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Dynamic modeling study for a solar evaporator with expansion valve assembly of a transcritical CO_2 heat pump

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ABSTRACT

Recently, there has been an increased interest in natural fluids from industry and scientific community who see it as one of the most promising alternatives to replace the traditional CFCs and HCFCs, especially in heat pumps for residential water heating. This work presents an investigation of the behavior of the solar evaporator and expansion valve assembly of a transcritical CO_2 heat pump in transient and steady conditions. The dynamic behavior of systems using CO_2 as a refrigerant is significantly influenced by the dynamics of the heat transfer mechanisms. The solar evaporator model is based on the equations of conservation of mass, momentum, and energy. The model validation is realized by comparing simulation results and experimental data. The model is a useful tool for analyzing the behavior in transient and steady conditions simulating various operating conditions of the heat pump including solar radiation, ambient temperature, wind speed and atmospheric conditions.

Étude de modélisation dynamique pour un évaporateur solaire avec un assemblage de détendeur d'une pompe à chaleur au CO2 transcritique

Mots clés : CO2 ; Pompe à chaleur ; Modélisation dynamique ; Évaporateur solaire

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Nomenclature

A	heat transfer area/cross-sectional area [m^2]
D	tube diameter [m]
G	mass velocity [$kg\ s^{-1}\ m^{-2}$]
h	specific enthalpy [$J\ kg^{-1}$]
H	heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]
N	rotational speed [rpm]
$\dot{m}$	mass flow rate [$kg\ s^{-1}$]
p	perimeter
P	pressure [Pa]
$\bar{P}$	modified pressure [Pa]
S	solar radiation [$W\ m^{-2}$]
T	temperature [K]
U	overall coefficient of heat transfer [$W\ m^{-2}\ K^{-1}$]
v	specific volume [$m^3\ kg^{-1}$]
x	quality

Greek symbol

α	void fraction
β	evaporator inclination
η	efficiency
ρ	specific mass/reflectivity of the ground
θ	tube inclination

Subscripts

b	beam
cv	control volume
d	diffuse
e	external
evap	evaporator
f	fluid refrigerant
g	ground
i	internal/lower surface
IA	intermittent-annular
l	liquid
o	orifice
oc	outlet compressor
oe	outlet evaporator
ogc	outlet gas cooler
s	upper surface
strat	stratified
suc	suction
v	vapor
ν	volumetric
w	wall

1. Introduction

The increases in energy demand, depletion of fossil resources and environmental pollution problem have led to growth in interest in more efficient heating systems.

Heat pumps are one of the most efficient alternatives for energy saving in different applications such as water heating, heating spacing, cooling and drying, especially when associated with the use of renewable energy as can be observed in the works of Omer (2008), Chua et al. (2010), Goh et al. (2011), Omojaro and Breitkopf (2013).

Furthermore, the use of alternative refrigerants with low values of GWP and ODP plays an important role, due to the many constraints and regulations imposed by Kyoto and Montreal Protocols as demonstrated in the works of Esen (2004), Calm (2008), Babiloni et al. (2014) and Devecioğlu and Oruç (2015).

In this context, extensive research has been conducted for the purpose of identifying and quantifying critical variations in variables processes, heat pump components modeling, thermal performance analysis, alternative fluids efficiency analysis and economic feasibility as can be seen in the works of Esen (2000), Esen and Esen (2005), Kong et al. (2011), Rodríguez et al. (2012), Esen et al. (2015), Junghans (2015) and Liu et al. (2015).

The development of models for simulating the transient behavior of vapor compression machines is a topic of interest to the scientific community, especially when associated with the use of fluids considered environmentally friendly, as the case of CO_2. Models developed to simulate heating systems using conventional fluids cannot be used to model systems using CO_2 because the thermodynamic and transport properties of CO_2 are significantly different from the conventional fluids affecting directly the dynamic behavior.

The developed models have been used to analyze various situations, such as the control of the degree of superheat at the evaporator, problems related to starting heat pumps and instabilities associated with the evaporator and expansion valve.

Recent studies (Sarkar, 2009; Sarkar et al., 2010; Yang et al., 2010; Minetto, 2011; Islam et al., 2012) have discussed theoretical and experimental modeling of heat pumps operating with CO_2 in transcritical mode. However, they only presented models of the steady condition, without reference or comparison studies to the transient region. The relevance of the work presented here refers to modeling the dynamic behavior in transient and steady regimes of a heat pump operating with solar evaporator using CO_2 in transcritical mode.

To perform a theoretical and experimental analysis of solar evaporator and expansion valve assembly of the heat pump operating with CO_2, knowledge of the heat transfer mechanisms, mass and momentum are key to the development of models due mainly to the different thermodynamic and transport properties of CO_2 when compared to conventional refrigerants. In addition to these factors, the use of a solar evaporator implies an increase in complexity of the phenomena associated with the heat transfer process due to the variation of solar radiation, wind speed and the condensation of water vapor from atmospheric air on the external surface of the solar evaporator, which affects the transient behavior of the heat pump.