Industrial Engineering Journal
ISSN: 0970-2555
Volume : 52, Issue 12, No. 1, December : 2023

COMPREHENSIVE REVIEW ON SLIP CALCULATION MODEL FOR FAN BLADE DESIGN

Mr. A. Dhumal, Mr. M. Jagdale, Mr. N. Kate, Assistant Professor, Dept. Of Mechanical Engineering, Vishwakarma Institute of Information Technology, Pune.
Dr. A. Kulkarni, Professor, Dept. Of Mechanical Engineering, Vishwakarma Institute of Information Technology, Pune.

Abstract

Fans with significant blade categories are frequently used in many sectors to create airflow and improve heat transfer. However, the slip phenomenon has a substantial impact on these systems' overall performance. which causes a reduction in aerodynamic efficiency, an increase in energy consumption, and potential structural problems, is the relative movement of the fan blades with the surrounding air. The design and operation of fan blade systems can be optimized by analyzing the slip phenomenon and creating efficient models for slip prediction. In this research paper, our aim is to conduct a comprehensive review of the existing literature on slip prediction models in fan blade systems.

Keywords: Model, Slip Factor, Centrifugal Pump, Axial Fan, Centrifugal Impellers

I. Introduction

The slip factor quantifies the extent of slip experienced by the fan blades. The flow rate of fans, compressors, and pumps is actually lower than what is predicted, assuming that the flow at the rotor exit follows the trailing edges of the blades. The slip factor in radial flow machines is responsible for this drop in angular momentum.

Even with advances in computational fluid dynamics, engineers and students still need a reliable method to estimate the slip factor. Such a procedure should be simple, with no need for complicated iterations or conditions. It should have a solid foundation in fluid dynamics, be applicable to diverse impeller geometries such as blade number, blade angle, and impeller radius ratio, and provide reasonably accurate results.

Slip prediction models are able to anticipate the detrimental effects of slip, contributing to the design of more efficient and reliable fan blade systems. In this paper, we aim to review slip factor calculations by various slip prediction models proposed in this literature and understand the various theories and parameters involved in the anticipation of the slip factor and look for further scope of improvement and development in the estimation of slip. By examining and analyzing different approaches proposed by researchers, to identify the key factors influencing slip, the accuracy and applicability of existing models, and identify potential areas for further improvement based on the practical implications and limitations of these models.

Methods to determine Slip factor:

1.) Stodola equation:

A. Stodola (1927) obtained one of the oldest and simplest instructions for determining the slip coefficient. The slip factor is influenced by flow deviation resulting from the relative axial eddy, which reduces the velocity at the impeller output. The equation proposed by Stodola has been presented in various books and articles, including those by T.W. von Backström and Harrison H. M.

$$\mu_{\text{Stodola}} = \frac{\frac{\pi}{z} u_2 \sin\beta_{2b}}{u_2 - c_{2m}\,\mathrm{ctg}\,\beta_{2b}}.$$

2.) Stanitz equation:

The equation proposed by Stanitz for determining the slip factor was based on a theoretical study of eight centrifugal and diagonal compressor impellers with a vane exit angle ranging from 0 to 45 degrees. According to Stanitz, the slip velocity 2u Δc is not dependent on the blade angle β2b and only depends on the step of the blades. The equation proposed by Stanitz is related to the previous equation discussed in the text.

$$\mu_{\text{Stanitz}} = 1 - \frac{0.63\frac{\pi}{z}}{1 - \frac{c_{2\text{m}}}{u_2 \tan \beta_{2\text{b}}}}.$$

3.) Pfleiderer equation:

Pfleiderer's equation is used to estimate the theoretical pump head when there is a finite number of blades.

$$H_{\text{th}} = \frac{1}{1+p} H_{\text{th}\infty}.$$

The equation incorporates a correction factor, p, which takes into account the uneven distribution of pressure and velocity near the blade exit and the constant load per unit length of the blade surface. This equation is frequently referenced in the literature for this purpose.

Pfleiderer correction is not related to the slip factor, but rather it is a correction factor for the head due to the finite number of blades. Nonetheless, it can be expressed in a specific equation format that relates it to the slip factor.

$$\mu_{\text{Pfleiderer}} = \frac{1}{1+p}.$$

Where p is,

$$p = 2\frac{(0.55 \div 0.68) + 0.6 \sin \beta_{2\text{b}}}{z}\left[1 - \left(\frac{D_1}{D_2}\right)^2\right]^{-1}.$$

4.) Weisner equation:

The following modified Wiesner equation is suggested for calculating the slip factor:

$$\mu_{\text{Wiesner}} = 1 - \frac{u_2}{c_{2\text{u}\infty}}\left[1 - 0.98\left(1 - \frac{\sqrt{\sin \beta_{2\text{b}}}}{z^{0.7}}\right)\right].$$

5.) Backström equation:

An innovative method for estimating the slip factor has been proposed by T.W. von Backström in his papers. He claims to have developed an equation that combines the slip factor prediction methods of Stodola, Stanitz, and Wiesner for a centrifugal impeller. This method is said to be applicable to both radial and backward-facing impellers. Von Backström's analytical approach calculates the slip velocity using a single relative eddy (SRE), which is centered on the impeller's axis, instead of the multiple eddies (one per blade channel) used by Stodola. He also introduced the concept of "blade stiffness," which is the ratio of blade length (l) to t2 = πD2/z at the impeller output. The parameter l/t2 is considered the main variable that determines the slip factor.

The coefficient F (impact factor of blade stiffness in applying the SRE method) depends on the angle β2b and z, and may be determined by applying the equation below:

$$F = 2 + \left(2.71 + \frac{\pi}{z}\sin \beta_{2\text{b}}\right)\sin \beta_{2\text{b}}.$$

Thus, the slip coefficient is given by,

$$\mu_{\mathrm{EU}} = 1 - \frac{u_2}{c_{2u\infty}} \frac{1}{1 + F\dfrac{l}{t_2}}.$$

II. Literature

A new slip factor for centrifugal impellers by K S Paeng and M K Chung [1]

A new correlation for the slip coefficient of centrifugal wheels. The functional form of the correlation is obtained by studying the radius of a relative vortex recorded by two adjacent blades and the escape ring of a flow channel in the wheel. Two functions are introduced to correct the slip coefficient obtained from the current relativistic vortex model concerning the previous analytical results of the Visser, Brouwers, and Badie experiments. The suggested correlation is a function of the number of propellers (Z), the exit angle of the propellers (β'2), and the in-out radius ratio (r1/r2).

Z= No. of vanes
β’2= exit vane angle
εlim = impeller radius ratio at the limit of ‘blade solidity

A Review of Slip Factors for Centrifugal Impellers by F. J. WIESNER [2]

The many approaches that have been suggested for estimating the fundamental slip factors for centrifugal impellers are reviewed in general in this work. The findings of this study lead to the conclusion that the conventional approach, first put forth by Busemann in 1929, continues to provide the most broadly applicable forecast for the fundamental slip factor of centrifugal impellers. The study then offers a remarkably straightforward empirical expression that, up to a limiting inlet-to-outlet radius ratio for the impeller, fits the Busemann results admirably across the whole range of useful blade angles and the number of blades. For situations where this limiting radius ratio is exceeded, an empirical correction factor is also suggested.

β2 = impeller discharge blade angle, deg
Z = number of blades
σ = slip factor

Improving slip factor prediction for centrifugal pumps using artificial neural networks by Mohsen Ghaderi, Amir F Najafi [3]

In this study, an artificial neural network (ANN) technique was employed to predict the slip factor of centrifugal pumps. Over 70 different impellers were analyzed using computational fluid dynamics (CFD), and the numerical model accurately estimated the slip factor. The ANN model incorporated the blade turning rate and modified blade solidity as inputs, improving the predictive ability compared to previous models. The network was trained using a random subset of CFD outcomes, and the optimal structure was determined through trial and error. The predicted values showed good agreement with the target values, with most predictions within 0.03 of the CFD estimates. The model outperformed other slip models, proving its effectiveness for impeller design.

A compact equation for the prediction of eddy-induced slip in centrifugal impellers by T W von Backstrom [4]

The text presents the single relative eddy (SRE) method, which challenges the conventional belief of multiple eddies in centrifugal impellers. Instead, it proposes the existence of only one slip-inducing eddy in a rotating impeller. By incorporating an auxiliary coefficient F, the SRE method determines the eddy-induced slip factor based on blade solidity. The study introduces a set of improved expressions for F, leading to a compact equation for the slip factor. The SRE approach with RR taken as 0.5 when RR, 0.5, combined with the relatively simple expression F4 = 2+{2.7+(3/Z)*cos β}*cosβ, is recommended as a compact method for the calculation of the eddy-induced slip factor of all impellers with RR, 0.6. For high-solidity impellers, the use of the expression F3 = 2+3*cosβ is recommended.

F =shape factor coefficient
Z = No. of blades
β = blade angle at rotor periphery (from radial direction)

A dynamical basis for a slip in centrifugal impellers by Nzumbe-Mesape Ntoko [5]

In order to determine the slip factor, the impeller outlet relative flow angle was obtained from the expression for the angle. The ability to obtain a new expression for the slip factor was then made possible by an attempt to describe the phenomena of slip using an oblique coordinate system with axes in the direction of the tangent to a vane and in the tangential direction, use of an oblique coordinate resulting formulation for slip factor is simpler given as,

Suitable for values of pump vane numbers (5–12) and vane outlet angles (between 50 and 70 degrees). The use of an angle of overlap improves agreement between some calculated and reference values of the slip factor.

σ = slip factor at impeller vane

σ’ = slip factor

Ø = flow coefficient (absolute velocity of a fluid particle at impeller outer radius/ impeller tangential velocity at impeller outer radius)

β = flow or vane angle measured relative to the radial direction (rad).

Analysis and Validation of a Unified Slip Factor Model for Impellers at Design and Off-Design Conditions by Xuwen Qiu [6]

In this study, The model utilizes the blade loading near the discharge and the relative eddy in the impeller passage as core factors. Estimating the blade loading and employing Stodola's assumption, the slip velocity is derived, resulting in a slip factor model that applies to different impeller types.

This model is based on the blade loading analysis and the slip factor modeling work of Stodola and Eck. This model states that when the blade-turning rate at the impeller discharge is significant, the impeller rotation on the radial plane and the blade rotation has a significant impact on the slip factor. For an axial impeller, it has been shown that the slip factor is comparable to Carter's rule deviation model. Neglecting the blade-turning effect, the new slip factor model for radial impellers is comparable to Stodola's model. However, the blade turning term is important for many radial impellers and is the primary element that regulates the trend of slip factor change at off-design conditions.

A Unified Correlation For Slip Factor In Centrifugal Impellers by Theodor W. von Backström [7]

The slip factor, which indicates the difference between actual slip velocity and ideal fluid velocity, is discussed in this article. There are two definitions of slip factor: one divides slip velocity by rotor rim speed, and the other uses ideal slipless fluid velocity. The Single Relative Eddy (SRE) method is used to analyze the slip factor, which reveals that it grows as the radius ratio decreases. Inaccuracies and discrepancies in slip factor predictions are revealed by comparisons with the Stodola, Weisner, and Stanitz equations. The work emphasizes the derivation of the slip factor from a single relative eddy at the rotor axis center and recognizes the impact of blade solidity. The paper contributes a straightforward way of integrating analytical and numerical approaches to harmonize distinct equations for impeller geometries.

A New Slip Factor Model For Axial And Radial Impellers by Xuwen Qiu, Chanaka Mallikarachchi, and Mark Anderson [8]

In this study, A new slip factor model for several impeller types, including axial, radial, and mixed flow, is proposed. The model incorporates blade loading analysis as well as the effect of impeller rotation on the radial plane and blade turning. The study discovers that the blade-turning rate has a considerable effect on the slip factor, particularly at the impeller discharge. The slip factor for axial impellers corresponds to the generally used deviation models. The effect of blade rotation on slip factor changes becomes critical in radial impellers. The suggested model bridges a theoretical gap in meanline modeling by providing a consistent approach to calculating the slip factor for diverse impeller designs. It emphasizes the significance of the impeller discharge blade-turning rate as a vital metric.

Losses in Vaneless Diffusers of Centrifugal Compressors and Pumps," by J. P. Johnston and R. C. Dean, Jr.[9]

The article examines the slip factors of centrifugal impellers and expresses agreement with the author's results. However, it raises concerns regarding the lack of a fundamental explanation for variations in the slip factor. The critique emphasizes the importance of gaining better knowledge of the slip phenomenon and taking additional variables into account. It emphasizes the importance of fluid flow deviation from the blading by pointing out that the slip factor is not constant for a given impeller. The criticism proposes using Busemann's theory to precisely quantify slip deviation near the impeller tip. It continues by urging the development of a comprehensive approach to predicting slip and its variations in various impeller designs.

Estimation of Slip Factor by W.J. Love [10]

The author is known for this extensive comparison of experimental data with the various methods which have been proposed for estimating slip factor. The prediction of slip factor has continued to be an important and somewhat uncertain procedure despite a long history of consideration. The laboratory with which this reviewer is associated has found reasonable agreement using a slip factor correlation developed by Eck. This equation form was compared with the experimental data

The article involves a plot of all the test values versus slip factor equation value which suggests that Eck's equation may be valid. Eck's equation would have the added advantage of not requiring modification to accommodate large impeller radius ratios.

A Method of Calculating the Slip Factor of Centrifugal Compressors from Deviation Angle

By Pampreen, R.C. and Musgrave D. S. [11]

The rotor exit deviation angle is used in this research to estimate the working coefficient of a centrifugal compressor. The calculation is based on Carter's rule, which is often used for axial compressors. In the study, the deviation angle coefficient was found to be high for radial impellers and low for backswept impellers calculation is based on Carter's rule, which is often used for axial compressors. In the study, the deviation angle coefficient was found to be high for radial impellers and low for backswept impellers. This coefficient is determined to be dependent on the impeller's ideal diffusion, which is related to the position of the separation point on the blade. More data, however, is required to evaluate the model's accuracy. Additional information, such as the distribution of blade surface velocity, is required to demonstrate the association between the deviation angle coefficient and ideal diffusion. Data from a laser velocimeter would provide further information on the centrifugal impeller's deviation angle.

Studying the variation of the slip factor when trimming the impeller of centrifugal pumps

By Kliment Klimentov, Desislava Nikolova, Gencho Popov and Boris Kostov [12]

The study obtained experimental results for the theoretical and potential heads of two centrifugal pumps with different specific speeds when operating with untrimmed impellers. CFD models of the impellers were established, and the numerical results for theoretical and potential heads had a relative deviation below 5% when operating with untrimmed impellers in the range of 0.92 to 1.15. The study also obtained numerical results for the slip factor of the pumps when operating with untrimmed and trimmed impellers, which were compared to hydraulic equations. The best match for the slip factor when operating with a trimmed impeller was found to be between the numerical results for the 6E32 pump and the Stodola equation. The study examines how impeller trimming affects the slip factor variation and establishes hydraulic relationships. The relationships are expressed through equations, and the coefficients for the equations are determined specifically for pumps 6E32 and 12E20.

Effect of Rotation Speed and Flow Rate on Slip Factor in a Centrifugal Pump

By Bo Chen, Baolin Song, Bicheng Tu, Yiming Zhang, Xiaojun Li, Zhigang Li, and Zuchao Zhu [13]

The article examines the use of PIV to measure the velocity field of a five-blade centrifugal pump and calculate the slip factor at various rotation speeds. The findings indicate that the slip factor increases with both flow rates and rotation speeds. The article also analyzes the effect of flow rate on the slip factor and notes that the presence of clockwise vortexes leads to an impact on the average slip factor. The comparison of data from different rotation speeds shows that the slip factor increases with rotation speeds. The article proposes a deviation coefficient of slip velocity based on the experimental data and modifies the Stechkin slip factor calculation formula. The modified model is suitable for correcting the slip factor at part-load flow rates, and the article concludes by discussing the potential implications of the work on the hydraulic performance design and prediction of centrifugal pumps.

Numerical Study of Slip Factor in Centrifugal Pumps and Study Factors Affecting its Performance

By H.A.Elsheshtawy [14]

The slip factor of a centrifugal pump is influenced by several factors, but the most significant ones are the exit blade angle (dβ) and the impeller's operating condition. The exit blade angle determines whether the slip factor trend is upward or downward. To better understand the impeller behavior, the author recommends that a new graph be added, similar to the H-Q Curve and efficiency-Q curve, which shows the effect of the operation on the energy transfer to the fluid in terms of the slip factor-Q curve.

ANALYSIS OF SLIP FACTORS IN CFD CALCULATIONS – ASSESSMENT OF LITERATURE MODELS

By M. Waesker , T. Goetz, B. Buelten, N. Kienzle [15]

The paper presents a study in which centrifugal compressor impeller geometries are varied with a DOE comprising 598 designs. Slip factors are derived based on CFD analysis and empirical models from the literature. The results are compared through statistical evaluation to assess the accuracy of the empirical models, with the Wiesner model found to be the most accurate. The analysis of variance is conducted to identify the four main parameters that influence the compressor slip, including the blade number, blade outlet angle, specific speed, and blade outlet turning rate. The data can be used to create a new CFD-based slip model, with the Wiesner model showing the most promise. The researchers plan to introduce an original CFD-based slip model and conduct detailed flow analyses for different DOE impellers to better understand the phenomena leading to compressor slip and slip modeling differences.

III. Conclusion

Slip prediction models such as 'Gulich-Wiesner', 'Aunginer-Wiesner' and 'Pfleidrer' are prominently used in the design of a blade for axial, radial, and mixed flow systems with some limitations including the model's sensitivity to input parameters, inability to detect localized stress fluctuations, and limited ability to handle complex slide behaviors. In this review paper, recent modifications to those empirical relations such as changing to an oblique coordinate system, and imposing new techniques such as ANN, CFD, and other advancements are used to increase the accuracy and robustness of the model. Further research and development are needed to address these limitations and improve the accuracy and reliability of slip prediction models.

References

[1] Paeng, K. S., and Chung, M. K., 2001, "A New Slip Factor for Centrifugal Impellers," Proc. Inst. Mech. Eng., Part A, 215, pp. 645–649.

[2] Wiesner, F. J., 1967, "A Review of Slip Factors for Centrifugal Impellers," ASME J. Eng. Power, 89, pp. 558–572

[3] Ntoko, N. M. (2012). A dynamical basis for a slip in centrifugal impellers. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 226(5), 706-711.

[4] von Backstro¨m T. A compact equation for the prediction of eddy-induced slip in centrifugal impellers. Proc IMechE, Part A: J Power and Energy 2006; 220: 911–915

[5] Ntoko N-M. A dynamical basis for a slip in centrifugal impellers. Proc IMechE, Part A: J Power and Energy 2012; 226: 706–711.

[6] Qiu X, Japikse D, Zhao J, et al. Analysis and validation of a unified slip factor model for impellers at design and off-design conditions. J Turbomachinery 2011; 133: 041018.

[7] Backstrom T W, 2006, "A Unified Correlation for Slip Factor in Centrifugal Impellers,", Journal of Turbomachinery, Vol 128

[8] Xuwen Qiu, Chanaka Mallikarachchi, and Mark Anderson," A New Slip Factor Model For Axial And Radial Impellers", GT2007-27064 ASME Turbo Expo 2007

[9] 3 J. P. Johnston and R. C. Dean, Jr., "Losses in Vaneless Diffusers of Centrifugal Compressors and Pumps," JOURNAL OF ENGINEERING FOR POWER, TRANS. ASME, Series A, vol. 88, 1966, pp. 49-62

[10] Eck, B., 1973, Fans, Pergamon, Germany

[11] Pampreen, R.C., and Musgrave D. S., 1978, "A Method of Calculating the Slip Factor of Centrifugal Compressors from Deviation Angle", Journal of Engineering for Power, Vol. 100, pp.121-128.

[12] Kliment Klimentov et al 2023 IOP Conf. Ser.: Earth Environ. Sci. 1128 012015, "Studying the variation of the slip factor when trimming the impeller of centrifugal pumps".

[13] Bo Chen, Baolin Song, Bicheng Tu, Yiming Zhang, Xiaojun Li, Zhigang Li, and Zuchao Zhu, Volume 2021, Article ID 6614981, "Effect of Rotation Speed and Flow Rate on Slip Factor in a Centrifugal Pump".

[14] H.A.Elsheshtawy, International Conference on Mechanical Engineering and Material Science (MEMS 2012), "Numerical Study of Slip Factor in Centrifugal Pumps and Study Factors Affecting its Performance"

[15] M. Waesker, T. Goetz, B. Buelten, N. Kienzle, Proceedings of 14th European Conference on Turbomachinery Fluid dynamics & Thermodynamics ETC14, April 12-16 2021; Gdansk, Poland, Paper ID: ETC2021-528, "ANALYSIS OF SLIP FACTORS IN CFD CALCULATIONS – ASSESSMENT OF LITERATURE MODELS".