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Empirical models for efficiency and mass flow rate of centrifugal compressors

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ABSTRACT

Centrifugal compressors are widely used in refrigeration systems, heat, power and chemical plants, turbochargers, and vehicle engines, including flight vehicles. Empirical models of efficiency and mass flow rates of centrifugal compressors are required for the design, energy analysis, performance simulation, and control- and/or diagnose-oriented dynamic simulation of such compressors and systems. This work presents a comprehensive review of empirical models for efficiency and mass flow rates of centrifugal compressors. An experimental investigation of a centrifugal compressor for air-cycle refrigeration systems of aircraft is carried out. Then, the available models are evaluated with the experimental data of the refrigeration centrifugal compressor and two turbocharger centrifugal compressors. It is found that the most models for centrifugal compressors of vehicle engines and turbochargers are not satisfactory for refrigeration centrifugal compressors, and thus accurate models for refrigeration centrifugal compressors need to be developed.

Modèle empirique pour l'efficacité et le débit massique de compresseurs centrifuges

Mots clés : Compresseurs ; Modèle empirique ; Efficacité ; Débit massique

1. Introduction

Centrifugal compressors are widely used in air-cycle refrigeration systems such as aircraft environmental control systems (Ordonez and Bejan, 2003; Conceição et al., 2007; Fang et al., 2010). It is also used for vapor-cycle refrigeration (Letlow and Jenkins, 1998; Ashford and Brown, 2000). Centrifugal compressors have been standard in turbochargers and some vehicle engines, including jet engines, where they are driven by gas turbines (Sieros et al., 1997; Eriksson et al., 2002; Canova, 2004), and in industries such as oil refineries, chemical and petrochemical plants, heat and power plants, and

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Nomenclature

a_i	constant ($i = 0, 1, 2, \ldots$)
c_p	constant pressure specific heat, J kg^{-1} K^{-1}
d_c	blade wheel diameter, m
G_c	mass flow rate, kg s^{-1}
k	isentropic exponent
M	Mach number
n	rotational speed, rev s^{-1} (RPS)
n_{nond}	non-dimensional speed, n/n_{ref}
n_{tc}	rotational speed parameter, $n/\sqrt{T_{in}}$, rev s^{-1} K$^{-1/2}$
p	pressure, Pa
R	gas constant, J kg^{-1} K^{-1}
R^2	coefficient of determination
R_c^2	corrected coefficient of determination
s^2	residual mean square
T	temperature, K
U_c	blade tip speed, m s^{-1}
V_d	displacement volume, m^3 rev^{-1}
W_c	compression work, W

Greek symbols

γ	polytropic exponent
η_c	isentropic efficiency
π_c	compression ratio
ρ	density, kg m^{-3}
ϕ_c	normalized compressor mass flow rate
ϕ_{corr}	corrected mass flow parameter, kg s^{-1}
ψ	dimensionless head parameter

Subscripts

corr	corrected parameter
exp	experimental
in	inlet
out	outlet
pred	predicted
ref	value at a reference point
top	maximum value on a speedline
s	isentropic

natural gas processing plants where they are driven by electric motors or by steam or gas turbines.

The models of compressor efficiency and mass flow rate are necessary for performance study, energy analysis, and control- and/or diagnose-oriented dynamic simulation (Eriksson et al., 2002; Canova et al., 2009; Chu et al., 2012). The compressor efficiency is also called the compressor isentropic efficiency or the compressor adiabatic efficiency.

Mathematical models of compressors can be built either theoretically or experimentally. Theoretical modeling is based on physical laws of mass, energy and momentum conservation (Schiffmann and Favrat, 2010; Liu et al., 2012; Chamoun et al., 2013). The high complexity of this modeling approach and its computational requirement make it unsuitable for control- and/or diagnose-oriented dynamic simulation and less attractive than compact and time-efficient models in design, analysis and performance simulation. Experimental modeling can yield compact and time-efficient mathematical models, which not only meet the need of control- and/or diagnose-oriented dynamic simulation, but also possibly apply to design, analysis and performance simulation. An experiment-based model is often referred to as an empirical model or a semi-empirical model, and is also called a mean value model in some literature regarding turbochargers, vehicle engines, and jet engines (Jensen et al., 1991; Biteus, 2004; Canova et al., 2009).

There are a number of mean value models for compressor efficiency and mass flow rates of turbochargers, vehicle engines, and jet engines (Jensen et al., 1991; Kolmanovsky et al., 1997; Mueller, 1997; Sieros et al., 1997; Guzzella and Amstutz, 1998; Eriksson et al., 2002; Biteus, 2004; Andersson, 2005; Canova et al., 2009). However, a systematic review has not been found. Some papers presented brief review, but the number of the models covered was very limited. Moraal and Kolmanovsky (1999) compared the models of Jensen et al. (1991), Mueller (1997), and Kolmanovsky et al. (1997) to the data of three turbocharger compressors. Andersson (2005) compared the models of Jensen et al. (1991) and his own with the measured data.

Most empirical efficiency and mass flow models of centrifugal compressors are derived from and applied to compressors of vehicle engines, turbocharger, and jet engines. For refrigeration compressors, there are no such models found. Due to lack of available models, most control and performance modeling of refrigeration centrifugal compressors opted for theoretical modeling (Schiffmann and Favrat, 2010; Liu et al., 2012), look-up tables (Tsujikawa, 1985; He et al., 2004), or neural network methods (Fast et al., 2009; Wang et al., 2011; Li and Li, 2012).

Our literature survey has not found any paper providing an overall review on the empirical models of efficiency and mass flow rates of centrifugal compressors and any empirical model for refrigeration centrifugal compressors. This paper presents a comprehensive review on empirical models of the compressor efficiency and mass flow rates of centrifugal compressors. The reviewed models are evaluated with the experimental data of two turbocharger centrifugal compressors and a centrifugal compressor for air-cycle refrigeration systems. The experimental investigation of a centrifugal compressor for air-cycle refrigeration systems is conducted to provide data for assessing the potential of centrifugal compressor models of turbochargers and vehicle engines to refrigeration centrifugal compressors.

2. Review of empirical models of compressor efficiency and mass flow rates

2.1. *Compressor performance map*

Empirical models of compressor efficiency and mass flow rate are essentially a mathematical interpretation of the compressor performance map. The operating behavior of a centrifugal compressor can be defined by a map with pressure ratio and non-dimensional mass or volume flow rate as coordinates (Fig. 1). The useable portion of the map is limited by the surge, choke and maximum permissible speed lines.