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Modeling of gas leakage through compressor valves

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ABSTRACT

This paper describes a model developed to predict gas leakage in cases of incomplete sealing of the reed-type valves of small reciprocating compressors adopted for household refrigeration. The model assumes a one-dimensional formulation for the flow, considering the effects of viscous friction, slip-flow regime and compressibility. Reed bending into the port due to the pressure load is also taken into account to characterize the valve clearance. Computations are carried out during the compression cycle and the effect of leakage on both the isentropic and volumetric efficiencies is quantified for two operating conditions. It was found that leakage significantly reduces the compressor efficiency even for very small valve clearances and that leakage in the discharge valve is of greater importance than that in the suction valve.

Modélisation des fuites de gaz dans les soupapes du compresseur

Mots clés : Compresseur ; Soupape ; Fuites ; Modélisation

1. Introduction

Refrigeration compressors adopt automatic valves, which open due to the pressure difference between the compression and suction/discharge chambers. The specification of such valves is one of the most important steps in the design of a high efficiency compressor. For instance, in the case of incomplete valve sealing due to surface irregularity or misalignment, gas leakage will occur and significantly reduce the compressor performance. There are a number of studies reported in the literature in which the flow through small gaps of reed-type valves was modeled using a simplified formulation of incompressible laminar flow between parallel disks (Ferreira et al., 1989; Ghila, 1995; Livesey, 1960; Savage, 1964). Fleming et al. (1984) solved the compressible flow in a radial diffuser taking into account the effect of viscous friction and the variation in the cross-sectional area of the flow. Sato et al. (2005) developed a methodology to linearize the equations governing the adiabatic compressible flow between parallel disks for both outward and inward flow. Their approximation is valid when the effect of viscous friction is less important

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Nomenclature

A	cross-sectional area of the flow (m^2)
A_{ee}	effective flow area (m^2)
A_{ef}	effective force area (m^2)
c_v	specific heat at constant volume ($m^2\ s^{-2}\ K^{-1}$)
C	valve damping coefficient ($N\ s\ m^{-1}$)
C_f	skin friction coefficient (–)
d	molecular diameter (m)
D	flexural rigidity (N m)
D_h	hydraulic diameter (m)
E	modulus of elasticity (Pa)
F_v	valve flow induced force (N)
F_0	valve pre-load force (N)
h	specific enthalpy ($J\ kg^{-1}$)
k_B	Boltzmann constant ($J\ K^{-1}$)
Kn	Knudsen number (–)
K	valve stiffness ($N\ m^{-1}$)
L_c	characteristic length (m)
m	mass (kg), molecular mass (kg)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
$\dot{m}_{th}$	ideal mass flow rate ($kg\ s^{-1}$)
M	Mach number (–), amount of leaked gas (kg)
M_{eq}	valve equivalent mass (kg)
n	number density of the gas (m^{-3})
p	pressure (Pa)
p^*	critical pressure (Pa)
p_b	back pressure (Pa)
$\dot{Q}$	heat transfer rate at the cylinder wall
r	radial coordinate (m)
r_d	radius of the disc that represents the reed (m)
r_o	radius of the valve orifice (m)
R	gas constant ($m^2\ s^{-2}\ K^{-1}$)
Re	Reynolds number (–)
s	valve lift (m)
$\dot{s}$	valve velocity ($m\ s^{-1}$)
$\ddot{s}$	valve acceleration ($m\ s^{-2}$)
t	time (s), valve thickness (m)
T	temperature (K)
v	specific volume ($m^3\ kg^{-1}$)
V	velocity ($m\ s^{-1}$), volume (m^3)
w	displacement of bending valve (m)
$\dot{W}_{ind}$	indicated power (W)
X	dimensionless radial coordinate (-)
z	axial coordinate (m)

Greek letters

γ	specific heat ratio (–)
δ	clearance between reed and seat (m)
δ_e	clearance at the edge of the valve orifice (m)
Δ	difference
Δp_v	pressure difference acting on the valve (Pa)
η_s	isentropic efficiency (–)
η_v	volumetric efficiency (–)
λ	mean free path (m)
μ	dynamic viscosity (Pa s)
ν	Poisson ratio (–); kinematic viscosity ($m^2\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
σ_v	tangential momentum accommodation coefficient (–)
τ_w	wall shear stress ($N\ m^{-2}$)

Subscripts

bd	backflow in the discharge valve
bs	backflow in the suction valve
c	compression process
CS	control surface
CV	control volume
cyl	cylinder
d	discharge, downstream
dc	discharge chamber
e	expansion process
ld	leakage in the discharge valve
lpc	leakage in the piston-cylinder clearance
ls	leakage in the suction valve
s	suction
sc	suction chamber
u	upstream
0	stagnation flow condition
1	compressor inlet
2,s	compressor outlet for an isentropic process

Superscripts

*	without bending

than that of a change in the area. All of the aforementioned studies are focused on the flow itself and do not consider the effect of leakage on the compressor performance.

Machu (1990) adopted an integral formulation of the energy equation to simulate a double acting cylinder compressor and estimated leakage with reference to an isentropic compressible flow through a nozzle and the concept of effective leakage area proportional to the valve passage area. The author concluded that leakage may considerably reduce the compressor efficiency. Habing (2005) modeled the leakage in a broken valve plate of a two-stage air compressor considering the leakage area proportional to the maximum valve opening. Elhaj et al. (2008) carried out simulations of an air double-stage reciprocating compressor and presented a mathematical model based on incompressible flow to predict the effect of gas leakage through small holes in the plate valve.

This paper reports a simulation model to predict gas leakage through the incomplete sealing of compressor valves during the compression cycle. The model assumes a one-dimensional formulation for the flow, considering the effects of viscous friction, slip-flow regime and compressibility. Reed bending into the port due to the pressure load is also taken into account to characterize the valve clearance. The effect of leakage on both the isentropic and volumetric efficiencies is quantified for different operating conditions.

2. Mathematical model

2.1. Leakage through valves

The pressure difference between the compression and suction/discharge chambers is the driving force of gas leakage