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Validation of a black-box heat pump simulation model by means of field test results from five installations

Jörn Ruschenburg*, Tomislav Ćutić, Sebastian Herkel

Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany

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ABSTRACT

In the residential sector, heat pumps are applied for domestic hot water and space heating. Simulations are widely used for general research in the field of heat pumps and to some extend to plan such installations. The advantages are low expenditure of time and costs compared to laboratory or field tests.

Validation of simulation models is mandatory to guarantee a sufficient quality. In the presented paper, the field monitoring results of five ground-source installations are utilised for the validation of a black-box heat pump model. The model is similar to TRNSYS Type 201, but implemented in IDA ICE and then modified to handle the difficulties caused by non-standard mass flow and rampant polynomials. As overall result, deviations between 1% and 32% regarding modelled and measured efficiency are seen on monthly basis. The overall result appears as convincing, taking into account typical inaccuracies of laboratory and field tests as well as tolerances during heat pump production.

As a side effect, the influence of standby consumption was quantified. For the five presented installations, standby amounts to fractions between 2 and 5% of the annual electricity consumption of the heat pump units.

1. Introduction

Heat pump models can be used during planning processes to predict the performance of heat pumps with electrically driven compressors (henceforth referred to just as heat pumps), or in research and development to analyse the component performance and dynamic behaviour, for example when a heat pump is integrated in different system layouts. Black-box models are often applied for such purposes. They provide a sufficient level of detail – i.e. the dependency of the heat pumps' performance on source and sink temperature, when necessary also on mass flow – and their parameterisation does not require more than a limited set of parameters, i.e. no information about used refrigerants, internal heat transfer and losses, thermodynamic cycles, etc.

Afjei and Dott [1] stated that such models are most wide-spread in dynamic simulation programs like TRNSYS, ESP-r, EnergyPlus, IDA ICE and MATLAB/Simulink. The heat pump performance, in particular its coefficient of performance (COP) and heating power, is usually implemented by means of polynomials. The operating range is then covered by these polynomials, which comprises interpolation and extrapolation. Afjei and Dott categorise such models as "performance map models". The polynomials are derived from parameters, mostly provided by standardised laboratory test results, i.e. according to EN 14511 or withdrawn EN 255. They are usually found in laboratories' publications or in the heat pumps' data sheets published by manufacturers.

Thus, it is possible to parameterise heat pump models exclusively with laboratory test results. However, the conditions in the field are not fully mirrored in the laboratory—the fact that heat pumps are tested exclusively under steady-state conditions is the most obvious proof. The start-up phase, e.g., is characterised by full electricity consumption but heating power reaching nominal level just after many minutes. The method of choice to analyse technical systems under real-life conditions is therefore field monitoring.

Comparing simulation results to field monitoring results is a good possibility to assess the quality of modelling and simulation. It is a very important detail that boundary conditions in the field, e.g. source temperatures, and of course the dynamics show a wider variance compared to test rigs. In the following section, the whole comparison process will be further described and labelled as validation.

This paper presents an adaption of an existing black-box heat pump model and its validation through comparing simulation results to field-test results of five ground-source heat pump

* Corresponding author. Tel.: +49 761 4588 5738.
E-mail address: joern.ruschenburg@ise.fraunhofer.de (J. Ruschenburg).

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Nomenclature

COP	coefficient of performance according to EN 14511 [5]
DHW	domestic hot water
$k_{[1...6]}$	coefficients for COP calculation
$l_{[1...6]}$	coefficients for the calculation of heating power
NRMSD	normalised root mean square deviation
Q_{DHW}	heat consumption for domestic hot water
Q_{SH}	heat consumption for space heating
q_{SH}	area-specific heat consumption for space heating
$\dot{Q}$	heating power
RMSD	root mean square deviation
SPF_{HP}	seasonal performance factor of the heat pump according to Malenković et al. [6]
$SPF_{HP,m}$	measured SPF_{HP}
$SPF_{HP,s}$	simulated SPF_{HP}
xtrpltn	parameter indicating the range of polynomial extrapolation
$\vartheta_{sink,mean}$	sink-side mean temperature between inlet and outlet
$\vartheta_{sink,out}$	sink-side outlet temperature = flow temperature
$\vartheta_{source,in}$	source-side inlet temperature
$\vartheta_{source,in,max}$	maximum tested source-side inlet temperature

installations. It is based on intermediate results published as [2], then utilising just three installations and a preliminary model.

2. Methods

In a first step, nomenclature and the state of the art regarding black-box heat pump modelling are presented in a literature review. Strengths and weaknesses of such models are explained. Afterwards, the new heat pump model, the applied software and the examined field test installations are introduced.

2.1. Literature review

2.1.1. Nomenclature

Laboratory testing procedures and performance map models analysed by Afjei and Dott [1] treat heat pumps as black boxes characterised by efficiency and heating power depending on source and sink temperatures. By doing so, no information about refrigerants, heat transfer, thermodynamic cycles and other technical aspects is required. According to Fig. 1, this abstraction is called model qualification, and the black box is one example of a conceptual model. This applies both to laboratory tests and calculative methods. If standardised tests are used to analyse a specific heat pump, the obtained results can be used to parameterise the performance maps of computer models, thus called parameters.

After programming and implementing a computerised version of this model, verification confirms that the computerised model represents the conceptual model. Validation, in turn, shows that a simulation carried out with the computerised model matches reality. The process of verification and validation may result in modifications and iterations before the actual model is finalised [4].

Regarding the assessment of heat pumps installed in heating systems, boundaries must be defined. As for the efficiency, the coefficient of performance (COP) definition of EN 14511 [5] is applied. To evaluate on daily, monthly or annual basis, the seasonal performance factor of the heat pump according to [6] is chosen, called SPF_{HP}. It is defined as the ratio of the heat delivered and electricity consumed by the heat pump over the season. The system

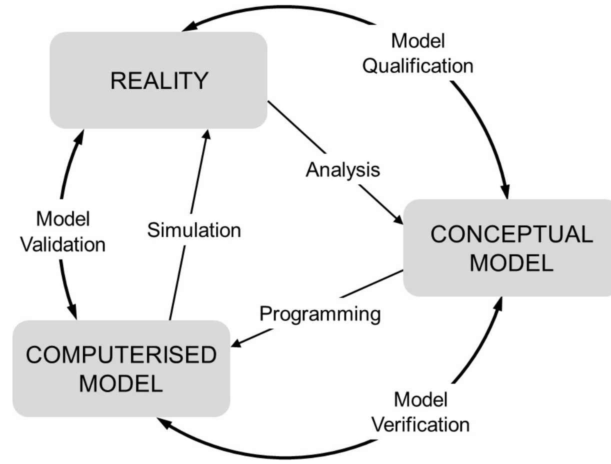

Fig. 1. Phases of modelling and simulation and the role of verification and validation (created according to [3] as cited in [4]).

boundaries of SPF_{HP} and COP are identical, with compressor included as well as the heat pump's safety and supporting elements. However, the seasonal approach of the SPF_{HP} considers influences like dynamics and standby.

2.1.2. Original heat pump model

Following a black-box approach, COP and heating power are calculated as functions of temperatures at source and sink side. These functions are known from Afjei and Wetter [7] as TRNSYS Type 201 or Type 204, or earlier from Fischer and Rice [8]. They can be described as second-degree, mixed polynomials with 6 unknowns each. Laboratory test results for 6 operating points are required for parameterisation. In mathematical terms, an equation system with 6 unknowns has to be solved during pre-processing. The data can be acquired easily if the testing institution follows the complete procedure described by EN 14511 [5] (or previously EN 255) and if the manufacturers permit making the results available to the public.

The heat pump as black box is shown in Fig. 2, with the outline shown in black to be literally understood as black box. Its inner elements – condenser, evaporator, compressor, refrigerant, etc. – and their physical behaviour are of no relevance for the conceptual model. Fig. 2 also defines inlet and outlet nomenclature used throughout this paper.

In the following step, the electric power consumption is calculated by reversing the COP definition, i.e. as ratio between heating power and COP. Similarly, the outlet temperature on source side and the return temperature on sink side can be calculated because mass flow and power on both sides are known, and the complementary temperature is already given as input variable.

Afjei and Wetter [7] model the dynamic start-up phase by a first-order equation. However, the required time constant is usually unknown as there is no reference from standard laboratory tests. Afjei and Wetter applied 180 s as default value, whereas the

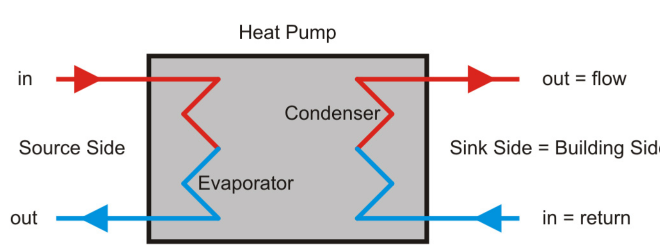

Fig. 2. Heat pump seen as black box.