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Digital twin for the transient operation of a real heat pump

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Abstract: Efficiency and flexibility are key aspects of modern heat pumps for the household. A nonlinear model of the refrigeration cycle is developed in the framework of Matlab/Simulink that allows for simulation and control design of multiphase fluid dynamics of an existing heat pump. A finite difference model of the evaporator and the condenser is coupled with phenomenological models of the separator, collector, 4-port valve and pipes. The standard components expansion valves and compressor are characterized by operation maps obtained from the supplier. The detailed ther-modynamic model is benchmarked against real measurements at stationary operation. This capability is then expanded to simulate the dynamic behaviour during the transition between different operation points. Finally, a delayed model-predictive control is employed for a time-efficient change in real-time operation.

Keywords: refrigeration cycle , numerical thermodynamics, heat pump

INTRODUCTION

Modern heat pumps are optimised for high efficiency and flexibility in daily operation. This demands a detailed thermodynamic model for achieving high accuracy in the prediction of the stationary and transient behaviour. Such a model consists of large-scale nonlinear system of equations that include complex nonlinearities and are computationally costly. The modelling complexity of the digital twin is a challenging task in which the balance between complexity and accuracy must be considered. Two modelling approaches are commonly used for heat exchangers: the finite volume method with distributed parameters and the moving boundary method with lumped parameters Pangborn (2015). In the present work, we develop a finite difference model in Matlab/Simulink in the framework based on the first principles following Rasmussen (2006), Pangborn (2015) and Zamojski (2021). The model captures the detailed dynamics of the heat exchange components of a real industrial heat pump shown in Fig. 1. The corresponding simplified thermodynamic circuit is visualised in Fig. 2. The regenerator are omitted in the sketch but included in the digital twin. The finite difference model of the evaporator and the condenser is coupled with phenomenological models of the separator, collector, 4-port valve and pipes. The standard components expansion valves and compressor are characterized by operation maps obtained from the supplier.

For the finite difference model, the first principles in thermodynamics for mass and energy conservation of a two-phase fluid

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0, \tag{1}$$

$$\frac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = \rho \vec{f} + \nabla \cdot \sigma, \tag{2}$$

Figure 1 – Domestic heat pump iPump-A (3-11) from IDM Energiesysteme GmbH with an air heat exchanger.

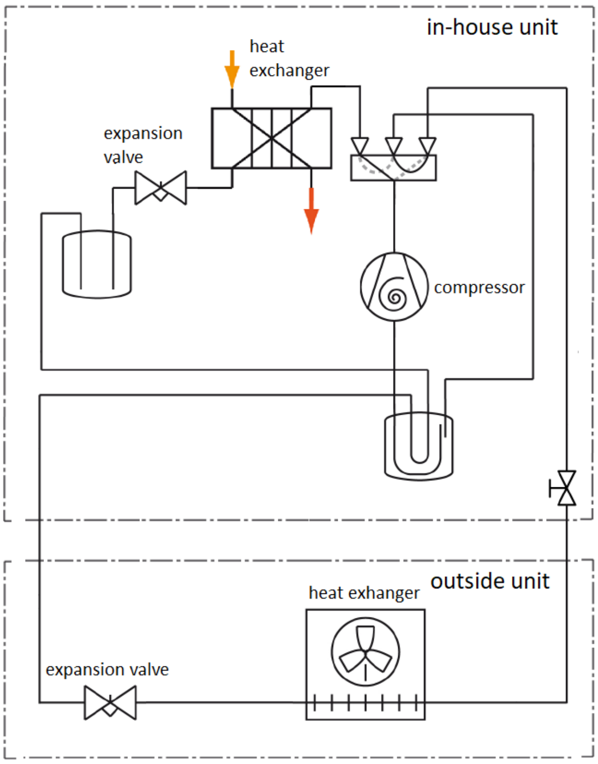


Figure 2 – Simplified thermodynamic circuit showing the most critical components of the heat pump in Fig. 1.

are converted to partial differential equation with linearised coefficients for the working fluid (see Rasmussen (2006) for more details)

$$\frac{\partial(\rho A_{cs})}{\partial t} + \frac{\partial(\dot{m})}{\partial z} = 0, \tag{3}$$

$$\frac{\partial(\rho A_{cs} h - A_{cs} h)}{\partial t} + \frac{\partial(\dot{m} h)}{\partial z} = p_i \alpha_i (T_w - T_r), \tag{4}$$

$$(C_p \rho A)_w \frac{\partial(T_w)}{\partial t} = p_i \alpha_i (T_r - T_w) + p_o \alpha_o (T_a - T_w). \tag{5}$$

The last equation describes the energy transfer between a tube wall and the fluid. The notations herein are listed in Table 1.

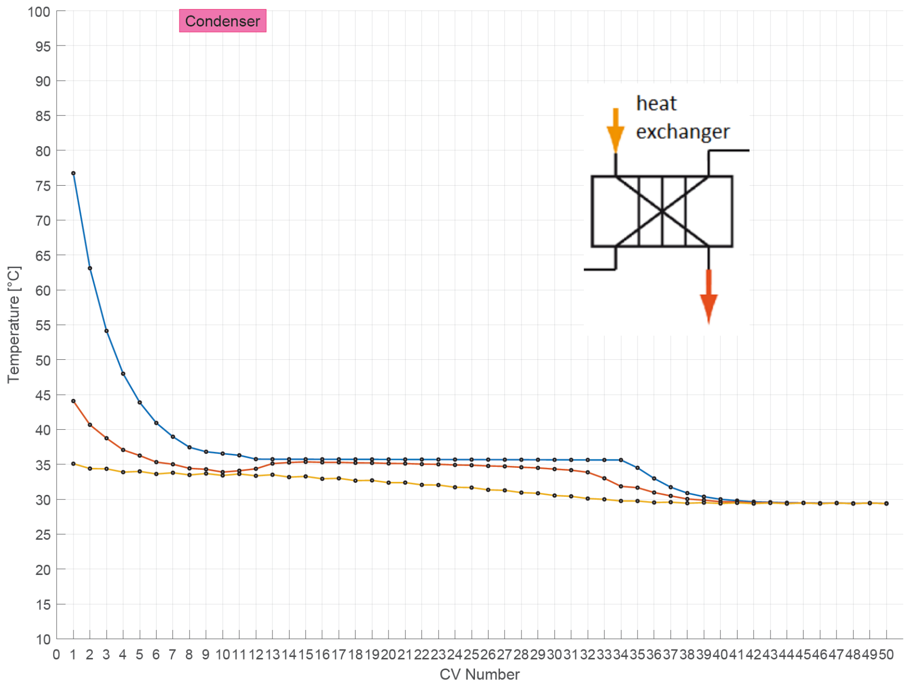
Table 1 – Coefficients and variables of partial differential equations describing the heat exchangers.

coefficient	description
ρ	density of refrigerant
A_{cs}	inner cross-sectional area of tube
α_i	heat transfer coefficient between refrigerant and tube wall
α_o	heat transfer coefficient between tube wall and secondary fluid
$(C_p \rho A)_w$	thermal capacitance of tube wall per unit length

variable	description
$\dot{m}$	mass flow rate of refrigerant
h	enthalpy of refrigerant
p_i	inner surface area per unit length
p_o	outer surface area per unit length
T_r	temperature of refrigerant
T_w	temperature of tube wall
T_a	secondary fluid temperature

RESULTS

We investigated systematically the stationary and transient behaviour of the heat pump. The validated model for the condenser in Zamojski (2022) was expanded to physical models of the condenser and the evaporator. Other components were either incorporated by a phenomenological model based on measurement data or characterized by operation maps obtained from the supplier of the expansion valves and the compressor. This enabled the establishment of the full thermodynamic digital twin of the real heat pump iPump-A in Fig. 1. It is a domestic heat pump between 3 to 11 kW heat capacity depending on the configuration. Several measurements were performed under real conditions in order to tune the data-modelled components and benchmark the physically-modelled components of the digital twin. The numerical results for an arbitrary operation point is depicted in Fig. 3. Respecting the multi-phase ability of the refrigerant, the temperature distributions of the refrigerant, the wall and the secondary fluid are established along the two main heat exchangers: the condenser and the evaporator.



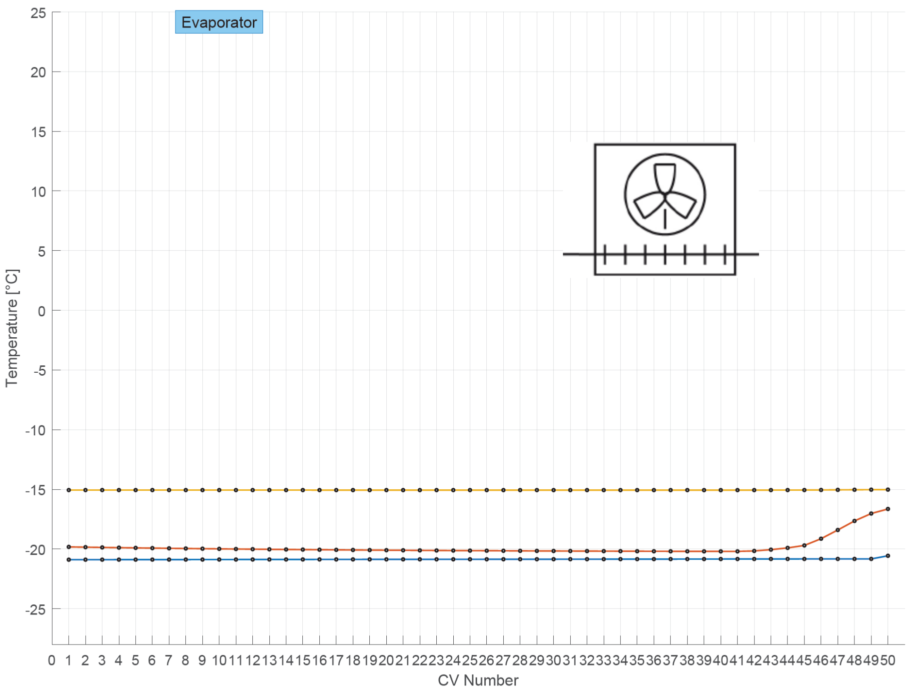


Figure 3 – Numerically calculated temperature distributions of refrigerant, wall and secondary fluid in the main heat exchangers: (top) condenser, (bottom) evaporator. CV denotes the control volume of the finite difference model.

The full thermodynamic model is utilized for parametric studies to identify the most critical parameters during transient operation. Such an operation is typical for switching between stationary operating points and during the start of a heat pump. This is still a demanding task, and many manufacturers rely on their in-house experience instead of physical models.

The validated digital twin allows for:

- the simulation of the dynamic behaviour during the transition between different operation points and
- the derivation of a delayed model-predictive controller for a time-efficient change in real-time operation.

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REFERENCES

Pangborn, H., Alleyne, A. and Wu, N., 2015, A comparison between finite volume and switched moving boundary approaches for dynamic vapor compression system modeling, International Journal of Refrigeration, Vol.53, pp. 101–114

Rasmussen, B.P. and Alleyne, A.G., 2006, Dynamic Modeling and Advanced Control of Air Conditioning and Refrigeration Systems, PhD thesis, University of Illinois, Urbana, IL, USA

Zamojski, M., Sumerauer, P., Bacher, Ch. and Dohnal, F., 2022, Towards Online Transient Simulation of a Real Heat Pump, in Springer Proceedings in Mathematics & Statistics, Perspectives in Dynamical Systems I: Mechatronics and Life Sciences, pp. 69–78

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