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Experimental and numerical investigations of a new high temperature heat pump for industrial heat recovery using water as refrigerant

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ABSTRACT

A new high temperature heat pump using water as refrigerant has been designed and built for testing on a laboratory test bench that reproduces the operating conditions of real-case industrial applications. Experimental investigations of this heat pump were carried out in the condensing temperature range of 130–140 °C. A new dynamic model has also been developed using Modelica to take into account the presence of non-condensable gases and the purging mechanism. In addition, a new combined finite-volume and moving boundary method (FV-MB) approach is applied for the plate heat-exchanger models and a moving boundary (MB) approach between phases is implemented for the models of the purging and the flash evaporation systems. The start-up phase of this high-temperature heat recovery and heat enhancement of the heat pump are simulated experimentally and numerically. A comparison between both results is presented and analyzed. Global energy savings and the environmental benefits have been illustrated.

Etudes expérimentales et numériques d'une nouvelle pompe à chaleur à température élevée pour la récupération de chaleur utilisant l'eau comme frigorigène

Mots clés : Pompe à chaleur à température élevée ; Fluide actif à l'eau ; Modélisation Modelica ; Régime transitoire ; Procédure de mise en route

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Nomenclature

a,b,c,d,e,f	coefficients
A	section area, m^2
c_p	specific heat, J kg^{-1} K^{-1}
C_{scf}	surface enhancement correction factor, –
D	diameter, m
G	mass flux, kg m^{-2} s^{-1}
h	specific enthalpy, J kg^{-1}
K_v	flow coefficient, l mn^{-1} bar^{-1}
L	length, m
M	mass, kg
$\dot{m}$	mass flow rate, kg s^{-1}
P	pressure, Pa
P'	partial pressure, Pa
Pr	Prandtl number, –
$\dot{Q}$	heat transfer rate, W
Re	Reynolds number, –
t	time, s
T	temperature, °C
V	volume, m^3
X	mass fraction of refrigerant in the mixture, –

Greek letters

α	heat transfer coefficient, J m^{-2} K^{-1}
Δ	difference, –
λ	thermal conductivity, $W(mK)^{-1}$
λ'	friction coefficient, –
ρ	density, kg m^{-3}
ψ	partial pressure fraction, –

Subscripts and superscripts

a	dry air
cond	condensation
g	gas
h	hydraulic
i	ith élément
in	inlet
k	kth élément
l	liquid
m	mixture
out	outlet
p	plate's wall
r	refrigerant
w	water
COP	coefficient of performance
FV	finite volume
MB	moving boundary
ODP	ozone depletion potential
TEWI	total equivalent warming impact
VFR	volume flow rate

1. Introduction

Due to the increase of oil prices, energy efficiency improvement has become a major challenge for all energy systems (FY, 2010). This challenge involves a reduction of the fuel consumption of industrial processes through better recovery of waste process heat and using it to meet heating requirements. Otherwise, the environmental context involves a strong awareness concerning emission reduction.

Several studies have been performed to assess numerous discharges of large amounts of heat losses at 80 °C–90 °C in different sectors like paper drying, distillation, etc. Nevertheless, the operation of applications requires higher levels of temperature, typically 120 °C–130 °C (Berail, 2009; Dupont and Sapora, 2009; US Department of Energy, 2003). A high temperature heat pump technology can be used to recycle these wastes for use at higher temperatures. In some applications this technology could replace burning fossil fuel for heating while greatly reducing CO_2 emissions. It can also be extended to be combined with renewable energies such as solar energy and geothermal energy to meet heating and hot water requirements (Bi et al., 2004; Kaygusuz, 1995; Li and Yang, 2009; Liu et al., 2005; Zhang et al., 2010).

Presently, the heat pumps implemented in different industries are limited to heat production at a temperature of 100 °C. Therefore the development of a new industrial high temperature heat pump using a natural refrigerant represents a step toward improving industrial energy efficiency while reducing environmental impact, which is the goal of the present work.

Alternative synthetic refrigerants have been proposed to replace prohibited working fluids in residential air-conditioners and industrial heat pumps (Parka et al., 2007, 2008; Parka and Jung, 2009). These working fluids are still harmful for the environment and are not adapted to high temperature levels.

In this study, experimentations reproducing industrial operating conditions are carried out to estimate the potential of a high temperature heat pump using water as working fluid. The technological choices, electrically-driven heat pump design and test bench are presented. The present work explains why this experimental setup meets technologically challenging. Indeed, the use of water needs adequate compressor (operating at required phase change temperature levels) which can simultaneously meet the requirements of high compression ratio, high efficiency and low cost of investment. Another drawback is due to the subatmospheric evaporation pressure which induces the air inlets in the heat pump which must be purged and the reduced densities at the low pressure side which impose large components.

A new dynamic model of the heat pump has been developed to take into account the presence of non-condensable gases and the purging mechanism (purging reservoir), especially during the start-up procedure. A new combined finite-volume and moving boundary method (FV–MB) approach has been developed and used for the plate heat-exchanger models while a moving boundary (MB) approach between phases is implemented for the models of the purging and flash evaporation systems. The models are developed using Modelica as a modeling language (Fritzon, 2003; Modelica