INTERNATIONAL JOURNAL OF REFRIGERATION 56 (2015) 186–197

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/ijrefrig

Thermodynamic analysis of natural gas reciprocating compressors based on real and ideal gas models

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ARTICLE INFO

Article history:
Received 3 August 2014
Received in revised form
11 November 2014
Accepted 12 November 2014
Available online 24 November 2014

Keywords:
Reciprocating compressor
Natural gas
Thermodynamic modeling
AGA8 equation of state

ABSTRACT

The accurate modelling and investigating effects of various parameters of the reciprocating compressors are important subjects. In this work, based on first law of thermodynamics, conversation of mass and real and ideal gas assumptions, a theoretical analysis has been constructed to simulate natural gas reciprocating compressors. For computing the thermodynamic properties of natural gas based on real gas model, the AGA8 equation of state has been used. Numerical results validated with previous measured values and showed a good agreement. The effects of important parameters such as: angular speed, clearance and pressure ratio have been studied on the performance of the compressors. The results reveal the in-control volume temperature for ideal gas is more than real gas model but the mass flow rate and work for real gas is higher than ideal gas model. On the other hand, the indicated work that required for compression is greater for ideal gas model.

Analyse thermodynamique de compresseurs à piston au gaz naturel basée sur des modèles de gaz réel et idéal

Mots clés : Compresseur à piston ; Gaz naturel ; Modélisation thermodynamique ; Equation d'état AGA8

1. Introduction

One of the most important equipment for producing high pressure gas is reciprocating compressors. These compressors are used widely in industries such as: refineries and power plants, refrigeration system (chillers), Compressed Natural Gas stations (CNG stations) and etc. due to high pressure ratio achievement.

As noted above, the CNG station is one of the most applications of reciprocating compressors. In CNG station, natural gas from the distribution pipeline is compressed using a large multi-stage compressor (three or four stages) to pressure

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http://dx.doi.org/10.1016/j.ijrefrig.2014.11.008

Nomenclature

a	lengths of rod m
A	area (m^2)
C_d	orifice discharge coefficient
c_p, c_v	Constant pressure &volume specific heats ($kJ\ kg^{-1}\ K^{-1}$)
g	Gravitational acceleration ($m\ s^{-2}$)
h	Specific enthalpy ($kJ\ kg^{-1}$)
L	crank m
$\dot{m}$	Mass flow rate ($kg\ s^{-1}$)
M	Molecular weight ($kg\ kmol^{-1}$)
P	Pressure (bar or Pa)
$\dot{Q}$	Heat transfer rate (kW)
S	stroke m
T	Temperature (K or °C)
u	internal energy ($kJ\ kg^{-1}$)
υ	specific volume ($m^3\ kg^{-1}$)
V	Volume (m^3)
V_0	Dead Volume (m^3)
v	Velocity ($m\ s^{-1}$)
W	Actual work ($kJ\ kg^{-1}$)
$\dot{W}$	Actual work rate (kW or MW)
x	displacement (m)
z	Height (m)
ρ	Density ($kg\ m^{-3}$)
ω	Angular Speed ($rad\ s^{-1}$)
α	Heat Transfer Coefficient (Wm^2/K)
θ	Degree (Degree)
Subscript	
cv	Control Volume
s	Suction
d	discharge
p	piston

between 20 MPa and 25 MPa (Farzaneh-Gord et al., 2014, 2012). A large part of the initial and current costs of CNG stations are due to reciprocating compressor input work (Farzaneh-Gord et al., 2012). By modeling CNG compressors, one could optimize design parameters which lead to higher efficiency and lower input work for compressing in CNG stations.

Researchers have used different methods for modeling reciprocating compressor. These methods usually divided into two methods: global models and differential models, that in these methods the variable depends on crank angle (Stouffs et al., 2000). Stouffs et al. (2000) with utilizing global model studied reciprocating compressors thermodynamically. In their model five mains and four secondary dimensionless physical parameters were important and they computed the volumetric effectiveness, the work per unit mass and the indicated efficiency. Casting et al. (Castaing-Lasvignottes and Gibout, 2010) modeled compressor operation using performance explanations like volumetric, isentropic and effective. They thought that these efficiencies depend basically on two parameters, the dead volumetric ratio, having particular influence on volumetric efficiency, and a friction factor mainly influencing both isentropic and effective efficiencies. Elhaj et al. (Elhaji et al., 2008) studied a two-stage reciprocating compressor numerically. An important achievement of this research was expansion of diagnostic features for predictive condition monitoring. Winandy et al. (2002) exhibited a simplified model of an open-type reciprocating compressor. Their analysis presented the main processes influenced the refrigerant mass flow rate and the compressor power and the discharge temperature. Also Ndiaye and Bernier (2010) did a dynamic model of a hermetic reciprocating compressor in on-off cycling operation. Also Farzaneh-Gord et al. (2013) optimized design parameters of reciprocating air compressor thermodynamically. They developed a mathematical model according to the mass conservation, first law and ideal gas assumption to study the performance of reciprocating compressors.

All the researchers mentioned above used the first law of thermodynamics for modeling as basic tool. The second law of thermodynamic is also used to analysis performance of the reciprocating compressors. McGovern and Harte (1995) investigated the compressor performance with employing the second law. The non-idealities are characterized as exergy destruction rates as losses to friction, irreversible heat transfer, fluid throttling and irreversible fluid mixing. Defects in the use of a compressor's shaft power identified and quantified. Aprea et al. (2009) presented a research that detected for variable speed compressors the current frequency that optimizes the exergy, energy and economy aspects. Also, Bin et al. (2013) investigated thermal performance of reciprocating compressor with stepless capacity control system. In their research an experimental setup was working and the compressor with designed stepless capacity control system operate all right. Morriesen and Deschamps (2012) investigated transient fluid and superheating in the suction chamber of a refrigeration reciprocating compressor experimentally. Also Yang et al. (2012) simulated a semi-hermetic CO_2 reciprocating compressor comprehensively.

The effects of a few more design parameters on the performance of the compressor have also investigated in various studies. Perez-Segarra et al. (2005) carried out the comprehensive analysis of various famous thermodynamic efficiencies such as the volumetric efficiency, the isentropic efficiency and the combined mechanical-electrical efficiency, which these efficiencies prevalently employed to characterize hermetic reciprocating compressors. They separated these efficiencies into their main components (physical sub-processes). Da Riva and Del Col (2011) introduced the performance of a semi-hermetic reciprocating compressor experimentally. This compressor has been installed in a heat pump for producing 100 kW heating capacity. The effect of the use of an internal heat exchanger between liquid and vapour line on the performance of the compressor is discussed. Damle et al. (2011) studied the simulation that applies an object-oriented unstructured modular methodology for the numerical modeling of the elements forming the hermetic reciprocating compressor domain to predict the thermal and fluid dynamic behavior (temperature, pressure, mass flow rates, power consumption, etc.) of the compressor. Link and Deschamps (2011) investigated a simulation methodology, experimental validated, to study the compressor in transients time. Furthermore, their model is used to appraise the minimum voltage needed for the compressor startup as a function of the