How to cite / Как сослаться на статью:
Ivanov, V.M., Kozhukhov, Y.V., Danilishin, A.M. Calculation of the impellers head characteristics of the low-flow centrifugal compressor stages based on quasi-three-dimensional inviscid and viscous methods (2019) AIP Conference Proceedings, 2141, № 030064. DOI:10.1063/1.5122114

Calculation Of The Impellers Head Characteristics Of The Low-Flow Centrifugal Compressor Stages Based On Quasi-Three-dimensional inviscid And Viscous Methods

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Abstract. The paper shows the results of calculation internal head characteristics of the intermediate low-flow centrifugal compressor stages impellers. The type of stages is used at the last stages of multistage centrifugal compressors of the high and ultrahigh pressure. Inviscid quasi-three-dimensional and viscous three-dimensional calculation methods are used. Numerical models of the objects of study represent the flow part of the impeller and the blade-free diffuser with width equal to the height of the blade at the output of the impeller. For a CFD calculation, two interfaces are considered: frozen rotor and stage. It is found that the most qualitative character has a viscous calculation with the Stage interface and inviscid quasi-three-dimensional calculation.

INTRODUCTION

Low-flow stages with 2D impellers are used as the last stages of multistage centrifugal compressors of high and ultrahigh pressure. Such machines are most often used at booster compressor stations for compression of natural and associated petroleum gases. The stages are characterized by a high density at the inlet, which reduces the gas volume flow. In studies of these stages it is necessary to consider the influence of the Reynolds number, roughness, friction and leakage. The experimental facilities are subject to special requirements for accuracy and methodology of the experiment. Study of centrifugal compressors high-pressure dedicated to work in SPBPU (exp. Leningrad Polytechnic University), Lenniihimmash, VNIIkompressormash, Bauman, Kazan state technological University, etc. Numerous theoretical and experimental studies of the topic [1] at the high-pressure facility with a closed circuit under the guidance of K. P. Seleznev were conducted at the Department of Compressor, Vacuum and Refrigeration Engineering SPbPU.

The analysis of the efficiency of the designed low-flow stages faces difficulties due to the complex nature of the turbulent flow. Such stages are characterized by a relatively small ratio b_2/D_2. This leads to the closure of the boundary layers and the appearance of a developed turbulent velocity profile. The presence of a gap and labyrinth seal in the shroud and the main disk in such stages plays a major role in the appearance of increased losses. To generalize research and build a mathematical model of head characteristics requires thorough computational and theoretical research.

PURPOSE OF WORK

The purpose of the work is to conduct a preliminary calculation of head characteristics of impellers of low-flow stages of centrifugal compressor based on quasi-three-dimensional inviscid and viscous methods. The object of the study are the impellers series Q, R, S licensed model stages of the company Dresser&Clark. The scheme of a typical intermediate stage is shown in figure 1. The main parameters of the stages are shown in table 1.

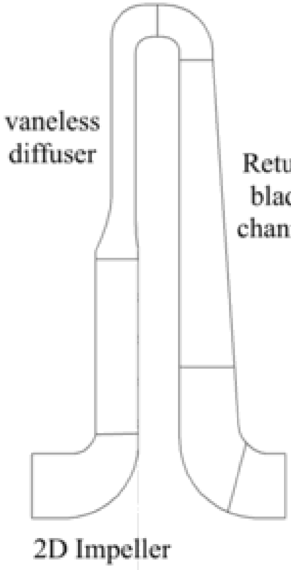

FIGURE 1. The scheme of the experimental model stage Dresser&Clark base XX3

Conditional flow rate coefficient is

$$\Phi = \frac{4 \cdot \overline{m}}{\rho_{inl}^{*} \pi D_2^2 U_2} \tag{1}$$

Internal head coefficient is

$$\psi_i = \psi_p^{*} / \eta_p^{*} \tag{2}$$

Table 1. Objects of research for development of verification base

№	Index	D_2, m	b_2/D_2	M_u
1	Q-482	0.4826	0.0263	0.785
2	R-482	0.4826	0.0228	0.802
3	S-482	0.4826	0.0198	0.802
4	Q-508	0.5080	0.0250	0.785
5	R-508	0.5080	0.0216	0.802
6	S-508	0.5080	0.0189	0.802
7	Q-533	0.5334	0.0238	0.785
8	R-533	0.5334	0.0206	0.802
9	S-533	0.5334	0.0180	0.802

NUMERICAL CALCULATION

The software package Ansys CFX 18.0, turbulence model k-ω, the size of the computational grid ~1.1 million elements were used. Figure 2 shows a general view of the design grid in the impeller and the flow structure. The calculation was carried out in two versions of the connection between the domain of the impeller and the vaneless diffuser: stage (mixing plane - transmission of parameters averaged over a circumferential coordinate) and frozen rotor (frozen rotor - transmission of parameters without averaging). The quasi-three-dimensional calculation was performed using the Ansys Vista Throughflow program based on the approach [3]. Control of calculations was made on the basis of available experimental data of 9 model stages for the following range of conditional flow coefficient Φ=0.009-0.025.

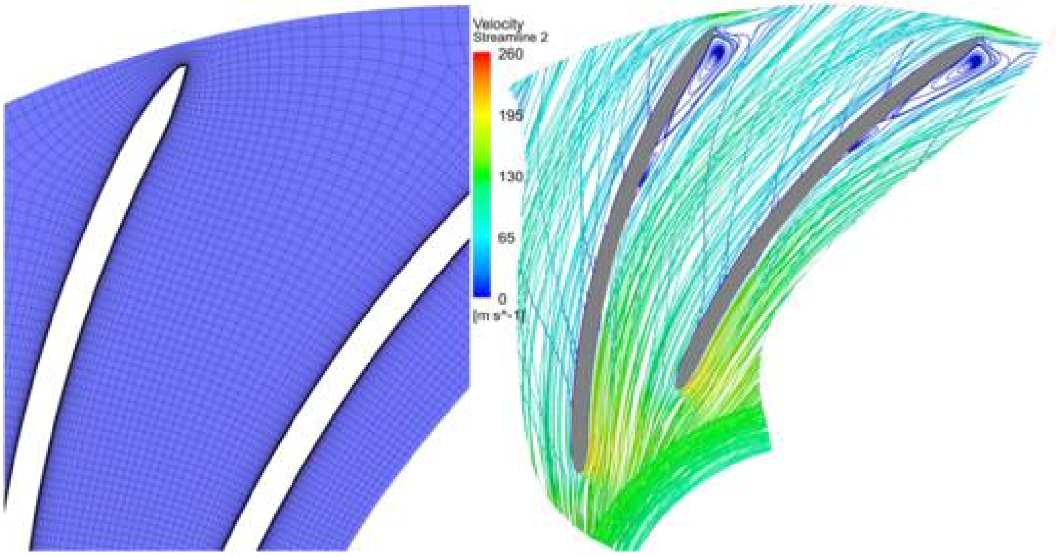

FIGURE 2. Computational grid (left) the flow structure in the impeller (right)

There were no interdisks gaps and labyrinth seals in the calculation model (simplified model). Respectively, are not considered components β_{fr} and β_{lk}. For viscous calculation we have $\psi_i \sim \psi_t(1+\beta'_{fr})$ (stroke(') means accounting for only part of the energy in the inter-blade channel). The difference is small and the maximum value of β'_{fr} is 0.009. This value determines the additional work on the limiting surfaces at the outlet of the impeller after blade trailing edge. For inviscid calculation $\psi_i=\psi_t$.

Experimental characteristics were presented in the form of polytrophic efficiency and head coefficients in total parameters. To assess the theoretical head coefficient, it is effective to use data, for example [1], where the element-by-element experimental studies of low-flow stages were carried out. The current characteristics of the internal head of the stage should be compared with all the elements of the flow part. So far, this paper has made a preliminary assessment of the simplified models. In detailed models, the impeller should have a slightly higher mass flow rate than was specified due to leakage on the cover disc. These circumstances will be taken into account in the next work, but for now a qualitative assessment of the head characteristic is made Figures 2, 3, 4 present the results of calculations in the form of graphs of the dependence of ψ_i on the conditional flow coefficient of model stages of series Q, R, S for two calculation options. On some charts in the experimental data, an increase in the internal head at the maximum flow rate is noticeable. This does not correspond to the classical concepts of the centrifugal compressor stage work and can be explained by the relatively greater error of the experimental data at this mode or by the presence of the flow preswirl at the inlet. The swirl of the flow could occur due to the presence of a return blade channel apparatus in the model stage.

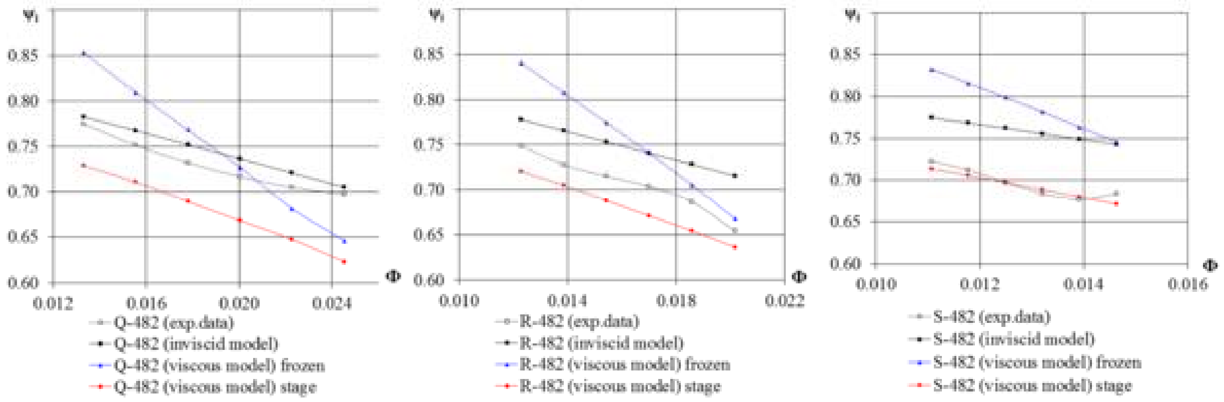

FIGURE 4. The plots of the ψ_i dependencies on the conditional flow coefficient Φ for the models Q,R,S-482

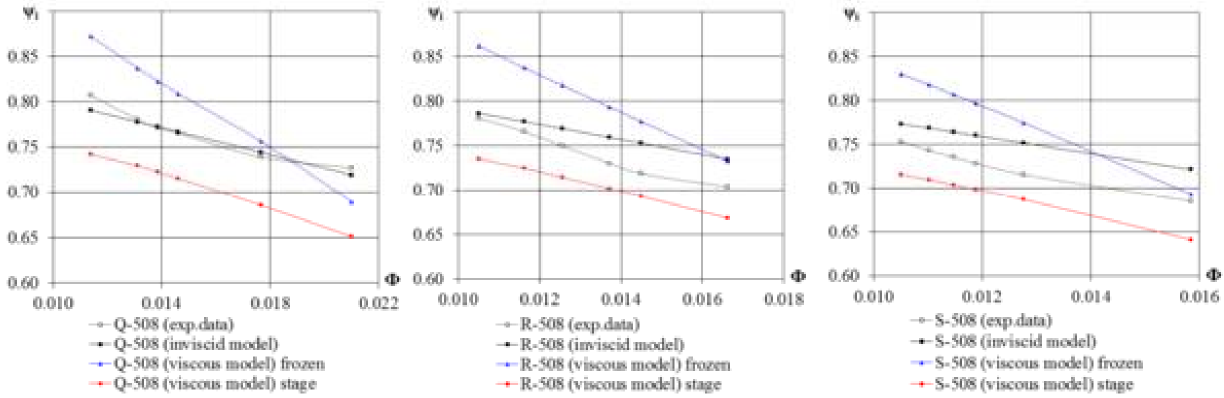

FIGURE 5. The plots of the ψ_i dependencies on the conditional flow coefficient Φ for the models Q,R,S-508

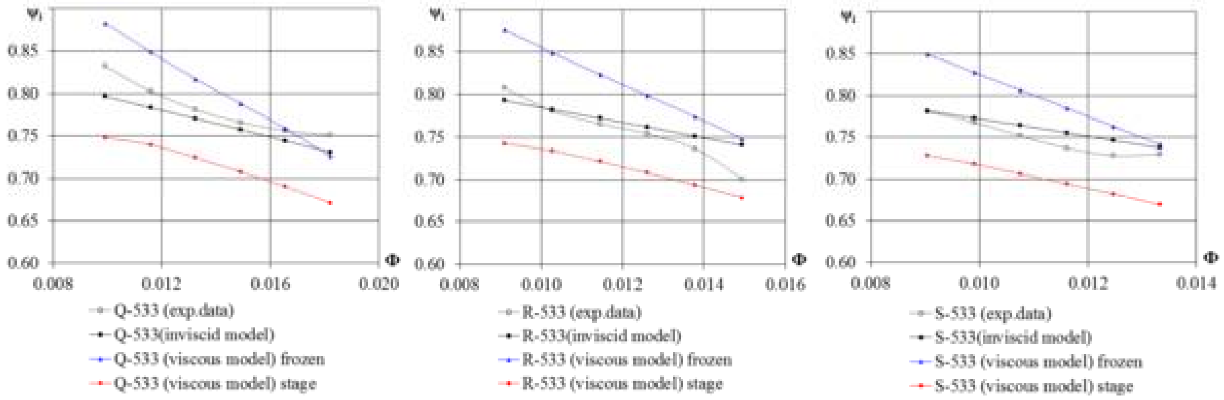

FIGURE 6. The plots of the ψ_i dependencies on the conditional flow coefficient Φ for the models Q,R,S-533

The analysis of the graphs shows that the use of the frozen rotor interface entails a qualitative change in the characteristics and an overestimation of the internal head values. The nature of the change in the internal pressure on the Stage interface and the inviscid calculation is of a qualitative nature, repeating the slope of the experimental curve.

Quantitatively, due to the lack of friction, the inviscid calculation should be compared with the experimental characteristic of the theoretical head, since the dependence on the size of the low-energy zone – wake, the magnitude of the flow separation is strong, however, for almost all calculations, the position of the line is above the experimental curve. In the inviscid calculation, a thin boundary layer model is used, i.e. the boundary layer does not affect the flow in the main flow in the interscapular channel. In low-flow impeller stages, the thickness of the boundary layer is commensurate with the width of the channel, respectively, the model of the boundary layer is not applicable, but as the calculation showed, a qualitative analysis of the slope of the head characteristic is possible. The position of the viscous calculation with the "stage" interface is lower for the stages Q, R, S. Since the experimental data are not sufficient for the quantitative analysis of the calculations of specific impellers, it is necessary to calculate the full stage taking into account all the elements of the flow part. This may allow further generalization of data for the calculation of pressure characteristics for low-flow centrifugal compressors on the basis of inviscid calculation.

CONCLUSIONS

The results of comparison of the internal head characteristics with the experimental data of 9 models are obtained. A good agreement with the experiment was obtained for the slope of the characteristics for the inviscid and CFD calculation with interface “stage”. For CFD calculation with the “frozen rotor” interface, an incorrect angle of slope was obtained.

For further calculations of the detailed model, it is recommended to use the "stage" interface for the entire range of the conditional flow coefficient Φ=0.009-0.025. For all calculations, leakage through the gap was not taken into account, overestimation of the mass flow rate was not taken into account. In the future, modeling will be performed taking into account the missing elements

ACKNOWLEDGEMENT

The results of the work were obtained using computational resources of Peter the Great Saint-Petersburg Polytechnic University Supercomputing Center (www.spbstu.ru)

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