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Dynamic model and experimental study of an air–water heat pump for residential use

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ABSTRACT

This paper presents a study of the dynamic behavior of a vapor compression heat pump for residential water heating. The mathematical models for heat exchangers are formulated by using mass, momentum, and energy conservation equations, while capillary tube model is based on the equations of conservation of momentum. The model is formulated from the manufacturer experimental data and the energy conservation balance. The contribution of this study to the field of dynamic modeling appears on the convergence of models of heat exchangers, this being accomplished with a variable error in spatial and time minimizing the instabilities in the calculation. The coupling among the four components allows the determination of the spatial and temporal profiles of temperatures, pressures and mass flow rates, as well as the refrigerant distribution in the heat exchangers during the water heating process. The validation of the model is done by comparison with the experimental results.

Modéle dynamique et étude expérimentale sur une pompe á chaleur résidentielle air-eau

Mots clés : modélisation ; expérience ; pompe á chaleur ; résidentielle ; eau chaude sanitaire

1. Introduction

Residential water heating by electric showers and similar equipment is responsible approximately for 26% of the residential electric energy consumption in Brazil (BEN, 2003). Therefore alternative ways to heat water for residential and commercial use are welcome as means for reducing the energy demand at peak hours and help to alleviate the risks of collapse of the national energy system, like what happened in 2002. With the objective of proposing an alternative water heating system which uses less electrical energy, the heat pump is considered a good option and for this reason is well

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Nomenclature

A	heat transfer area (m^2)
D	tube diameter (m)
F	friction factor
f_{LM}	Lockhart-Martinelli correction factor
G	mass velocity
H	specific enthalpy (kJ kg^{-1})
H	heat transfer coefficient (W m^{-2} K^{-1})
N	rotational speed (rpm)
M	mass flow rate (kg s^{-1})
P	perimeter
P	pressure (Pa)
ΔP	pressure drop (Pa)
A	heat transfer area (m^2)
T	temperature
V	piston volumetric displacement (m^3 h^{-1})
ν	specific volume (m^3 kg^{-1})
x	Quality

Greek symbol

α	void fraction
η	efficiency
ρ	specific mass
ω	humidity

Subscripst

1	input of the volume control
2	output of the volume control
a	air
cond	condensation
evap	evaporation
f	refrigerant
l	liquid
lv	liquid–vapor
pa	specific heat at constant pressure
va	specific heat at constant volume
v	vapor
ν	volumetric
w	wall

diffused in Europe. The heat pump uses the energy present in ambient air for water heating and hence a significant reduction of electrical energy consumed is achieved in comparison with electric showers. The advance of simulation techniques and computers displaced at least partially the traditional way of development complicated products, of components and systems, to a new approach using simulations and model analysis instead of the slow time consuming and expensive experimental work. Individual models for each component of a complex system as the heat pump, makes it possible to develop not only the components and system design but also investigate the viability of using alternative refrigerants that are not noxious to the ozone layer and ambient.

This paper presents the development and formulation of a numerical model to simulate the behavior of a heat pump for residential water heating, using R134a as refrigerant; the model is validated by comparing the numerical predictions with experimental results obtained from the experimental. The main goal is developing a low cost heat pump for residential water heating, as an efficient and potential substitute for residential electric showers and electric storage hot water tanks.

A major problem associated with the construction of dynamic models systems in vapor compression refers to modeling instabilities caused by transients starts (*start–stop*), the transition regions in the two-phase flow and variations in thermal load. A model should exhibit a balance between system complexity and the accuracy required to provide adequate information on the dynamic system behavior to be used as, for example, projects controllers or as a diagnostic tool.

Recently, some authors presented a method called "moving boundary" to contemplate such instabilities.

McKinley and Alleyne (2008) developed an advanced nonlinear switched heat exchanged model for vapor compression cycles using the moving boundary method. In this work the authors have developed a complete model of the vapor compression cycle that included non-circular tubes, fin effects, structure thermal resistance, air temp nonlinear distribution, upwind wall treatment for rezoning and variable number of zones. Although the work does not include an experimental validation of the model, note that the results were stable and the behavior of the temperature curves are fully consistent physical.

Two papers published recently Li and Alleyne (2009, 2010) a dynamic model for vapor compression cycles. These papers follow the same tendency in which the authors model a system of air-conditioning and refrigeration under dynamic on/off operation with switched moving boundary. The models developed in these works handle the dynamics of transitions states while keeping track of refrigerant vapor and liquid regions during start-stop transients. The great results show the potential for this dynamic switched model approach for controller designs for vapor cycling.

Liang et al. (2010) developed a dynamical lumped parameter model to simulate the transient behaviors of refrigeration system with variable capacity in both normal and abnormal conditions. The heat exchanger models were built using the moving boundary method for normal and abnormal modes by the discriminant of the enthalpy at outlet of the heat exchangers. The authors built a test system with variable frequency, water cooling condenser, evaporator and electronic expansion valve in order to validate the dynamic model. The results obtained from the simulations agree with the experimental results with acceptable error and show that the transient behavior of the system under abnormal conditions can be reliably calculated by the dynamic model when the rotary speed or the opening of electronic expansion valve changes abruptly.

Overall, one of the problems related to the construction of discrete models for simulation and analysis of vapor compression systems refers to disturbances caused by changes heat transfer conditions, which directly affect the dynamic behavior of mechanism of heat transfer, mass and momentum. In the case of evaporators and condensers these mechanisms show significant changes closely to the transition regions between two-phase and single-phase flow.

Discontinuity caused by the different correlations used, for example, to calculate the coefficient of heat transfer can lead