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Modeling of a semi-hermetic CO_2 reciprocating compressor including lubrication submodels for piston rings and bearings

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ABSTRACT

A comprehensive model for a semi-hermetic CO_2 reciprocating compressor is presented. This comprehensive model is composed of three main sub-models simulating the geometry and kinematics, the compression process, and frictional power loss. Valve and leakage sub-models are included in the compression process model. The frictional power loss model includes the friction at the bearings and between the piston ring and cylinder wall. The predicted results of the comprehensive model are validated using external compressor performance measurements of compressor input power and mass flow rate. The mass flow rate and compressor input power are predicted to within 4.03% and 6.43% mean absolute error, respectively, compared to the experimental datum. Additionally, a parametric study is presented which investigates compressor performance as a function of the stroke-to-bore ratio.

Modélisation d'un compresseur à piston semi-hermétique au CO2, y compris des sous-modèles pour la lubrification des segments de piston et des paliers

Mots clés : Compresseur à piston ; Modèle ; CO2 ; Optimisation ; Frottement

1. Introduction

Since the rediscovery of carbon dioxide (CO_2 or R744) as a suitable refrigerant by Lorentzen and Pettersen (1992), many studies have been conducted on CO_2 compressors and systems. The operating temperatures of typical refrigeration or air-conditioning systems dictate that a cycle using CO_2 as a working fluid would need to operate as a trans-critical cycle. In these systems, the CO_2 reciprocating compressor runs with a relatively high operating

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Nomenclature

A	area [m^2]
C	discharge coefficient [–]
C_1, C_2	integration constant [–]
D	diameter [m]
E_1, E_2	Young's modulus for ring and cylinder wall [Gpa]
F	force [N]
G	gravity [N]
P	power [W]
H_{pc}	instant frictional loss between the top piston ring and cylinder wall [W]
L	axial length of the bearing [m]
N_j	rotational speed of the journal [rps]
N	the number of asperities per unit contact area
Q	quantity of heat transferred to control volume through boundary from its ambient [J]
R	gas constant of carbon dioxide [$J\ kg^{-1}\ K^{-1}$], or radius [m]
S	piston stroke [m]
T	temperature [K]
U	velocity [$m\ s^{-1}$]
V	volume [m^3]
W	work [J], power [W] or force [N]
W^*	Dimensionless load capacity [–]
Z	compact factor of carbon dioxide [–]
a	piston acceleration [$m\ s^{-2}$]
b	piston ring thickness [m]
$\bar{c}$	clearance [m]
c_1, c_2, c_3, c_4, c_5	crankshaft dimensions [m]
h	unit enthalpy [$J\ kg^{-1}$] or oil film thickness [m]
h_{valve}	valve lift [m]
m	mass [kg]
$\dot{m}$	mass flow rate of refrigerant of the compressor [$kg\ s^{-1}$]
n	compressor rotational speed [rpm]
p	pressure [Pa]
p_1, p_2	inlet and outlet pressure of piston ring lubrication region [Pa]
u	unit internal energy [$J\ kg^{-1}$]
v	specific volume [$m^3\ kg^{-1}$]
x	piston displacement [m]
x_C	cavitation point [m]

Greek letters

α	Relative clearance volume [–]
β	angle between the axis of connecting rod and center line of cylinder [rad]
β'	asperity radius of curvature
η	efficiency
θ	crank angle [rad]
κ	specific heat ratio [–]
λ	ratio of crank radius to the length of the connecting rod
μ	dynamic viscosity [Pa S] or friction coefficient [–]
$\nu_{1,oil}$, $\nu_{2,oil}$	kinematic viscosity at 37.8 °C and 93.3 °C respectively [cS]
ν_1, ν_2	Poisson's ratio [–]
ν_{r1}	the surface roughness variance ratio [–]
ρ	density [$kg\ m^{-3}$]
σ	composite surface roughness
σ_1, σ_2	surface roughness for ring and cylinder liner
τ	thermal conductivity of refrigerant in control volume [$W\ m^{-1}K^{-1}$]
ϕ_f, ϕ_{fs}	shear stress factors, dimensionless
ϕ_x, ϕ_s	Pressure flow factor and shear flow factor
ω	angular speed of the crankshaft [$rad\ s^{-1}$]

Subscripts

0	clearance volume
A	asperity
b	ring back
bearing	crankshaft bearing and crank journal bearing
bush	bearing bush
c	refrigerant in control volume
case	compressor case
cir	circumferential
contact	asperity contact
CS	crankshaft
cyl	cylinder
d	downstream
dis	discharge
f	friction
gap	piston ring gap
gas	gas in the un-lubricated region of piston ring
H	hydrodynamic
high	high pressure side
ind	actual indicated power
input	compressor input
journal	crankshaft journal
l	connecting rod
li, lo	leak in and out
loc	local
low	low pressure side
M	electric motor
mean	mean velocity of piston
oil	lubricating oil
p	piston
radius	radius
ring	piston ring
shaft	crankshaft
suc	suction
sup	oil supply
T	ring tension
t	total
u	upstream
valve	valve

pressure compared to other reciprocating compressors using conventional refrigerants, which presents practical challenges. Thus, the unique operating cycle and practical challenges for CO_2 compressors necessitate the need for careful modeling of a CO_2 reciprocating compressor as presented in this work.

Many steady-state simulation models for reciprocating compressors are presented in the literature. Navarro et al. (2007)