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Research paper

A new method for reliable performance prediction of multi-stage industrial centrifugal compressors based on stage stacking technique: Part II–New integrated model verification

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HIGHLIGHTS

- New performance prediction approach for multi-stage centrifugal compressors.
- It is used to predict the efficiency at both design and off-design conditions.
- The new method is valid for both high and low flow coefficients applications.
- The obtained characteristics have been tested and validated against measured data.
- More accurate estimation for compressor efficiency and stability range.

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ABSTRACT

This is the second part of a conducted study to develop a new integrated model for reliable performance prediction of multi-stage industrial centrifugal compressors. The conducted evaluation in part 1 revealed a high deviation between the predicted surge flows using Casey–Robinson approach and measured values especially at low rotational speeds. Besides, a significant difference between the estimated and the experimental characteristics was observed at choke and surge conditions and this deviation is growing as the Mach number increases. One of the main disadvantages of this model is the dependency on the peak and design efficiencies and associated flow coefficients at both normal and low Mach number operations which are obviously not available at early preliminary stage. In contrast, Lüdtke method fails to detect the instable flow regions and with lower degree of accuracy in the predicted efficiencies. However, the predicted design efficiency was found very close to the experimental value. Therefore, this paper introduces a new approach to estimate the performance map of multistage industrial centrifugal compressors based on stage staking principle and by incorporating the advantages of both methods. The new model has been tested at both low and high flow coefficients applications and for vaned and vaneless diffusers. Comparing with the existing models, the developed method was proven to generate more accurate estimation for performance characteristics of multistage centrifugal compressors with less dependency on the geometrical features. One of the unique advantages of the new method is the fact that it does not require a prior knowledge of the peak and design efficiencies and associated flow coefficients.

1. Introduction

The wide stable operating range and the high efficiency have been the most two features that drive the selection of centrifugal compressor for any particular applications. However, the variation in the suction parameters and operating circumstances makes the testing of the acceptability of any compressor unit to deal with these variables essential during the preliminary design stage. The performance of the new compressor has to be reliable and able to develop the required polytropic head at the expected efficiency within the stable region and using the specified speed range and input shaft power.

The conducted review in the first part of this study showed three basic approaches for the performance prediction of

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Nomenclature

Mu	tip speed Mach number
n_v	volume polytropic exponent
n_T	temperature polytropic exponent
D_1	impeller inlet diameter
D_2	impeller exit diameter
MW	molecular weight
$\varnothing$	flow coefficient
Re	Reynolds number
k_{df}	disc friction coefficient
k_s	correlation coefficient
β_2	exit impeller angle
d	design point
γ	degree of reaction
s	work coefficient
$\dot{V}$	inlet volume flow
Q	flow capacity
A, B, C, D, G, H	empirical coefficients
λ	friction factor
Z	compressibility factor
k	specific heat ratio
v	absolute flow velocity
U	tip blade speed
N	rotational speed
W	relative flow velocity
H_p	polytropic head
R	gas constant
CR	Casey–Robinson

List of subscripts

r	rated point
i	different rotational Speed
U	tip blade speed
W	relative flow velocity
N	rotational speed
H_p	polytropic head
R	gas constant
c	choke point
b	basic
act	actual
std	standard
θ	tangential direction
rel	relative
s	compressor suction
a	absolute
m	radial direction
p	polytropic

centrifugal compressors. Several researches have been done by using the CFD simulation such as: L. Walitt et al. [1], Niazi et al. [2], Prasad et al. [3], Jie Li et al. [4], Fabrie et al. [5] and Kalinkevych et al. [6]. Despite the relative accuracy which was achieved in estimating the stage performance, implementing this technique becomes more difficult while dealing with multi-stage centrifugal compressors since it fairly requires detailed information of each single stage geometry. The scaling-based- method was used also in extensive number of studies for the same purpose including: Dimitriadis [7] and C. Kong et al. [8]. However, a significant deviation was observed between the estimated and measured performance parameters when there is a dramatic change in the flow and work coefficients and Mach number from the initial tested stage.

The third alternative in the open literature is based on the algebraic correlations such as: Cumpsty [9], Herbert [10], Swain [11,12], Oh et al. [13], Rodgers [14] and Casey [15]. Such method requires deep details about the stage geometrical features at least on one dimensional scale. Therefore, the empirical coefficient in the developed equation has to be tweaked to be valid for others designs. This can be quite easy with single stage machines but not for multistage compressors.

Two most common existing approaches have been evaluated and adapted in part 1 of this study in order to be valid for this application which are: Casey–Robinson [16] and Lüdtke [17] models. Based on the conducted optimization, this paper will introduce a new model for more precise and reliable prediction of multi-stage centrifugal compressor performance. The developed method combines the advantages of both models in order to achieve more accurate estimation for performance parameters and stability range. The obtained characteristics using the new approach have been compared with the previous methods results and they were also tested against the measured data at both high and low flow coefficients applications. This will assess the validity of this method for shrouded 3D structure and unshrouded 2D geometry impellers and for both vaned and vaneless diffusers. One of the unique features of the derived model over the existing approaches is the fact that it can be used for multistage centrifugal compressors with less dependency on the geometrical features. Furthermore, the conducted evaluation emphasizes the validity of this approach for various impeller blades structures and diffuser categories.

2. New developed integrated model

The derived method consists of three main steps as shown in Fig. 1:

- Design efficiency calculation using the adapted Lüdtke method at fixed speed value and variable suction flow. The predicted curve is then used to define the peak efficiency and the associated flow coefficient.
- The determined efficiencies and flow coefficients are used to obtain the off-design efficiency value at various speed lines for the first mechanical stage by implementing the adapted Casey–Robinson model.
- The developed stage stacking approach is used to derive the characteristics of the following stage reaching to flange-to-flange performance curve.

One of the main disadvantages of the Casey–Robinson model is the dependency on the design and peak efficiencies and associated flow coefficients for every speed line in order to derive the off-design efficiency value. This indeed necessitates the need for iteration process since these variables are most often unknown at this design stage.

However, this becomes more difficult when the stage stacking technique is used in which the design efficiency of each mechanical stage has to be known. In the original method, the efficiency curve at constant speed line is derived and then corrected based on the peak efficiency and flow coefficient.

To determine design efficiency value for every single mechanical stage, the Lüdtke model is used by correcting the efficiency value of