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Application of a lumped model for predicting energy performance of a variable-speed vapour compression system

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ABSTRACT

This work presents a model for a variable-speed vapour compression system that is able to predict accurately the system performance using data easily obtained from an industrial facility. The model uses information on the secondary fluids input conditions and the compressor speed to predict the secondary fluids output temperatures, the operating pressures, the compressor power consumption and the system overall energy performance. This model has been validated experimentally with steady state tests, presenting a prediction error lower than 10%. Finally, an application of the model to evaluate the influence of the operating variables on the energy performance of a chiller is presented.

1. Introduction

Nowadays, there is a high energy consumption associated with refrigeration and air conditioning systems [1], most of these facilities are based on the vapour compression cycle. In order to reduce their consumption, it is necessary both to have efficient systems and to operate them properly. To achieve these objectives, it is convenient to use complete models, which take under consideration a large amount of factors and facilitate the design of efficient systems. In the same way, there is also a need for models, with low computational cost, to simulate the performance of any facility and that can be used to improve the system operation and to evaluate its performance easily. Taking into account that operating the facilities properly is as important as having efficient systems, this work is focused on developing a model that can be used in any installed facility to simulate the system performance in order to optimize its operation.

It is well known that the air conditioning and refrigeration systems operate during most of their lifetime under part-load conditions [2], being necessary an appropriate adaptation of the cooling capacity to thermal load conditions. It has been proved theoretically that compressor speed variation is the most efficient method of controlling refrigeration capacity [3]. However, there are other factors, such as secondary fluid flow rates, which affect energy efficiency. These factors have to be taken into account for efficient system operation focused on improving its energy performance under any operating condition. A model is required to analyze the influence of compressor speed and other factors related to system efficiency, with the main objective of evaluating and improving energy performance. This model should be easily adapted to an existing facility, with low cost in terms of data requirements.

In the available literature, there is a large body of work that deals with modelling vapour compression systems [4,5]. Focusing on the models based on Physics laws, Braun et al. [6] developed a model for variable speed centrifugal chillers useful for predicting power requirement and cooling capacity. Beyene et al. [7] modelled and simulated conventional chillers using DOE2 software, obtaining performance values to compare among different kinds of chillers. Browne and Bansal [8] presented a model for predicting vapour compression chiller performance from secondary fluids temperatures, using an elemental NTU-efficiency methodology. Saiz Jabardo et al. [9] proposed a model for automotive air conditioning systems based on a NTU-efficiency model that predicts refrigerant capacity, power consumption and other important parameters for the performance of the system from secondary fluids conditions and evaporating temperature.

Continuing with the main objective of these works, this paper proposes a model to predict the performance of a vapour compression plant, and the use of this model for energy optimization in a chiller. The proposed model uses only geometric data and secondary fluids information as input variables to make a complete characterization of the system in terms of energy performance.

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Nomenclature

COP	coefficient of performance
COP_t	global coefficient of performance
c_p	specific heat (J/kg K)
D	diameter (m)
h	specific enthalpy (J/kg)
k	thermal conductivity (W/m K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
N	compressor speed (r.p.m.)
P	power consumption (W)
p	pressure (Pa)
Q	volumetric rate of flow (m^3/s)
q	heat transfer rate (W)
r	radius (m)
S	area (m^2)
T	temperature (K)
t	time (s)
U	overall heat transfer coefficient (W/m^2 K)
V_G	geometric compressor volume (m^3)
v	velocity (m/s)
x	refrigerant quality

Suffixes

air	environment
avg	average
b	brine
C	compressor
e	evaporation
i	inner
in	input
k	condensation
L	liquid
M	metal
o	outer
out	output
r	refrigerant
sat	saturated
V	vapour
w	water

Greek symbols

α	heat transfer coefficient (W/m^2 K)
λ	phase change latent heat (J/kg)
μ	dynamic viscosity (Pa s)
η_V	compressor volumetric efficiency
η_{is}	compressor isentropic efficiency
η_G	global electromechanical compressor efficiency
ρ	density (kg/m^3)
σ	surface tension (N/m)

The proposed model takes only five variables as input variables, namely compressor speed N, brine input temperature ($T_{b,in}$) and mass flow rate ($\dot{m}_b$) at the evaporator, and water input temperature ($T_{w,in}$) and mass flow rate ($\dot{m}_w$) at the condenser. These variables, together with the thermophysical properties of the refrigerant and the main geometric characteristics of the system, are used to compute evaporating and condensing pressures, brine and water output temperatures, power consumption and energy efficiency. In this way, one can easily analyze the influence of changes in operating variables on the system behaviour and use this information to optimize the system operation.

The rest of this paper is organized as follows. In Section 2, the model structure is presented. In Section 3, the experimental test bench and the tests used to validate the model are briefly described. Section 4 shows the results of model validation and its application for energy characterization and optimization of the system performance. Finally, in Section 5, the main conclusions of the work are summarized.

2. Vapour compression systems modelling

The general structure of the proposed model is presented in Fig. 1, where it can be seen that the model inputs are the secondary fluids input variables and the compressor speed, neglecting subcooling degree at the condenser outlet and superheating degree at the evaporator outlet, for simplicity. Using these inputs and the main characteristics of the compressor and heat exchangers, the model predicts the operating pressures (without considering pressure drops), secondary fluids output variables and the energy performance.

The model computes the refrigerant properties using dynamic libraries of REFPROP [10], while the thermophysical properties of secondary fluids are evaluated by means of interpolating polynomials calculated from the ASHRAE handbook [11].

The kernel of the model consists of a set of five equations based on physical laws describing the main parts of the system, as shown schematically in Fig. 2. The refrigerant states are numbered in Fig. 3.

The refrigerant mass flow rate has been modelled using Eq. (1), where the compressor volumetric efficiency, η_V, has been expressed as a function of operating pressures and compressor speed, N, as shown in Eq. (2). For simplicity, the refrigerant density considered is the one corresponding to the saturated vapour at the evaporating pressure

$$\dot{m}_r = \eta_V \cdot \rho_1 \cdot V_G \cdot N, \tag{1}$$

$$\eta_V = 0.73341 - 0.00003062 \cdot N + 0.04561 \cdot p_e - 0.01237 \cdot p_k. \tag{2}$$

The volumetric efficiency has been experimentally adjusted for the test facility compressor as a function of three independent variables [12–15], by means of a statistical software [16], showing that there is a statistically significant relationship among these variables with a confidence level of 99%.

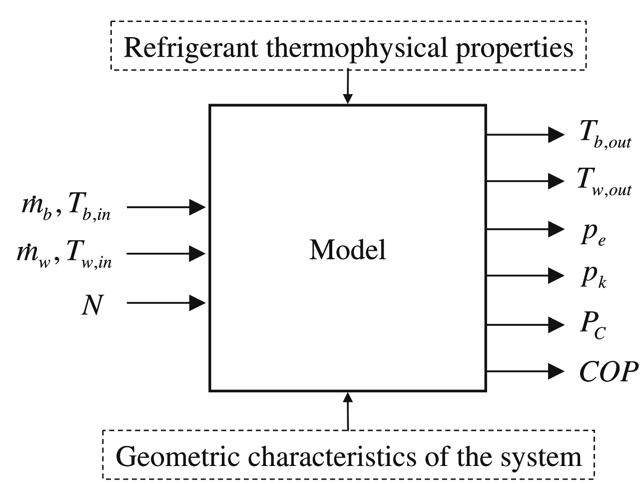

Fig. 1. Model scheme.