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Development of an internal air cooling sprayed oil injection technique for the energy saving in sliding vane rotary compressors through theoretical and experimental methodologies

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ABSTRACT

The present work highlights the energy saving potential of the lubricant fluid supplied in Sliding Vane Rotary air Compressors. A Lagrangian theoretical model of a sprayed oil injection technology assessed the cooling effect of the lubricant due to the high surface to volume ratio of the oil droplets and predicted a reduction of the indicated power. The model validation was carried out through a test campaign on a mid-size sliding vane compressor equipped with a series of pressure swirl atomizers. The oil injections took place along the axial length of the compressor. The reconstruction of the indicator diagram and the direct measurement of the mechanical power revealed a reduction of the energy consumption close to 7% using an injection pressure of 20 bar. A parametric analysis on the injection pressure and temperature and on the cone spray angle was eventually carried out to identify an optimal set of operative injection parameters.

Développement d'une technique de refroidissement d'air interne à injection d'huile aspergée pour les économies d'énergie dans des compresseurs rotatifs à palettes mobiles grâce à des méthodologies théoriques et expérimentales

Mots clés : Compresseur rotatif à palettes mobiles ; Systems à air comprimé ; Injection d'huile ; Buse à tourbillon sous pression ; Diagramme à indicateur ; Transducteur à pression piézoélectrique

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Nomenclature

γ	half of cone spray angle [deg]
θ	angular coordinate [deg]
λ	latent heat of vaporization [J]
μ	dynamic viscosity [Pa s]
ρ	density [kg/m^3]
σ	surface tension [N/m]
ω	revolution speed [RPM]
c_p	specific heat at constant pressure [J/kg/K]
d	droplet diameter [m]
k	thermal conductivity [W/m]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
n	number [–]
p	pressure [Pa]
B_M	Spalding mass transfer number [–]
B_T	Spalding heat transfer number [–]
C_d	drag coefficient [–]
D	molecular diffusivity [m^2/s]
F	force [N]
Nu	Nusselt number [–]
Pr	Prandtl number [–]
$\dot{Q}$	thermal power [W]
R	radius [m]
Re	Reynolds number [–]
Sc	Schmidt number [–]
Sh	Sherwood number [–]
T	temperature [K]
V	velocity [m/s]

Subscripts and superscripts

a	air
cor	Coriolis
d	droplet
ev	evaporation
inj	injection/injector
m	air-oil vapors mixture
o	oil
or	orifice
*	corrected

1. Introduction

Compressed air accounts for a mean 10% of the global industrial electric energy consumptions (Radgen, 2001) and this share may reach 20% if commercial and residential needs are included (portable tools, air pumps, pneumatic heating, ventilation, air conditioning, etc) (US Department of Energy, 2003). In order to accomplish global energetic and environmental commitments, energy saving is nowadays recognized as the main action that needs to be put into action. Within this framework, in Compressed Air Systems (CAS) lots of saving measures have been employing with efforts upstream and downstream of the compressed air production: pipeline leakages reduction, CAS design, adjustable speed drives, optimization of the end use devices, frictional losses, etc. As concerns the compressor technology, the saving potential was estimated to be around 10–20 % (740 TWh in 2012) (Cipollone and Vittorini, 2014; Vittorini et al., in press). In industrial applications, rotary volumetric machines are the most widespread technology in the range 7–12 bar and flow rates less than 1000 m^3/min with an electrical power from a few kW to several hundred kW. Among them, Sliding Vane Rotary Compressors (SVRC) represent only few points percent of the overall market. However, they have some intrinsic features which state an unforeseen potential. Indeed, a recent study on the energy reduction perspectives in positive displacement machines stated that SVRCs behave more efficiently than screw compressors if on\off load conditions were taken into account while estimating the energy consumptions (Cipollone, 2014). In order to additionally increase the premium performance of SVRCs, a thermodynamic improvement was highlighted approaching the current adiabatic transformation towards an isothermal one by means of a sprayed oil injection technology that preliminary demonstrated its ability to internally cool the air during the compression phase (Cipollone et al., 2012, 2013, 2014).

The performance enhancement through a sprayed oil injection technology has been assessed almost exclusively on screw compressors. Mathematical models on heat transfer between oil droplets and air have been set up (Seshaiah et al., 2007; Stosic et al., 1988) as well as experimental activities on the sole atomizers (Paepe et al., 2005) or the whole compressor test rig have been carried out (Stosic et al., 1992; Fujiwara and Osada, 1995), even using different working fluids (Seshaiah et al., 2010). Among them, a reduction on the energy consumptions from 2.8 % to 7.4 % was assessed (Stosic et al., 1992). The roles of the main injection parameters have been investigated: injection pressure and temperature, oil flow rate, orifice diameter (Paepe et al., 2005), injectors positioning (Ferreira et al., 2006), etc.

In the current work, the Authors pursued the investigation of the effects due to spraying the oil in sliding vane compressors presenting a comprehensive theoretical model for the axial injection. The model was further validated through tests on a mid-size SVRC equipped with pressure swirl nozzles. A series of piezoelectric pressure transducers allowed to assess an overall matching between the simulations and the experimental indicator (pressure-Volume) diagram. A parametric analysis on the main injection operating parameters eventually addressed further improvements to the innovative injection technology.

2. Axial oil injection modeling

The oil sprayed injection was modeled following a lumped parameter approach for the thermodynamics of the compressor cells, while a Lagrangian one was adopted to track the oil particles and their interactions with air. The injectors were located on a side cover of the machine such that the oil droplets sprayed propagated along the axial direction of the compressor. The model aimed at understanding the interactions between oil sprays and compressing air in order to identify the optimal set of injection parameters to address the experimental activity. To ease the computations without