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Optimal operational efficiency of chillers using oil-free centrifugal compressors

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A B S T R A C T

In chiller design, oil-free variable-speed centrifugal compressors are becoming increasingly popular. However, the management of systems equipped with this kind of compressor is a non-trivial task. This work focuses on the efficient operation of variable-speed air-condensed chillers with variable-speed centrifugal compressors paired with (oil-free) magnetic bearings. Multiple operating conditions, at any moment in time, together with wide cooling ranges and potentially high energy efficiencies during off-peak demands create the need for an open-loop energy optimisation strategy via an efficiency-based fitness function. The physical variables of this function and their constraints are discussed including several variable dependencies. The problem of devising strategies for improving chillers' efficiency is here formulated as a model-based optimisation and it is solved by means of an ad hoc hybrid algorithm which combines a deterministic method and stochastic one. The results of simulations, which are based on two chiller layouts, show the potential of the proposed approach.

Efficacité opérationnelle optimale des refroidisseurs fonctionnant avec des compresseurs centrifuges sans huile

Mots clés : Refroidisseur ; Compresseur centrifuge ; Paliers magnétiques ; Optimisation d'énergie ; Algorithme de recherche gravitationnel

1. Introduction

Air-conditioning accounts for a large portion of the energy consumed by industrial and commercial facilities, with 30–40% of energy consumed by chillers (Saidur et al., 2011). Therefore, optimal operational efficiency of chillers plays an important role within HVAC systems.

Regarding chillers, the use of variable-speed centrifugal compressors paired with (oil-free) magnetic bearings produces several advantages as compared to conventional volumetric compressor technology (e.g. reciprocating, scroll, or screw). This

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Nomenclature

Acronyms

DLL	dynamic link library
EA	evolutionary algorithm
EER	energy efficiency ratio ($P_e P_{in}^{-1}$)
EEV	electronic expansion valve
GA	genetic algorithm
GSA	gravitational search algorithm
HVAC	heating, ventilation and air conditioning
IGV	inlet guide vanes
LM	Levenberg–Marquardt
PLR	part load ratio ($P_e P_{e,100\%}^{-1}$)
PSO	particle swarm optimisation
rpm	revolutions per minute
VSD	variable speed driver

Symbols

Δp_{air}	air pressure loss [kPa]
$\dot{m}_{ref}$	refrigerant mass flow rate [kg s^{-1}]
$\dot{Q}_c$	rejected heat [kW]
$\dot{Q}_e$	cooling demand [kW]
igv_{cmp}	opening of the compressor's inlet guide vane [%]
N_{cmp}	number of active compressors per circuit [–]
P_e	chiller cooling capacity [kW]
P_{cmp}	compressor input power [kW]
$P_{e,100\%}$	maximum chiller cooling capacity [kW]
P_{fan}	fan input power [kW]
P_{in}	overall input power ($P_{cmp} + P_{fan}$) [kW]
rpm_{cmp}	compressor shaft speed [rpm]
rpm_{fan}	fan speed [rpm]
T_c	saturated discharge temperature [°C]
T_e	saturated suction temperature [°C]
T_{air}	external air temperature [°C]
T_{in}	evaporator inlet water temperature [°C]
T_{out}	evaporator outlet water temperature [°C]
T_{sp}	chilled water supply set-point [°C]

setup promises significant reductions in energy consumption and environmental emissions associated with energy production (Pacific Northwest National Laboratory, 2012). Centrifugal compressors with magnetic bearings and the finest screw compressors offer similar efficiencies when chillers are at peak load whereas, at part load, these centrifugal compressors ensure the highest available efficiency when integrated with a variable frequency drive.

This type of turbo-machinery combined with a variable frequency drive and magnetic bearings is not just more energy efficient for chillers; it is frictionless and noiseless with virtually no structure borne vibration due to the absence of mechanical contact. Further, less maintenance is needed through the elimination of wear, oil and oil management systems and the whole chiller layout becomes more compact and lightweight (Conry et al., 2002; Kus and Nekså, 2012). Nevertheless, this technology adds other mechanical and electrical complications (e.g. centrifugal compression, auxiliary feedback controls, touchdown bearings, etc.), see Fig. 1.

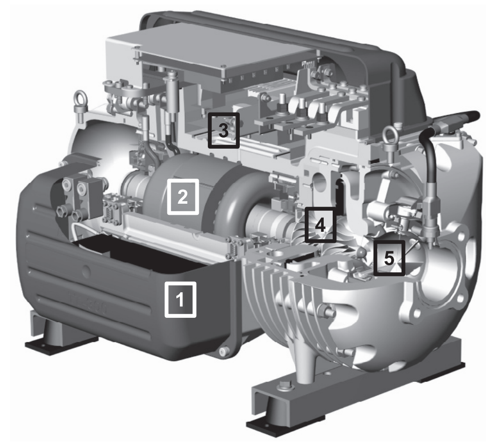

Fig. 1 – Oil-free variable-speed centrifugal compressor (Danfoss Turbocor: Danfoss, 2012): (1) motor and bearing control; (2) permanent magnet motor; (3) inverter speed control; (4) two-stage, direct drive, hermetic centrifugal compressor; (5) inlet guide vane.

1.1. *Literature review*

Chillers are a major contribution to operating costs for building managers (i.e. energy and maintenance costs). Common chiller management adapts the modes of operation whenever load demand changes, but usually energy consumption is not considered. Maximisations or minimisations of certain efficiency-based fitness functions can improve significantly the operational efficiency of these machines (at full load, but mostly at part-load). The automation system in the back is a two-layer hierarchical structure: an optimisation layer, which computes the appropriate operating conditions, and a control layer, which keeps the controlled variables at the specified set-points (Beghi et al., 2011, 2012). Open-loop computation on non-linear steady-state process models is part of the optimisation layer and it feeds the control layer which is mainly based on feedback information.

Several studies regard the optimisation of chiller and multiple-chiller operation (Ardakani et al., 2008; Chang et al., 2005, 2006; Congradac and Kulic, 2012; dos Santos Coelho et al., 2014; Lee et al., 2011; Ma and Wang, 2011), few papers deal with air-condensed centrifugal chillers efficient operation (Yu and Chan, 2008), and to the best of the authors' knowledge, no work focuses on chillers using the new generation of variable-speed centrifugal compressors with magnetic bearings, see Fig. 1. This paper completes a previous conference version (Beghi et al., 2012). There is more emphasis on the dependencies among the physical variables, their effect on the energy efficiency of the compressor and, consequently, on the whole chiller. A better understanding of the physical problem, together with new tests on more complicated multi-compressor and multi-circuit systems, also suggests a practical energy optimisation strategy which is independent of any numerical optimisation. Lastly, additional details regarding the chiller model and the chiller data (in the Appendix) increase the reproducibility of the results.