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Scroll compressor modelling for heat pumps using hydrocarbons as refrigerants

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ABSTRACT

Hydrocarbons are today considered as promising alternatives to hydrofluorocarbons thanks to their low environmental impact and their easy implementation. However, some precautions have to be taken to thwart their flammability. European regulations impose to take stringent measures regarding components and to install heat pumps in unoccupied spaces. Nevertheless manufacturers keep working on components for hydrocarbons. In the frame of a research project on heat pumps for simultaneous heating and cooling, an R407C prototype working with a scroll compressor was built and tested. A near-industrial prototype is today being designed for propane with the help of recent modelling techniques. After having detailed the main issues regarding hydrocarbons as refrigerants, this article reviews scroll compressor modelling studies and presents the development of a thermodynamically realistic scroll compressor model. It was first developed for R407C and then adapted to thermodynamic properties of hydrocarbons and to other sizes of compressors.

Modélisation des compresseurs à spirale pour pompes à chaleur utilisant des hydrocarbures comme frigorigènes

Mots clés : Compresseur ; Spirale ; Modèle ; Hydrocarbures

1. Introduction

The study presented in this article is a part of a project on heat pumps for simultaneous heating and cooling (HPS), in which our research team worked on the implementation of R407C and natural refrigerant CO_2 (Byrne et al., 2009). At that stage of the project, we were not able to build a near-industrial CO_2 HPS because components were not easily available for the high operating pressures involved in the transcritical cycle of carbon dioxide. A first R407C prototype providing 15 kW heating capacity was then built, tested and simulated (Byrne et al., 2011a, 2011b, 2012). It can produce hot and cold water in two different water tanks at the same time (simultaneous mode), only hot water (heating mode) or only cold water (cooling mode). The main characteristic of the HPS is to operate using an alternation of two modes during winter. In a heating mode, the HPS produces heat and also stores some energy recovered by subcooling of the refrigerant in the cold water tank (not or rarely used for

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Nomenclature

Letter symbols:

A	heat exchange surface area (m^2)
D	hydraulic diameter (m)
e	edge length of a cube (m)
h	enthalpy (J kg^{-1})
HP	high pressure (Pa)
LP	low pressure (Pa)
$\dot{m}$	mass flow rate (kg s^{-1})
n	polytropic exponent (–)
Nu	Nusselt number (–)
P	pressure (Pa)
Pr	Prandtl number (–)
$\dot{Q}$	thermal capacity (W)
Re	Reynolds number (–)
T	temperature (K)
U	heat transfer coefficient (W m^{-2} K^{-1})
u	velocity (m s^{-1})
V_s	swept volume (m^3 s^{-1})
$\dot{W}$	compression work (W)

Greek symbols:

γ	isentropic exponent (–)
λ	thermal conductivity (W m^{-1} K^{-1})
ν	viscosity (m^2 s^{-1})

Superscripts:

n	polytropic exponent (–)
γ	isentropic exponent (–)
m	parameter for Dittus–Boelter correlation

Subscripts:

0	original value
amb	ambient
cd	condensation
ev	evaporation
ex	exhaust
HC	hydrocarbon
in	internal
nom	nominal
su	suction
w	wall

Abbreviations:

ATEX	explosive atmospheres
COP	coefficient of performance (–)
DHW	domestic hot water
GWP	global warming potential (kg_{CO_2})
HC	hydrocarbon
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
HPS	heat pump for simultaneous heating and cooling
LMTD	logarithmic mean temperature difference (K)
TEWI	total equivalent warming impact (kg_{CO_2})

cooling during winter). The water tank temperature rises up to a set point and the simultaneous mode is launched. During the simultaneous mode operation, the heat pump performance is increased thanks to a higher evaporating temperature using temperature-controlled water than using ambient air as a heat source. The objective of developing a second prototype with a near-industrial design using a fluid with low environmental impact is still the main goal of the project. HFOs being protected by patents were taken out of the list of the possible environmentally friendly refrigerants. The corrosive effect of ammonia in presence of copper would have led us to buy more expensive components made of stainless steel. Our heat pump would also have been submitted to more restrictive regulations. Finally, CO_2 technology staying difficult to acquire easily and to handle, we chose to use propane for the new prototype as this fluid is the most commonly used hydrocarbon for the applications of the HPS. The refrigerant charge of this prototype is less than 5 kg, which is the charge limit for category A (general occupancy) and indirect systems according to European regulation EN 378 (2008), corresponding to systems in which all the refrigerant containing parts are located in an unoccupied machinery room or in open air of unoccupied spaces. The issues regarding the implementation of a scroll compressor instead of a reciprocating compressor to this new HPS prototype working with a hydrocarbon are discussed in this study. Scroll compressors are well adapted to the applications targeted in our project and show higher efficiencies, low torque variations, low noise, reliability and tolerance to refrigerant droplets (Winandy et al., 2002a).

The objectives of this article are first to give the characteristics of hydrocarbons that are important for the application of low to medium capacity heat pumps, then to review the modelling techniques available in the literature to assess the performance of scroll compressors and finally, to present the development of a simplified scroll compressor model for future performance evaluation of a heat pump for simultaneous heating and cooling working with propane. The model was first developed for a R407C scroll compressor and validated using experimental results. Then the model was adapted to refrigerants R290 (propane), R600a (isobutane) and R1270 (propylene or also called propene). A simulation comparison is carried out to evaluate the mass flow rate and input power discrepancies and discharge temperature differences between R407C and hydrocarbons. Finally an adaptation procedure was applied to the model to deal with a change of the compressor size. The simulation results are compared to experimental data obtained on a homemade prototype or another set of data provided by a compressor manufacturer.

2. Hydrocarbons as refrigerants

Since decades hydrocarbons have been used in some applications such as domestic refrigeration and small capacity exhaust air heat pumps (Granryd, 2001) but they have not yet entered some markets on which their thermodynamic and environmental properties would have let them become alternatives to R22. This paragraph presents the main characteristics of hydrocarbons that explain this situation such as safety and standards, environmental impact and thermodynamic properties.