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Optimization of heat pump system

Róbert Sánta [a, *], László Garbai [b], Igor Fürstner [a]

[a] Subotica Tech – College of Applied Sciences, Subotica, Serbia
[b] Department of Building Service and Process Engineering, Budapest University of Technology and Economics, Hungary

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ABSTRACT

The purpose of this study is to produce a mathematical model to describe the operation of a water-to-water heat pump system for steady-state condition. The set-up model is deterministic. It consists of distributed as well as lumped parameters. The proposed mathematical models of heat exchangers were described by coupled differential equations, while the models of the compressor and the expansion valve are of lumped parameters. The Runge–Kutta and the Adams–Moulton predictor-corrector methods were applied for the numerical solution of differential equations, i.e. the equation systems. The developed mathematical model is validated with 118 tests using R134a as a working fluid. The results show that an average difference between the modeled and experimental results for the coefficient of performance is 1.73%, which means that the proposed mathematical model can be used to determine the optimum operating point of a heat pump system for a given heat demand for heating, by determining the maximum value of the coefficient of performance.

1. Introduction

Early 2008, the European Commission adopted a future-oriented proposal [1], intended to reduce greenhouse gases still causing increases of the greenhouse effect, and at the same time to increase the application of renewable energy resources to a 20% ratio within the total of energy use by 2020. Hungary, as an EU Member State, incorporated the EU decision on such major increase of renewable energy resources in its legal system, and its objective is to raise the proportions of renewable energy use from the current 5–6% to14.65%. In the authors' view, the spreading of heat pump technology, the most energy-efficient method for heating and cooling buildings, is the best solution for Hungary, having in mind the given natural conditions.

In order to improve the energy efficiency of heat pumps and to increase the quality of operation, it is unavoidable to strive to describe, as precisely as possible, heat pump operation and the processes therein. Therefore, on the one hand, the theoretical basis of the present study is the development and refinement of the mathematical model of the heat pump, while on the other hand, it is the optimization of the system's operation.

A thorough literature review reveals that the mathematical modeling of heat pumps was discussed extensively in the past. Koury et al. [2] proposed a model for a refrigeration system with distributed parameters model for heat exchangers. Numerical simulations were carried out to verify the possibility of controlling the refrigeration system and the superheating of the refrigerant in the evaporator outlet by varying the compressor speed and the throttling valve position. Choi et al. [3] also carried out numerical simulations for a multi-type heat pump, to examine the performance of the system in transient conditions. Hermes et al. [4] presented a mathematical model for transient and steady simulations of the thermal and fluid-dynamic behavior of the refrigerant flow through adiabatic and non-adiabatic capillary tubes. Youbi–Idrissi et al. [5] developed a rather simple simulation model, which allows the highlighting of the behavior of a water-to-water heat pump operating under steady-state conditions, from its heat exchangers geometry and compressor characteristics.

In their paper Sheng et al. [6] investigated the energy saving potential of HTHP&DW system compared to the reference technologies based on vapor compression (CVC (conventional vapor compression) system) and desiccant cooling (HDC (hybrid desiccant cooling) system).

Zhenjun et al. [7] presented the biogas engine-driven heat pump air conditioner in a new-style system which includes a biogas engine driven heat pump, primary heat exchanger, second heat exchanger, sprayed room and fans, pumps, etc. The authors investigated the influence of various factors including the outdoor air temperature and humidity both in summer and winter.

The mathematical model of the heat pump enables the design of optimal systems, searching for more economical solutions,

* Corresponding author. Tel.: +36 309556449.
E-mail address: santa@vts.su.ac.rs (R. Sánta).

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assessment of operational characteristics, as well as lifetime and cost planning. The energy optimum of a heat pump is realized when the COP (coefficient of performance) takes up the maximum value.

In the design phase, the nominal state of the maximum energy efficiency can be set by selecting the optimal system parameters, in an effort to jointly minimize the total cost of system installation and operation. In the case that the system had already been designed and manufactured, the coefficient of performance can only be improved by reducing the mechanical work invested. Therefore, the aim is to set the optimum operating point by aligning the rpm of the motors running the compressor and the pumps as well as by other decisions detailed later on, which, in turn, can be realized by setting up a mathematical model to enable the optimization of operation.

The literature review shows that numerous researchers have discussed the optimization and analysis of heat pump operation. Nyers et al. [8] discussed the COP value of the heat pump condenser, by varying the mass flow of the heated media and the refrigerant. Sarkar et al. [9] presented the experimental results for a heat pump system for simultaneous water cooling and heating. The cooling and heating capacities and the COP have been studied for various operating conditions (water mass flow rates and water inlet temperatures of both evaporator and gas cooler) and expansion valve openings. Primal et al. [10] detected an important influence of the evaporator conditions on the charge, when a water-to-water heat pump under different evaporation temperatures was tested. They found that the optimal charge decreased with the evaporating temperature. Zhang et al. [11] presented a system optimization of air source heat pump water heater, including calculation and testing. Zhao et al. [12] analyzed the steady state performance of the heat pump system, showing that the overall system is a two time-scale dynamic system.

Based on the presented literature review it can be concluded that the researchers carried out a deep and thorough analysis of numerous specific heat pump systems. The present study aims at contributing to this field in order to fill a gap in literature by discussing the scientific design of the steady state operation of the water-to-water heat pump system that was missing or just partially discussed in literature. Thus, the objective is to describe, more precisely than before, the thermodynamic heat transfer and fluid mechanics processes within the system components in order to realize the heat pump's cycle, as well as to be able to identify changes of state at each point – and otherwise at discretionary points – of the cycle.

The proposed mathematical model allows the optimization of the system operation for different heating demands; that is, it examines how to satisfy a given heat demand by using a minimum amount of electric power. Therefore, the aim is to maximize COP as the target function of the system by examining what decision parameters can be used to set it, both on the water side of the evaporator and the condenser – and what values thereof –, taking into consideration the behavior of the compressor and the expansion valve at operating points other than nominal ones. The goal function of system operation is:

$$COP = \left|\frac{Q_{con}}{W}\right| \rightarrow max!. \tag{1}$$

Heating capacity:

$$Q_{con} = Q_{eva} + W. \tag{2}$$

Cooling capacity:

$$Q_{eva} = f\left(\dot{m}_{cw},\ T_{cw,i},\ T_{cw,o}\right). \tag{3}$$

Compression power:

$$W = f\left(\dot{m}_{ref},\ p_{eva,i},\ \ p_{con,o}, \eta\right). \tag{4}$$

2. Design of the mathematical model for the heat pump system

The physical model of the major elements of the heat pump system is shown in Fig. 1. This physical model, which is described mathematically, consists of an evaporator, a compressor, a condenser, and an expansion valve.

The presented study focuses on shell and tube heat exchangers. The test model developed for the entire heat pump system also includes investigations of plate heat exchangers; however, the characteristics of different types of heat exchangers – the relationship of input and output profiles – are specified by the manufacturers.

In the present case, the refrigerant is R134a; flowing in the tubes of heat exchangers, while the primary and secondary fluid-water, flows in the shell side. In the shell side of heat exchangers baffles are applied primarily for supporting the tubes and for inducing cross flow over the tubes, resulting in improved heat transfer performance. The baffles are perpendicular to the tube bundle. The examined heat exchangers have segmental baffles.

The mathematical model of the heat pump system is set up for steady state behavior. It is deterministic, and of distributed parameters, meaning that the relations between variables can be uniquely defined. They are independent of time, and the parameters with their values are taken into account according to location. The mathematical model of the heat exchangers consists of basic equations – governing equations in a different terminology – and auxiliary equations, while the models of the compressor and the expansion valve are of lumped parameters.

The following assumptions have been made regarding the physical and mathematical models:

- refrigerant flow in the evaporator and the condenser is one-dimensional and permanent,
- refrigerant liquid and vapor phases are in thermodynamic equilibrium,
- in heat exchangers, only axial flows are taken into account.

In the following subsections, basic equations and conditional equations are stated separately for each system component. By solving them, changes of state of the refrigerant can be specified at certain points of the cycle, namely in the evaporator, at the inlet and outlet points of the compressor, in the condenser, and in the expansion valve, thereby making it possible to set control parameters according to discretional consumer demands, which in turn can be used for specifying the optimal operating point of the system.

2.1. Heat exchangers

2.1.1. Basic equations

For the mathematical model of heat exchangers, a two zone model is utilized. The evaporator is divided into two zones