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Small-scale turbocompressors for wide-range operation with large tip-clearances for a two-stage heat pump concept

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ARTICLE INFO

Article history:
Received 9 May 2016
Received in revised form 7 June 2016
Accepted 8 June 2016
Available online 14 June 2016

Keywords:
Two-stage heat pump
Small-scale turbocompressors
Two-zone meanline modeling
Tip-clearance effects
Optimum blade design
Computational fluid dynamics (CFD)

ABSTRACT

Two mechanically driven small-scale turbocompressors running on gas lubricated bearings have been theoretically designed for a 6.5 kW two-stage heat pump functioning under variable operating conditions. The novelty in the heat pump system lies in the application of oil-free turbocompressor technology and the introduction of unused heat from various secondary heat sources. Managing the heat pump operational deviations with the secondary heat is difficult for the turbocompressors. The turbocompressors can potentially exceed their operating range defined by the surge, choke and maximum rotational speed margins. Furthermore, regulating the tip-leakage flow caused by large tip-clearances in small-scale turbomachinery is challenging. This paper will guide the readers through different stages of the design process of small-scale turbocompressors subjected to different operational and design constraints. The design review and the presented methodology will help the designers make suitable parameter selections for achieving high efficiency and wide compressor operating range.

Turbocompresseurs de petite taille pour un fonctionnement sur une large plage avec des jeux radiaux importants pour un concept de pompe à chaleur bi-étagée

Mots clés : Pompe à chaleur bi-étagée ; Turbocompresseurs de petite taille ; Modélisation de la ligne moyenne de deux zones ; Effets des jeux radiaux ; Conception optimale d'aube ; Mécanique numérique des fluides (CFD)

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http://dx.doi.org/10.1016/j.ijrefrig.2016.06.015

Nomenclature

a	speed of sound [$m\ s^{-1}$]
A	area [mm^2]
b	height or width [mm]
c	absolute velocity/coefficient [$m\ s^{-1}$/ –]
c_f	skin friction coefficient [–]
C_p	pressure recovery coefficient [–]
COP	coefficient of performance [–]
d	diameter [mm]
d_s	specific diameter [–]
DR	diffusion ratio [–]
i	incidence angle [deg]
k	relative surface roughness [–]
K	pressure loss coefficient [–]
$\dot{m}$	mass flow rate [$kg\ s^{-1}$]
M	Mach number [–]
n_s	specific speed [–]
N	rotational speed [min^{-1}]
p	pressure [Pa]
P	power [kW]
$\dot{Q}$	heat capacity [kW]
r	radius [mm]
R	range [–]
Re	Reynolds number [–]
SP	sizing parameter [–]
t	thickness/tip-clearance [mm/mm]
T	temperature [K]
u	blade speed [$m\ s^{-1}$]
w	relative velocity [$m\ s^{-1}$]
z	axial distance [mm]
α	absolute angle from the meridional axis [deg]
β	secondary heat fraction/relative angle from the meridional axis [– /deg]
χ	secondary mass flux fraction [–]
Δ	difference [%]
ε	relative tip-clearance [–]
η	efficiency [%]
λ	swirl parameter [–]
Λ	blade loading coefficient [–]
ν	kinematic viscosity [$m^2\ s^{-1}$]
θ	wrap angle [deg]
ρ	density [$kg\ m^{-3}$]
Φ	global flow coefficient [–]
Π	pressure ratio [–]
ψ	azimuthal angle [deg]

Subscripts

b	blade
c	critical, centroid
$cond$	condenser
clr	clearance
des	design
$evap$	evaporator
h	hub/hydraulic
int	intermediate
m	meridional/mixed-out
nd	non-dimensional
rel	relative
rot	rotor
sec	secondary
t	tip
vld	vaneless diffuser
vol	volute
θ	tangential
ψ	azimuthal angle
0	duct inlet/total condition
1	impeller inlet
2	impeller outlet
5	diffuser outlet
6	scroll outlet
7	volute outlet

Superscripts

–	average or mean value

1. Introduction

Heat pumps have been identified as a key technology for reducing exergy losses as compared to conventional boiler systems (Favrat et al., 2008). As the temperature levels are relatively low (about 30 °C to 60 °C), renewable energy sources can be utilized more effectively in place of fossil fuels. Heat pumps are not new; however, the technology has significantly evolved in terms of component and thermodynamic cycle efficiencies (Chua et al., 2010). One of the significant developments has been the realization of multi-stage heat pumps (Arpagaus et al., 2016; Bertsch and Groll, 2008; Favrat et al., 1997; Zehnder, 2004). Studies have shown that domestic-scale multi-stage heat pumps are feasible and achieve higher coefficient of performance (COP) values than single-stage types, but suffer from oil migration issues. Subsequently, a comprehensive design and experimental investigation of an oil-free gas bearing supported turbocompressor unit for a domestic two-stage heat pump has been made (Schiffmann, 2013, 2015; Schiffmann and Favrat, 2009). The demonstrator turbocompressor with its 20 mm diameter centrifugal compressor wheel spinning over 200,000 min^{-1} reached compressor isentropic and mechanical efficiencies of 80% and 95% mark, respectively, for R134a refrigerant fluid. The turbocompressor has seen application as a compressor-turbine unit in the experimental investigation of a thermally driven heat pump cycle with promising results (Demierre et al., 2014).

In this paper, a 6.5 kW two-stage heat pump concept driven by oil-free turbocompressors with two heat sources at different temperature levels is proposed for domestic applications. In addition to heat from the main source, a secondary heat from different unused sources such as waste heat, liquid from cooling circuits or process heat has been added to the thermodynamic cycle. It has been shown that additional heat input at higher temperature levels than the primary source has a benefit on the heat pump COP in heating mode (Granwehr and Bertsch, 2012). Fig. 1 illustrates the thermodynamic cycle of the two-