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Simplified steady-state modeling for variable speed compressor

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HIGHLIGHTS

► Physical-based modeling of variable speed.
► Three types of compressors: reciprocating, scroll and piston rotary are investigated.
► Characteristics of volumetric and isentropic efficiency for variable speed compressor are explored.

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ABSTRACT

This paper presents a detailed analysis of semi-empirical methods to calculate mass flow rate, shaft power and discharge temperature for three types of variable speed compressors: reciprocating, scroll and piston rotary. The proposed methods are an integration of physical-based models for constant speed compressor and the physical characteristics of volumetric efficiency and isentropic efficiency between different speeds. The physical-based models were first validated with good agreement with experimental data from publication for the three types of constant speed compressors. The comparison between modeling results and experimental data from publication for the three types of variable speed compressors shows the RMS errors are less than 3%, 3% and 3 °C for refrigerant mass flow rate, compressor power input and discharge temperature, respectively. The model of variable speed compressor will allow the reduction of the number of experimental data required to characterize variable speed compressor behavior in the modeling of refrigeration systems because of its physical mechanisms.

1. Introduction

Variable speed compressor is of great interest in air conditioning and refrigeration system because it offers better capacity regulation than the conventional on/off control. The modeling of this kind of compressor plays a very important role in the simulation of air conditioning and refrigeration system [1–3]. Whether in the refrigeration system simulation of steady state or unsteady state, an accurate compressor model which can provide reasonable and relatively accurate extrapolation outside the compressor envelope is also essential for the system modeling.

A lot of studies have been conducted on the semi-empirical modeling of the constant speed compressor through its efficiency [4–7]. In the current researches on the variable speed compressor, constant compressor efficiency [8] or polynomial functions of condensation temperature and evaporation temperature [9] or neural networks [10] are used in their compressor models. Among them, Yang et al. [10] proposed a model to calculate the volumetric and isentropic efficiencies for variable speed compressor using neural network. The kind of model will need a lot of data points to train the neural network. Shao et al. [9] presented a model of variable speed compressor based on the performance data provided by compressor manufacturers for each speed. The model is built at the basis frequency. Mass flow rate and power at the basic frequency are second-order polynomial functions of condensation temperature and evaporation temperature. These modeling methods of variable speed compressor have no any physical meaning, and therefore cannot represent the physical mechanisms appearing in variable speed compressor behavior.

The Characterization of a variable speed compressor itself can be analyzed through its volumetric efficiency and isentropic efficiency. Koury et al. [8] considered the efficiencies irrelevant to the operation frequency in their numerical simulation of a variable speed refrigeration system. Cuevas and Lebrun [11] presented that the compressor efficiencies are not enormously influenced by the compressor supply frequency between 35 and 75 Hz. However, as Shao et al. [9] pointed out, when the inverter compressor operates at low frequency, the lubrication worsens and friction loss increase,

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Nomenclature

a_1, a_2, a_3	fitting parameters for shaft power model
b_1, b_2	fitting parameters for mass flow rate model
c_1, c_2, c_3	fitting parameters for discharge temperature model
d_1, d_2, d_3	fitting parameters for volumetric efficiency model
e_1, e_2, e_3	fitting parameters for isentropic efficiency model
C	clearance fraction
dp	suction pressure drop [kPa]
h	enthalpy [kJ kg^{-1}]
k	refrigerant isentropic coefficient
m	mass flow rate [kg s^{-1}]
n	polytropic index
N	compressor rotation speed [rpm]
P	pressure [kPa]
P_r	pressure ratio of discharge pressure with respect to suction pressure
T	temperature [°C]
υ	specific volume [m^3 kg^{-1}]
$\underline{V}$	compressor displacement [m^3]
$\dot{V}$	volume flow rate [m^3 s^{-1}]
W	compressor power [W]
W_{loss}	constant part of power loss [W]
W_t	polytropic compression power
UA	overall heat transfer coefficient [J K^{-1}]
α	ratio of electromechanical losses to W_t
η	efficiency

Subscripts

amb	ambient
cal	calculation
comp	compressor
cond	condensing
dis	discharge
disp	displacement
evap	evaporation
exp	experiment
is	isentropic
ref	reference
shell	compressor shell
suc	suction
v	volumetric

resulting in worse operation performance of inverter-driven compressor. Shao et al. [9] also mentioned that the volumetric efficiency will increase when the inverter-driven compressor operation at high frequency due to the influence of leakage and heating on suction gas. Tassou and Qureshi [12] investigated the performance of compressors including open-type reciprocating, a semi-hermetic reciprocating and an open-type rotary vane through experiment and found out that the volumetric efficiency of all three compressors increases with the increasing of speed and reach maximum at the design speed and all three compressors exhibit a rising isentropic efficiency with a reduction in speed.

Therefore, the study of compressor efficiency is still an efficient way to characterize the performance of variable speed compressor. In this work, the author tries to present a semi-empirical method to calculate mass flow rate, power input and discharge temperature for three types of variable speed compressors: reciprocating, scroll and piston rotary. The method requires the integration of physical-based models for constant speed compressor and the physical characteristics of compressor efficiency between different speeds.

2. Analysis of variable speed compressor

Characterization of a compressor itself can be analyzed through its volumetric efficiency and isentropic efficiency, which are computed by the following equations:

$$\eta_v = \frac{\dot{V}_{suc}}{N_{comp}V_{disp}} \tag{1}$$

$$\eta_{is} = \frac{\dot{V}_{suc}(h_{is} - h_{suc})}{\upsilon_{suc}W} \tag{2}$$

where, N_{comp} is compressor speed, V_{disp} is compressor displacement, V_{suc} is volumetric flow rate, W is actual compressor work, h_{is} is the function of discharge pressure and suction entropy, h_{suc} is suction enthalpy and υ_{suc} is suction specific volume.

Volumetric efficiency and isentropic efficiency of a variable speed compressor vary with the pressure ratio of discharge pressure to suction pressure, as well with the compressor speed. One may expect that the volumetric efficiency and isentropic efficacy have a dependence on the compressor speed due to fluid acceleration effects and cross correlations to system pressure ratio and valve pressure drops. In general, a variable speed compressor is designed with maximum volumetric efficiency and isentropic efficiency at the design speed. The two efficiencies will decrease when actual operational speed deviates from the design speed. These are observed in the experiment of variable speed compressor [12].

Fig. 1 is the illustrations of the two efficiencies for a rolling piston type rotary inverter compressor. The compressor [9] has piston displacement of 20.7 cm^3. The experimental data from the literature is given at four different speeds of 30, 60, 90 and 120 Hz with the evaporating temperature from −10 to 15 °C and condensing temperature of 40, 50 and 60 °C. In Fig. 1, it can be seen that the compressor has maximum volumetric efficiency and isentropic efficiency at the speed of 90 Hz. Further observance in Fig. 1 shows that the variation tendency of the two efficiencies with the pressure ratio is similar at different compressor speed, indicating that the relations between different speeds for the two efficiencies may be independent of pressure ratio. By taking 60 Hz as reference speed, volumetric efficiency and isentropic efficiency are normalized with respect to the data at 60 Hz and are plotted as a function of normalized speed in Fig. 2. Evidently, the normalized volumetric efficiency and isentropic efficiency are determined only by the normalized speed and is independent of the pressure ratio. Consequently, the two efficiencies as function of normalized speed can be represented by a second-order polynomial function, as shown in Fig. 2.

As a result from above analysis, one can see that an accurate physical model of compressor at the reference speed is a necessary step for predicting the performance of a variable speed compressor. In reality, providing plenty of experimental data for all speeds is time-consuming work, specifically for the development of a new compressor. However, building a physical-based model is able to efficiently reduce the number of experimental data and can provide accurate predictions cover the extensive range of pressure ratio at different speed. Therefore, the following section will explore the semi-physical modeling of constant speed compressor so as to provide strong basis for further modeling of a variable speed compressor.

3. Simplified modeling of constant speed compressor and validation

Some literature [4,7,13] developed the simplified model of a scroll compressor based on a lot of detailed information of