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Optimization of a scroll compressor for liquid flooding

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ABSTRACT

In two companion papers, simulation models for the working processes of liquid-flooded scroll compressors and expanders have been developed and validated against experimental data. In this study, analytic models are presented for the modes of irreversibility generation in the liquid-flooded scroll compressor including built-in volume ratio maladjustment, pressure drop and leakage. A thermodynamic model is used to derive the ideal volume ratio for a liquid-flooded compressor, which is higher than that of dry compression. An optimum set of built-in volume ratio and scroll base circle radius is found which maximizes the overall isentropic efficiency by minimizing the leakage and pressure drop irreversibilities. The irreversibility generation models are used to optimize a scroll compressor for the Liquid-Flooded Ericsson cycle application. The model predicts scroll compressor overall isentropic efficiency of over 80% (based on the shaft power) at an oil mass fraction of 88%.

Optimisation d'un compresseur à spirale noyé

Mots clés : Compresseurs à spirale ; Cycle noyé ; Compression isotherme ; Efficacité élevée

1. Introduction

Scroll compressor performance optimization is a complex endeavor because many parameters affect the performance of the scroll compressor. A significant amount of information is required to make an intelligent optimization. Selection of the optimal design parameters is complicated by the fact that many of the design parameters are tightly coupled together. Some of the important design parameters that govern the compressor efficiency are

- Scroll wrap geometry
- Internal heat transfer coefficient
- Motor & mechanical losses
- Leakage gap widths
- Pressure drops

In the open literature, there is little formalized analysis for the optimization of scroll compressor efficiency, and none for scroll compressors with liquid flooding. One of the major reasons for this paucity of design optimization information is the highly

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Nomenclature

Roman

c_l	liquid specific heat, (kJ kg^{-1} K^{-1})
$c_{p,g}$	gas constant-pressure spec. heat, (kJ kg^{-1} K^{-1})
$c_{v,g}$	gas constant-volume spec. heat (kJ kg^{-1} K^{-1})
$\dot{E}$	rate of entropy generation, (kW)
e	specific exergy, (kJ kg^{-1})
f	frequency, (s^{-1})
k^*	effective ratio of specific heats, (–)
h	specific enthalpy, (kJ kg^{-1})
h_s	height of the scroll (m)
p	pressure, (kPa)
p_r	pressure ratio
r_o	orbiting radius, (m)
r_b	base [generating] circle radius, (m)
s	specific entropy, (kJ kg^{-1} K^{-1})
t	scroll wrap thickness, (m)
T	temperature, (K)
V	volume, (m^3)
V_{disp}	displacement volume, (m^3)
V_{ratio}	ratio of suction to discharge volumes, (–)
V_1	initial total volume, (m^3)
V_2	final total volume, (m^3)
W	work, (kJ)
$\dot{W}_{gas}$	gas compression power, (kW)
$\dot{W}_{ML}$	mechanical losses power, (kW)
x_l	oil mass fraction

Greek

β	liquid void fraction, (–)
δ	leakage gap width, (m)
ρ	density, (kg m^{-3})
ω	rotational speed, (rad s^{-1})
τ_{loss}	mechanical loss torque, (kN m)
η_m	mechanical efficiency, (–)
φ_{i0}	inner scroll initial angle (radians)
φ_{is}	inner scroll starting angle, (radians)
φ_{ie}	inner scroll ending angle, (radians)
φ_{o0}	outer scroll initial angle, (radians)
φ_{os}	outer scroll starting angle, (radians)
φ_{oe}	outer scroll ending angle, (radians)

Subscripts

a	initial total discharge chamber volume
b	intersection discharge chamber volume
cl	clearance
c1	the first compression chamber
c2	the second compression chamber
d	discharge
$d1$	the first outer discharge chamber
$d2$	the second outer discharge chamber
dd	the central discharge chamber
ddd	the merged central discharge chamber
down	downstream
f	Flank direction (along the scroll wrap)
r	radial direction (across the scroll wrap)
s	suction
total	mixture (oil + gas)
up	upstream
0	at the dead state

proprietary nature of scroll compressors. In particular, the details of the scroll compressor, such as leakage gap widths, cutting tool diameter, and motor efficiency are often not known *a priori*.

Bush et al. (1986) developed a framework for the analysis of the irreversibilities in the scroll compressor, the first step for the optimization of the compressor. Etemad and Nieter (1989) presented a method for optimization of the compressor and discussed all of the important parameters that enter into the design. Detailed results were not provided. Liu et al. (2010) carried out a detailed optimization of the scroll compressor frictional losses, and included enough information on the compressor design to fully characterize the scroll machine and its losses.

The analysis presented here for a scroll compressor with liquid flooding is focused on the optimization of the compressor by decreasing three main irreversibilities – leakage losses, pressure drop, and under- or over-compression losses due to built-in volume ratio maladjustment. A detailed analysis of the effects of motor and mechanical losses is not included as it is beyond the scope of this study.

2. Definition of irreversibility terms

The irreversibilities generated in the compressor are ultimately responsible for the deviation from the ideal working process for the scroll compressor. Bush et al. (1986) derived simple models for each of the irreversibilities in the scroll compressor based on scaling laws using empirical coefficients. The evaluation of the irreversibilities generated in the compression process in a reciprocating compressor has been developed by McGovern and Harte (1992). Wagner et al. (1994) present a means of calculating the exergetic losses in the compression process based on the conservation of exergy for each control volume. This framework allows for the calculation of the total irreversibility, but does not allow the tracking of the provenance of each portion of the total irreversibilities.

Based on the model presented in the companion paper (Bell et al., 2012a), the working process of the scroll compressor is determined. Based on the working process, the average irreversibilities over the course of a rotation can be calculated. The following sections present mathematical models for the irreversibilities generated in the scroll compressor. The names of the control volumes are consistent with the nomenclature presented in the companion paper (Bell et al., 2012a).

2.1. Suction losses

The ideal suction process is one in which there is no pressure drop between the suction line and the suction chamber, and