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Fluid flow in a screw pump oil supply system for reciprocating compressors☆

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ABSTRACT

This work presents a mathematical analysis of an oil supply system for reciprocating compressors. The system is based on a single screw pump attached to the bottom end of the vertical rotating shaft immersed in the oil sump. The fluid flow in the pump was modeled with a semi-analytical approach based on the solution for the laminar fully developed oil flow in a screw extruder via the Generalized Integral Transform Technique. The screw pump model is coupled with that for the flow in the shaft region so as to provide an estimate of the oil flow rate and of the so-called 'climbing-time', i.e., the amount of time needed for a fluid particle to travel from the oil sump to the top of the shaft. The calculation method was verified against experimental data and Computational Fluid Dynamics modeling results.

Ecoulement du fluide dans le système d'alimentation en huile des pompes à vis de compresseurs à piston

Mots clés : Compresseur à piston ; Lubrifiant ; Huile ; Pompe ; Vis-conception ; Modélisation-optimisation

1. Introduction

Lubrication is a major issue in compressor design because it is directly related to mechanical losses, wear and reliability. In addition to sufficiently large oil flow rates, one requires that the lubricant oil becomes immediately available to the hydrodynamic bearings and to the piston–cylinder gap immediately after the motor start-up (Prata and Barbosa,

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Nomenclature

Roman

e	screw flight width (m)
g	acceleration due to gravity ($m\,s^{-2}$)
H	height of the screw channel cross section (m)
h_B	screw height (m)
h_{oil}	height of the submerged tip of the pump in the oil sump (m)
k	dimensionless pressure drop
L	overall length of the pump channel (m)
p	pressure (Pa)
P	pumping power (W)
$P^* = P\sin(\beta)/\mu\Omega^2R_B^2h_B = kQ^*$	dimensionless pumping power (lower part)
Q	oil volumetric flow rate ($m^3\,s^{-1}$)
$Q^* = Q/\Omega H^2 R_B$	dimensionless oil flow rate
R_B	barrel radius (external radius) (m)
RES	normalized residuum
t	time (s)
$t^* = (h_B/\Omega R_B)t$	dimensionless time
$\overline{V}$	mean velocity in the channel ($m\,s^{-1}$)
w	velocity component in the z direction ($m\,s^{-1}$)
W	width of the screw channel cross section (m)
x	channel cross section coordinate (m)
y	channel cross section coordinate (m)
z	down-channel coordinate (m)

Greek

$\alpha_i = i\pi/\gamma$	eigenvalues
β	screw helix angle
$\gamma = W/H$	screw channel aspect ratio
$\kappa = H/R_B$	screw curvature ratio
$\Lambda = 2\pi R_B(\tan\beta)$	screw pitch (m)
μ	dynamic viscosity (Pa s)
Ω	angular velocity (s^{-1})
ρ	oil density ($kg\,m^{-3}$)
$\tau = \Lambda/R_B$	screw helix ratio

Superscripts

*	dimensionless variable
~	related to the shaft channel

2009). Since the geometry of oil supply systems is generally too complex for local measurements of the oil flow parameters, one frequently resorts to numerical modeling of the fluid flow in the pump, shaft and bearings in order to obtain specific parameters of the oil flow in such systems.

A number of computational fluid dynamics (CFD) studies of oil supply in hermetic compressors have been carried out in the open literature. Bernardi (2000), Cho et al. (2002), Cui (2004) and Lückmann et al. (2009) investigated different types of supply systems under transient and steady-state conditions in rotary and reciprocating compressors using commercial CFD software. Over time, these models have become increasingly more detailed and realistic with respect to the pumping system geometry used in the simulations. However, they still rely on a number of simplifying assumptions such as the absence of refrigerant dissolved in oil, isothermal conditions, constant physical properties etc. Although the simplifying assumptions help to keep the computating time at a tolerable level, this can still be considered very large and thus prohibitive for design and optimization purposes. Nevertheless, CFD models are very valuable in providing standard results against which more simplified approaches can be validated. The reader is referred to Lückmann et al. (2009) for a complete review of the literature on CFD modeling of oil supply systems in hermetic compressors.

Numerical and semi-analytical models of oil supply systems have also been proposed in the literature. Kim and Lancey (2003) and Kim (2005) presented two of such models for rolling piston rotary compressors based on an electrical circuitry analogy. The models allowed an evaluation of the oil distribution in several compressor parts (main and sub bearings, roller clearance etc.) and were validated with experimental data for the pumped oil flow rate. The biggest advantage of semi-analytical models is the much shorter computing times than CFD-based models. However, the dependence on empirical correlations for a specific system component can be their main drawback, especially when a geometry optimization of the oil supply system is pursued.

The purpose of the present paper is to advance a semi-analytical model for predicting the oil flow rate in the screw pump oil supply system for reciprocating compressors shown schematically in Fig. 1. As pointed out by Lückmann et al. (2009), the pump design must be simple and efficient and, in some hermetic compressors, use is made of the actual rotation of the shaft as the driving force to overcome gravity and friction as the oil is forced through the channels and passages to feed the shaft bearings (Fig. 1a). The lower part of the supply system, which is partially immersed in the oil sump, consists of a single screw extruder with a fixed center pin and an external rotating barrel (Fig. 1b). Viscous shear is the driving force for pumping the oil. After leaving the screw pump in the lower part of the system, the oil enters the shaft, where it flows through a helical groove machined on its outer surface and feeds the shaft bearings. From the top of the shaft, the oil is expelled to the internal crankcase environment and falls back to the sump in its lower part. A renderization of the fluid flow channel geometry in the oil supply system geometry is shown in Fig. 1c.

The Generalized Integral Transform Technique (GITT) (Cotta, 1993) has been used to determine analytically the down-channel component of the velocity field in the lower and upper parts of the supply system. The pumped oil flow rate is calculated numerically based on the individual relationships for the down-channel flow rates in the screw pump and shaft regions (Alves et al., 2009). The results are compared with experimental data and numerical predictions obtained via CFD. An important result of the present analysis is the so-called ‘climbing time’, i.e., the amount of time needed for a fluid particle to travel from the oil sump to the top of the shaft. This is of particular significance in the pursuit of