INTERNATIONAL JOURNAL OF REFRIGERATION 60 (2015) 174–189

Available online at www.sciencedirect.com

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A state-space dynamic model for vapor compression refrigeration system based on moving-boundary formulation

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ARTICLE INFO

Article history:
Received 25 July 2014
Received in revised form 23 May 2015
Accepted 18 July 2015
Available online 26 July 2015

Keywords:
Refrigeration system
State space
Dynamic model
Moving-boundary formulation

ABSTRACT

A transient response model for vapor compression refrigeration system has been developed in the paper. The system model contains four sub-models representing condenser, evaporator, compressor and electronic expansion valve (EEV). The condenser and the evaporator are developed based on the moving-boundary formulation. Through linearization, these dynamic models are transformed into state-space representation which is expressed in the form of matrix. The compressor and EEV adopt steady models because their thermal inertia is much smaller compared with the heat exchangers (i.e., condenser and the evaporator). The system model has been validated by experiment in terms of step change of EEV opening degree and heat load as well as ramp increase of inlet temperature of coolant oil of condenser. The results show that the model simulations have a good agreement with the experimental data. The simulation errors compared with the experimental data are mostly less than 10%. Since the model proposed in this study is expressed in the form of state-space matrix, they are featured by strong portability and high computation efficiency. It allows us to investigate the thermal dynamic characteristics of a refrigeration system under any complicated conditions and develop excellent control schemes.

Modèle dynamique espace-état pour un système frigorifique à compression de vapeur basé sur une formulation à limites mobiles

Mots clés : Système frigorifique ; Espace état ; Modèle dynamique ; Formulation à limites mobiles

1. Introduction

Vapor compression refrigeration systems, which are often employed to provide chilled media for space thermal environment control purposes in commercial and industrial applications, mainly comprise a single-speed compressor, a fixed-orifice expansion device, two heat exchangers (i.e., condenser and evaporator), and a volatile working fluid (named refrigerant)

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http://dx.doi.org/10.1016/j.ijrefrig.2015.07.027

Nomenclature

A	area of heat exchanger [m^2]
A_{val}	flow area of EEV [m^2]
c_p	specific heat at constant pressure [J (kg °C)$^{-1}$]
C_{val}	EEV orifice coefficient
d	diameter of pipe [m]
EEV	electronic expansion valve
F	cross-sectional area [m^2]
G	mass flow rate [kg s^{-1}]
g	gravitational acceleration [m s^{-2}]
h	enthalpy [J kg^{-1}]
L	length of flow [m]
M	molecular weight [g mol^{-1}]
N	compressor rotary speed [rpm]
n	polytrophic coefficient
Pr	Prandtl number
q	heat flux rate [W m^{-2}]
Re	Reynolds number
t	temperature [°C]
V	volume [m^3]
x	refrigerant vapor mass quality
Z	Hughmark correlation parameter
z	length coordinate [m]
α	convective heat transfer coefficient [W (m^2 °C)$^{-1}$]
γ	void fraction
ρ	density [kg m^{-3}]
τ	time [s]
η_v	compressor volume flow coefficient
λ	thermal conductivity coefficient [W (m °C) $^{-1}$]

Subscript

c	condenser
e	evaporator
f	coolant medium
hx	heat exchange
in	inlet
k	condensation
l	liquid
o	evaporation
oc	overcooling region
oh	overheated region
out	outlet
r	refrigerant
sat	saturated
tp	two phase region
v	vapor
vl	latent
wl	heat exchanger wall
0	initial conditions
1	condenser inlet/evaporator outlet
2	compressor outlet/condenser inlet
3	condenser outlet/EEV inlet
4	EEV outlet/evaporator inlet

that undergoes a reversed Rankine thermo dynamic cycle. To guarantee a stable space thermal conditions, the refrigeration system is required to regulate its cooling capacity to match the changing thermal load. Normally, the temperature of the cooled space is controlled by a thermostat that switches the refrigeration system on and off according to a cycling pattern. Recently, the refrigeration systems with variable-speed compressors have been widely employed in practice to obtain a continuous matching between the cooling capacity and the thermal load. It has been proved that the use of variable-speed compressor could improve significantly the overall energy performance of the refrigeration system (Tassou and Qureshi, 1998). Moreover, it has been also reported that the system performance improves further in cases where a variable-orifice expansion valves was additionally employed, as the evaporator is kept fully activated (i.e., flooded) during most of the system runtime (Aprea and Mastrullo, 2002; Choi and Kim, 2003). It is noteworthy that such refrigeration systems require proper control strategies for the simultaneous operation of a variable-speed compressor and a variable-orifice expansion valve (Schurt et al., 2010). In order to design good-performance controllers that can be applied to a broad range of operation, the dynamic models, which allow the simulation of its transient behavior for changing input conditions or control parameters, is very necessary to be developed.

There is a large amount of literature that deals with dynamic behavior of vapor compression chillers (Browne and Bansal, 2002; Deng, 2000; Fu et al., 2003; Grald and MacArthur, 1992; Leducq et al., 2006; Li et al., 2008; Liang et al., 2010; Llopis et al., 2008; McKinley and Alleyne, 2008; Navarro-Esbri et al., 2007; Rasmussen, 2006; Romero et al., 2011; Wang, 1998; Willatzen et al., 1998; Yao et al., 2013; Zhao and Zaheeruddin, 2005). These models can be classified into two groups: empirical models and physical models. The empirical models bring about convenience of model establishment for its quick identification from data (Leducq et al., 2006; Li et al., 2008; Navarro-Esbri et al., 2007; Romero et al., 2011), but they are only valid for a specific system or particular conditions. The physical models are based on detailed information of components in the system and their modeling using equations derived from physics laws. Since the physical models provide a greater insight into the physical processes occurring within the chillers under fluctuating conditions and assist us to develop some advanced control strategies that can potentially improve control performance of the system, they are still preferred by many researchers (Browne and Bansal, 2002; Deng, 2000; Fu et al., 2003; Grald and MacArthur, 1992; Liang et al., 2010; Llopis et al., 2008; McKinley and Alleyne, 2008; Rasmussen, 2006; Wang, 1998; Willatzen et al., 1998; Yao et al., 2013; Zhao and Zaheeruddin, 2005).

Wang (1998) built a dynamic model of centrifugal chiller to simulate the dynamics of a seawater-cooled chilling system controlled by EMCS on-line strategies. The dynamics of the chiller was simulated by assuming two thermal storages, one at the cooling water inlet of the condenser and the other at the chilled-water inlet of the evaporator. Deng (2000) presented a dynamic model for a direct expansion (DX) water-cooled air-conditioning system. The model was used to study the influence of refrigerant mass flow rate, evaporation pres-