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Determination of a suitable set of loss models for centrifugal compressor performance prediction

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Abstract Performance prediction in preliminary design stages of several turbomachinery components is a critical task in order to bring the design processes of these devices to a successful conclusion. In this paper, a review and analysis of the major loss mechanisms and loss models, used to determine the efficiency of a single stage centrifugal compressor, and a subsequent examination to determine an appropriate loss correlation set for estimating the isentropic efficiency in preliminary design stages of centrifugal compressors, were developed. Several semi-empirical correlations, commonly used to predict the efficiency of centrifugal compressors, were implemented in FORTRAN code and then were compared with experimental results in order to establish a loss correlation set to determine, with good approximation, the isentropic efficiency of single stage compressor. The aim of this study is to provide a suitable loss correlation set for determining the isentropic efficiency of a single stage centrifugal compressor, because, with a large amount of loss mechanisms and correlations available in the literature, it is difficult to ascertain how many and which correlations to employ for the correct prediction of the efficiency in the preliminary stage design of a centrifugal compressor. As a result of this study, a set of correlations composed by nine loss mechanisms for single stage centrifugal compressors, conformed by a rotor and a diffuser, are specified.

1. Introduction

Centrifugal compressors are an integral part of the industry due to their good performance, large tolerance to process fluctuations, and higher reliability compared to other compressors, and they are, in many cases, considered as critical equipment in multiple processes.[1] Centrifugal compressors have different sizes depending on their pressure ratio, which can vary from 1:3 by stage to 12:1 in experimental models.[2] However, their performance calculation, for both design point and off-design conditions, requires the knowledge of the many phenomena which give rise to a series of losses that contribute to significant decrease of their efficiency. Therefore, the accurate calculation and proper weighting of these losses are crucial to the design of centrifugal compressors because if certain

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design parameters are not properly controlled, their efficiency may decrease dramatically, which will generate a substantial increase in operating costs.

Correctly predicting the efficiency of a turbomachine is actually quite difficult. It demands a combination of theoretical and experimental results, from which a set of semi-empirical correlations can be obtained. These semi-empirical correlations, dating from several decades, are “black boxes” that produce a relationship between inputs and outputs (without a physical description of the phenomenon), and are still the resource used to predict off-design characteristics of turbomachines, because available computational methods fail to predict their performance with sufficient accuracy.[3]

The aim of this paper is to establish a set of correlations that adequately predict the performance of centrifugal compressors in preliminary design stages, and since the wide variety of correlations and mechanisms available in the literature becomes problematic, it is a priority to know how many and which mechanisms should be used in order to properly predict the performance of centrifugal compressors. The present study conducts an analysis of different loss correlations reported in the open literature and then implements them in FORTRAN code, in order to determine the loss correlation set most suitable for predicting the efficiency of single stage centrifugal compressors experimentally tested. Efficiency results of several experimental tests reported in the literature are compared with the computed isentropic efficiency obtained using the different loss correlation sets in order to determine the one that fits better with all of the centrifugal compressors analyzed in this study.

2. Centrifugal compressor losses

In some open literature sources, such as Refs.[4,5], the losses are typically collected together as a slip factor and/or loss coefficient. The disadvantage of this procedure is that the effects of the individual losses are not clearly characterized and therefore its influence is little recognized. On the other hand, some authors, such as Aungier[6] and Boyce,[2] document the individual losses in much greater detail. According to them, there are 11 well-documented loss mechanisms that affect the impeller, and these loss mechanisms are: (A) shock; (B) incidence; (C) diffusion; (D) choke; (E) skin friction; (F) clearance gap; (G) blade loading; (H) hub-shroud loading; (I) wake mixing; (J) expansion; (K) supercritical Mach number.

However, the losses with the highest impact on the performance of the compressor according to Aungier[6] are: (A) skin friction loss; (B) entrance diffusion loss; (C) recirculation; (D) incidence loss; (E) clearance loss; (F) disk friction loss.

Besides losses on the impeller, energy losses must likewise be evaluated in both the vaneless diffuser and vaned diffuser. In the vaneless diffuser, the losses are due to skin friction and diffusion.[6] The vaned diffuser exhibits energy losses associated with skin friction, incidence angle, blockage, wake mixing, and choking.

However, some of the correlations available in the literature, obtained experimentally, for different loss mechanisms, take into consideration several mechanisms of loss simultaneously due to the extreme difficulty of differentiating its effects, either for technical or conceptual issues, so the use of correlations for all loss mechanisms would lead to an overestimation of the overall loss of the compressor.

Consequently, the selection of a set of correlations for calculating loss of efficiency in turbomachines is not a trivial task, so it requires proper selection of mechanisms and correlations to be considered for the correct prediction of the overall efficiency. Below is presented a study aimed at evaluating the losses obtained using different loss correlations to establish a combination of models to predict the efficiency of various centrifugal compressors using an appropriate set of correlations.

3. Loss models

In this analysis, nine loss mechanisms will be considered. Three models will be used for evaluating clearance loss, four models for disk friction loss, two loss models for recirculation loss, two models for leakage loss, and one model for: skin friction loss, incidence loss, blade loading loss, vaneless diffuser loss and vaned diffuser loss. The different mechanisms and models are evaluated as described below.

3.1. Clearance loss

Clearance loss considers the flow escaping from impelling by the clearance between the blades and the outer casing of the compressor, from the pressure side to the suction side. In this work, the estimation of clearance loss is computed using the loss correlations proposed by Rodgers,[7] Krylov and Spunde,[8] Jansen,[9] and these correlations are shown in Eqs. (1)–(3) respectively.

$$\Delta H_{\mathrm{cl}} = 0.1\frac{s}{b_2}U_2^2 \tag{1}$$

$$\Delta H_{\mathrm{cl}} = 2\frac{s}{b_2}\left(\frac{r_{\mathrm{h}}+r_{\mathrm{s}}}{2r_2}-0.275\right)U_2^2 \tag{2}$$

$$\Delta H_{\mathrm{cl}} = 0.6\frac{s}{b_2}V_{\mathrm{u2}}\left(\frac{4\pi}{b_2 Z_{\mathrm{i}}}\cdot\frac{r_{\mathrm{s}}^2-r_{\mathrm{h}}^2}{r_2-r_{\mathrm{s}}}V_{\mathrm{u2}}V_1\bigg/\left(1+\frac{\rho_2}{\rho_1}\right)\right)^{\frac{1}{2}} \tag{3}$$

where ΔH_{cl} is the clearance loss, s is the clearance gap, b is the blade height, r is the radius, U is the circumferential speed, V is the absolute velocity at inlet, V_{u} is the circumferential component of the absolute velocity, ρ is the density of the fluid in the inlet and discharge of the impeller, Z_{i} is the number of impeller blades, and the subscripts “h”and “s” refer to the impeller inlet hub and shroud respectively, “1” refers to the impeller inlet and “2” refers to the impeller discharge.

3.2. Disk friction loss

This loss mechanism occurs as a result of adhesive forces between the rotating disk and the fluid in the surrounding enclosure. The induced flows depend on the geometries of the impeller and its enclosure.[10] The disk friction loss models evaluated in this work are shown in Eqs. (4)–(7) and were introduced by Aungier,[6] Daily and Nece,[11] Shepherd[12] and Boyce[2] respectively.

$$\Delta H_{\mathrm{df}} = (V_{\mathrm{mi}}+V_{\mathrm{md}})\rho_2 U_2^3 r_2^2/(2\dot{m}) \tag{4}$$

$$\Delta H_{\mathrm{df}} = f_{\mathrm{df}}(\rho_1+\rho_2)r_2^2 U_2^3/(8\dot{m}) \tag{5}$$

$$\Delta H_{\mathrm{df}} = 0.01356\rho_2 U_2^3 D_2^2/(\dot{m}Re^{0.2}) \tag{6}$$

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