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Generic network modeling of reciprocating compressors

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ABSTRACT

With the increasing applications of CO_2 trans-critical cycles, the design of reciprocating compressors returns to the center stage. Quick design and optimization of a compressor with arbitrary configuration is always a big challenge. This paper presents a new generic modeling approach to reciprocating compressors design. The reciprocating compressors were firstly torn down to components, e.g. compression chamber, valve, shaft, motor, crankcase, etc. Then the component models were developed to feature the sub-processes inside the components. Refrigerant flow, heat flow, power flow, and air flow (for intermediate cooler) between components were described on a network basis. Finally, the object-oriented programming method was applied to develop a graphical user interface for generic drag-and-drop modeling of reciprocating compressors with arbitrary configuration. Experimental data of a CO_2 two-stage compressor and a R410A single-stage compressor were used to validate the generic modeling tool. The deviations in the mass flow rate and power consumption of R410A compressor are mostly within ±3% and ±5%, respectively, while the deviations in the mass flow rate and power consumption of CO_2 compressor are mostly within ±8% and ±5%, respectively.

Modélisation par réseau générique de compresseurs à piston

Mots clés : Compresseur à piston ; Modèle ; CO_2 ; R410A

1. Introduction

Reciprocating compressors are widely used in various refrigerating units covering a large range of capacity. Due to relatively lower volumetric efficiency and larger dimension, reciprocating compressor is nowadays replaced by rotary compressors (e.g. rolling-piston, scroll, screw compressors) in most applications. However, with the increasing applications of carbon dioxide (CO_2) trans-critical cycles (Austin and Sumathy, 2011; Bansal, 2012; Pearson, 2005), reciprocating compressor is returning to the center stage because of its advantages in high pressure

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Nomenclature

a	acceleration, m s^{-2}
A	area, m^2
C	flow coefficient
d	diameter, m
F	force between two solid bodies, N
F_d	force acting on the discharge valve, N
F_s	force acting on the suction valve, N
F_i	inertial force of piston, N
F_p	pressure force on the piston, N
F_{rod}	total force acting on the rod, N
g	gravity acceleration, m s^{-2}
h	enthalpy, J kg^{-1}
k	spring factor of the suction valve
m	mass flow rate, kg s^{-1}
p	pressure, Pa
p_c	pressure in the crank chamber, Pa
p_d	discharge pressure, Pa
P_{input}	input power, W
$F_{b,x}$	Bearing force along x direction, N
$F_{b,y}$	Bearing force along y direction, N
Q	heat flow, W
S	valve displacement, m
t	time
T	temperature, K
V	volume, m^3
X	unknown variable set
v_s	suction valve velocity, m s^{-1}
v_d	discharge valve velocity, m s^{-1}
M	Mass kg

Greek symbols

ε	convergence tolerance
η	efficiency
ρ	density, kg m^{-3}
τ	time, s
Γ	torque, N m
θ	crank angle
κ	Specific heat ratio

Subscripts

i	inflow
I	inertial
o	outflow
d	discharge
s	suction
l	leakage

operation and good efficiency when running at lower pressure ratio.

To well design reciprocating compressor, numerical simulation has become a powerful approach and different simulation models are found in the literature. Some CFD simulations have been carried out for the compressor components (e.g. mufflers and valves) (Nakano and Kinjo, 2008; Pereira et al., 2008b) and the whole compressor (Birari et al., 2006). Despite of the recent advances in numerical methodologies, the computational cost of a full three-dimensional simulation of a reciprocating compressor is still impracticable for optimization purposes (Pereira et al., 2008a). Therefore, simpler methodologies which can offer satisfactory results for a preliminary design are still very important and worth further development. Pérez-Segarra et al. (2003) and Rigola et al. (2003) developed a detailed numerical model of the thermal and fluid dynamic behavior of small reciprocating compressors which are commonly used in household refrigerators and freezers. Later, to simplify the process on compressor performance evaluation, they developed a detailed model for the thermodynamic efficiencies to characterize the hermetic reciprocating compressors (Pérez-Segarra et al., 2005). They focused on the volumetric efficiency, isentropic efficiency and combined mechanical-electrical efficiency and detached them into several partial efficiencies so as to denote effects of different physical sub-processes. More recently, they presented a more generic object-oriented unstructured modular modeling methodology of reciprocating compressors (Damle et al., 2011). The new approach offers advantages of handling complex circuitry (e.g. parallel paths, multiple compressor chambers, etc.), coupling different simulation models for each element and adaptability to different configurations without changing the source code. Yang et al. (2013) found there was no comprehensive models for CO_2 reciprocating compressors in the literature. They therefore presented a comprehensive model to predict the CO_2 reciprocating compressor performance, which included both the frictional losses at piston ring-cylinder liner interface and at the journal bearings. For more information, state-of-the-art reviews of numerical methodologies applied to reciprocating compressors were made available by Rasmussen and Jakobsen (2000) and Ribas et al. (2008).

Most of the compressor models mentioned above can only cover a specific compressor or a series of compressors with fixed or similar configuration. In addition, the programming methods used were typically the ‘functional-programming’ approach which is of poor extension ability. Therefore, quick design and optimization of a compressor with arbitrary configuration is still a big challenge for both modeling and implementation methods.

Different from the existing ones, we apply a generic network based modeling methodology with the object-oriented programming method to carry out a graphical drag-and-drop modeling and simulation platform for reciprocating compressor design. The network model involves refrigerant flow, heat flow, power flow, and air flow between compressor components. Different configurations and complex circuitry of reciprocating compressors can be handled by an easy-of-use graphical drag-and-drop style. At last, the method is validated with different compressors.

2. Reciprocating compressor model

Fig. 1 is the typical schematic of a reciprocating compressor. Generally, the reciprocating compressor consists of a set of components. The low pressure refrigerant vapor from the evaporator enters the crankcase and is heated by the