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Semi-empirical modelling of a variable speed scroll compressor with vapour injection

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ABSTRACT

Vapour injection scroll compressors are nowadays gaining attention in vapour compression systems, especially in high temperature lift application, due to the advantages they provide. To date, proposed models of this kind of compressor are mainly deterministic models, requiring a detailed description of compressor geometry and allowing, in turn, minute calculation of the refrigerant state as function of orbiting angle. Semi-empirical models are largely proposed for standard scroll compressors in order to accurately compute compressor performance without the need of the knowledge of compressor geometrical feature. In this paper, a semi-empirical model of a variable speed scroll compressor with vapour injection is introduced and validated over a set of 63 experimental data finding that 89%–98% of calculated suction and injection refrigerant mass flow rates, compressor electrical power and refrigerant temperature at compressor discharge agree within ±5%, ±10% or ±5 K with respect to the experimental values.

Modélisation semi-empirique d'un compresseur à spirale à vitesse variable avec système d'injection de vapeur

Mots clés : Modélisation ; Compresseur à spirale ; Injection de vapeur ; Vitesse variable

1. Introduction

Scroll compressors are widely used in air conditioning and refrigeration industry due to their many positive characteristics such as few moving parts, low torque variation, low level of noise and vibration, high efficiency, high reliability and tolerance to refrigerant droplets. The scroll was invented by Creux (1905) at the beginning of 20th century but, due to the very small tolerances required for its manufacturing, it has been possible to start large scale production only in the seventies. Since then, many studies have been carried out to

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Nomenclature

A	Area [m^2]
BVR	Built-in volume ratio [dimensionless]
c_P	Isobaric specific heat [J kg^{-1} K^{-1}]
f	Rotational frequency [Hz]
h	Enthalpy [J kg^{-1}]
$\dot{m}$	Mass flow rate [kg s^{-1}]
NTU	Number of transfer unit [dimensionless]
p	Pressure [kPa]
$\dot{Q}$	Heat transfer rate [W]
s	Entropy [J kg^{-1} K^{-1}]
T	Temperature [K]
UA	Overall heat transfer coefficient [W K^{-1}]
$\dot{V}$	Volumetric flow rate [m^3 s^{-1}]
$\dot{W}$	Work transfer rate [W]

Greek symbols

α	Coefficient of proportionality in losses expression [dimensionless]
γ	Ratio of isobaric to isochoric specific heat capacity [dimensionless]
ε	Effectiveness [dimensionless]
ρ	Density [W m^{-3}]

Subscripts

1…9	Refrigerant state
ADP	Adapted conditions
AMB	Ambient
CALC	Calculated
COMP	Compressor
CRIT	Critical
DIS	Discharge
EXP	Measured experimentally
INJ	Injection
INT	Internal
LEAK	Leakage
LOSS	Lost
REF	Reference or refrigerant
SUC	Suction
THR	Throat
VCi	i-th Virtual Compressor
W	Wall

improve the compressor performance resulting in advanced technologies such as variable speed, liquid and vapour injection or flooded compression. Among them, the technology of refrigerant injection has gained increasing attention in high temperature lift application due to its inherent benefits such as the increase of system capacity (Wang et al., 2009c; Xu et al., 2013), the intrinsic modulation of system capacity trough injected refrigerant mass flow rate variation (Wang et al., 2009c; Xu et al., 2013) and the reduction of the refrigerant temperature at compressor discharge with the related enlargement of compressor operating envelope (Joppolo et al., 2010). However, despite the advantages this kind of compressor provides, the optimal control strategy (Xu et al., 2011; Heo et al., 2012) as well as the optimal architecture (Ma and Zhao, 2008; Wang et al., 2009a; Roh and Kim, 2011, 2012; Heo et al., 2011) of a vapour compression system equipped with it is still under investigation.

In this context, the development of a mathematical model of a scroll compressor with vapour injection may be helpful in supporting the analysis of system configuration or control. Indeed, many studies available in the open literature have deserved attention to the simulation of vapour injection scroll compressor but, differently from the modelling of standard scroll compressor where three distinct modelling techniques (geometrical, semi-empirical and empirical modelling) are largely proposed (Byrne et al., 2014), for the vapour injection scroll compressor mainly geometrical models are mainly proposed with few exceptions as discussed below.

Park et al. (2002) developed a deterministic model of a variable speed scroll compressor with vapour injection working with R22. The model was validated considering only the no injection condition showing deviations of the predicted compressor capacity and electrical power lower than 10% with respect to the experimental ones. The model was then used to investigate the influence of geometrical (injection hole diameter and position) and thermodynamic (refrigerant pressure and quality or superheat) injection parameters on compressor working parameters as function of rotational frequency. An optimal configuration leading to an increase of COP equal to 12% COP was found.

Winandy and Lebrun (2002) developed a semi-empirical model of a fixed speed scroll compressor with refrigerant injection working with R22. The semi-empirical model was able to calculate the refrigerant mass flow rate, the compressor electrical power and the refrigerant temperature at compressor discharge. The validation was carried out considering the no injection condition, the vapour injection condition and the liquid injection condition showing deviations of the predicted refrigerant mass flow rate in the range $-4.5\% - +4\%$ (with the exception of one liquid injection point where the deviation was $+13.5\%$), of the compressor electrical power in the range $-4.5\% - +4.5\%$ and of the refrigerant temperature at compressor discharge in the range -5 K $- +5$ K. No information about the validation of predicted injection mass flow rate was given.

Ma and Chai (2004) developed and validated (data from Ma et al. (2003)) a thermodynamic model of the compression process inside a fixed speed scroll compressor with vapour injection working with R22. Although the model was validated only in a single working condition, the agreement between calculated and experimental data was within $-1\% - +6\%$. The model was then used to investigate the influence of refrigerant injection pressure on compressor working parameters as function of evaporating temperature. Different injection pressures for maximum heating capacity or COP were found.

Wang et al. (2008) developed and validated a deterministic model of a fixed speed scroll compressor with vapour injection working with R22. The model was validated under different working conditions showing deviations of the predicted refrigerant mass flow rate, injected mass flow rate, compressor electrical power and refrigerant temperature at compressor discharge in the range $-4\% - +3\%$. A sensitivity analysis of the model was then carried out leading to the conclusion that both the heat transfer between the scroll wraps and the refrigerant and the back-pressure pocket