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The novel use of phase change materials in refrigeration plant. Part 2: Dynamic simulation model for the combined system

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Abstract

A dynamic mathematical model for coupling the refrigeration system and PCMs has been developed in this paper. Overall the model consists of the following basic components: a compressor, a condenser, an expansion valve, an evaporator cooler and a PCM heat exchanger. The model developed here, is based on a lumped-parameter method. The condenser and evaporator were treated as storage tanks at different states, which have a superheat region, a two-phase region and a sub-cooled region. In the single-phase region the parameters are considered homogeneous whereas in the two-phase region, the intensive properties are considered as in thermal equilibrium. The compressor model is considered as an adiabatic process; an isentropic efficiency is employed in this process. The expansion process in the thermostatic expansion valve is considered as an isenthalpic process. The PCM is treated as a one-dimensional heat transfer model. The mathematical simulation in this study predicts the refrigerant states and dynamic coefficient of performance in the system with respect to time. The dynamic validation shows good agreement with the test result.

Keywords: Dynamic simulation; Refrigeration cycle; Phase change materials (PCMs); Thermal energy storage

1. Introduction

The mathematical simulation of a refrigeration plant was first demonstrated in the 1970s. The first mathematical model of a refrigeration system used algebraic equations derived from the assumption of steady state flow [1]. During transient operation, the refrigeration system components experience unsteady state operation. The refrigerant mass flow rate is continuously changing, which causes spatial variations in the refrigerant distribution in the system components as well as variable refrigerant states at the inlet and outlet of each component. Of the four major components in the vapour compression system, the transients in the heat exchangers are usually the slowest to respond and have the largest impact on system performance [2]. It is necessary to consider the mass distribution within the heat exchangers as a function of time and space, and this requires transient mass balances to allow for local storage. Thermal capacitances of heat exchangers and the refrigerant have to be considered to account for local energy storage.

James and James [3] and Cleland [4] have reported comprehensive surveys of mathematical models in the area of industrial refrigeration system simulation. Bendapudi and Braun [2] also have reviewed the dynamic simulation of the refrigeration system. Generally, heat exchanger models dealing with compressible two-phase flow fall into two categories: the lumped-parameter approach or the spatially distributed approach [7]. The lumped-parameter approach is generally employed to integrated with thermal environment simulation

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Nomenclature

A	area (m^2)
C_d	mass flow factor
h	enthalpy ($J\,kg^{-1}$)
m	mass flow rate ($kg\,s^{-1}$)
n	rotation speed of the compressor (rpm)
q	heat flux ($W\,m^{-2}$)
P_e	compressor power (W)
rh	fusion heat of PCM ($J\,kg^{-1}$)
S	stroke of piston (m)
T_f	heat transfer fluid temperature (K)
u	specific internal energy ($J\,kg^{-1}$)
$\dot{V}$	volume rate ($m^3\,s^{-1}$)
W	work ($kJ\,kg^{-1}$)
x	coordinate (m)
C_p	specific heat ($kJ\,kg^{-1}\,K^{-1}$)
D	diameter (m)
h_{fg}	latent heat ($J\,kg^{-1}$)
Δm	the refrigerant flashing back into the vapour region ($kg\,s^{-1}$)
N	wetted perimeter (m)
P	pressure (Pa)
R	thermal resistance ($°C\,m^2\,W^{-1}$)
r	radius (m)
T	temperature (K)
U	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
V	volume (m^3)
v	specific volume ($m^3\,kg^{-1}$)
X	displacement of valve needle (m)

Greeks

α	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
η_v	volumetric efficiency of the compressor
ρ	density ($kg\,m^{-3}$)
η_i	compressor isentropic efficiency
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
τ	time (s)

Subscripts

a	air side
cond1	gas region in the condenser
cond3	sub-cool region in the condenser
evap	evaporator
evap2	saturation region in the evaporator
G	gas
L	liquid
pcm	phase change material
r33	the outlet to the saturation region in the condenser r31
r4	the outlet to the condenser
r55	the inlet to the gas superheat region in the evaporator
sub	sub-cool
V,sat	saturation area in the evaporator
$''$	vapour parameters,
0	initial state
2	outlet, zone 2
cond	condenser
cond2	saturation region in the condenser
comp	compressor
evap1	superheat region in the evaporator
f	heat transfer fluid
i	inside
o	outside
r3	the outlet to the compressor the outlet to the gas region in the condenser
r5	the inlet to the evaporator
r6	the outlet to the evaporator
TEV	thermal expansion valve
w	pipe wall
$'$	liquid parameters
1	inlet, zone 1
$2'$	compressor outlet at real condition

because of less calculation and proper accuracy. The spatial distributed approach can reveal details of the flow and heat transfer in the heat exchanger in the refrigeration cycle, however, more calculation and lengthy time consumption are required. In this paper, the lumped parameters approach is used because the PCM heat exchanger model is integrated.

For lumped parameters model, Marshal and James [5] were the first to simulate a complex system. They used 46 ordinary differential equations (ODEs) and approximately 100 algebraic equations to simulate a vegetable freezer and its dedicated refrigeration system. Cleland [4] is probably the first to simulate a thermal environment which involves a large meat industry refrigeration system at three different evaporating temperatures. For the refrigeration system simulation, much work can also be found in Grald and MacArthur [6,7], He et al. [8,9], Willatzen et al. [10]. From these studies, the main assumptions of the transient model can be assumed as follows:

(1) Liquid and vapour refrigerant in the heat exchangers are in thermal equilibrium.
(2) Effects of pressure wave dynamics are negligible.
(3) Expansion is isenthalpic.
(4) Compression is adiabatic.
(5) Thermal resistances of metallic elements in the system are negligible in comparison with other thermal resistances, however, their capacitance is important.