control unit verifies if the temperature setpoint is respected and indicates if the heating system has to start. The interaction between the building envelope and the HVAC system needs a simultaneous simulation.

Energy comparison

As we can see on figure 8, the different control systems between semi-static and dynamic models leads to a variation of 4% in heating demands. The figure shows also the different emitted heat energy and corresponding electric consumption during a simulation of a week of January. The computation time is also mentioned.

The average COP of the empirical dynamic model on this simulation week is 4.2. The semi-static model one is 3% up and the physic-based model is 5% down. The typical model for physical approach is very complex and need several iteration resolving loops. The computation time is consequently very high. To allow annual building simulation, the chosen model has to be simplified for instance in limiting the discretization of the heat exchangers or in deleting the superheat temperature control.

\[
P_{th} = P_{th}^{ss} \times (1 - \exp(-\frac{t}{\tau})) \tag{3}
\]

As seen on the review, the electric power is considered without time constant. Its value is calculated as a function of the operating temperatures by the same way of semi-static model during on period, and is equal to the stand by losses during off period:

\[
P_{elec} = \begin{cases} 
P_{elec}^{ss} & \text{during on period} \\ \alpha \times P_{elec}^{rated} & \text{during off period} \end{cases} \tag{4}
\]

The control unit imposes the start-up and the stand off of the system so as to maintain internal air temperature within a +/- 0.5°C band around 20°C. These phases are presented on the figure 7.
Parametrization

Both empirical models are easy to parametrize with limited number of parameters: a minimum of three manufacturer data (including rated one), $\tau$ and $\alpha$. However the determination of the operating performances could be compromised if the system works outside its nominal range defined from the manufacturer data. Conversely, the physical approach is less limited about these operating points but need an expert parametrization, each component has to be identified:

- the compressor characteristics,
- the geometry of both heat exchangers,
- the refrigerant thermodynamic properties, etc.

CONCLUSION AND PERSPECTIVES

Three air-to-air heat pump models representative of different approaches found in the literature were modeled for simulation on Modelica. The results tend to show that the semi-static model is incompatible with close loop control. Conversely a dynamic model makes it possible to have a real time-varying interaction between the building envelope and its heating system. A following study with experimental data will aim to validate if such an approach is necessary to have a good representation of these interaction. The next steps of our work are:

- prospect the influences of the uncertainties. Dymola environment allows Monte Carlo studies in order to evaluate the sensibility of the three models,
- generalize rules for heating systems simulation in low energy buildings from others studies based on the methodology presented in this paper.

ACKNOWLEDGMENT

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**NOMENCLATURE**

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<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>SEER</td>
<td>Seasonal Energy Efficiency Ratio</td>
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<tr>
<td>SCOP</td>
<td>Seasonal Coefficient Of Performance</td>
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<tr>
<td>COP</td>
<td>Coefficient Of Performance</td>
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<tr>
<td>PLF&lt;sub&gt;cycl&lt;/sub&gt;</td>
<td>Part load factor due to cycling losses</td>
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<tr>
<td>PLF&lt;sub&gt;sb&lt;/sub&gt;</td>
<td>Part load factor due to stand-by losses</td>
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<tr>
<td>PLR</td>
<td>Part load ratio = ( \frac{\text{Operating load}}{\text{Full load}} )</td>
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<tr>
<td>( \tau )</td>
<td>Start-up time constant</td>
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<tr>
<td>( \alpha )</td>
<td>Stand-by fraction = ( \frac{\text{Off-cycle power}}{\text{Rated electric power}} )</td>
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<td>( P_{th}\text{ss} )</td>
<td>Steady-state emitted heat</td>
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<td>( P_{elec}\text{ss} )</td>
<td>Steady-state electrical power</td>
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