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Experimental investigation of slip factors in centrifugal pumps

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ABSTRACT

The phenomenon of slip is known to strongly influence the performance of centrifugal pumps. In the present work, the slip phenomenon at the impeller outlet is studied experimentally for five industrial pumps at different flow rates and the slip factor is estimated for each of these cases. Theoretical slip factors are calculated using several existing methods taking into consideration the main geometric parameters of the impeller. Then the experimental slip factors are compared with the calculated theoretical values.

It was observed that in the design-point condition of the pumps, the experimental values are in a good agreement with the theoretical values. However, there are significant disagreements between the theoretical and experimental values at off-design regiments. The difference is more apparent at low flow rates. It is also found that the slip factor depends on the impeller-outlet velocity profile. By defining a flow distortion coefficient, a correlation is derived for evaluating the slip-factor value for off-design conditions.

Finally, a slip factor table is provided to calculate the slip factor in centrifugal pumps, using the geometry of impeller.

1. Introduction

1.1. Background

Slip phenomenon which occasionally happens in radial turbomachines, strongly influences their working conditions. From design and analysis point of view, it is of interest to know accurately the parameters influencing the slip factor. We also desire to be able to calculate slip-factor value. During the past eighty years, many researchers such as Busemann [1], Stodola [2], Stanitz [3], Pfleiderer [4], Balje [5], Fujie [6], and Wiesner [7], have studied this phenomenon, and several formulas have been investigated for the design-point condition. Perhaps the most well accepted work was developed by Busemann [1], who obtained values of the slip factor by means of potential flow analysis. However, the flow within a centrifugal pump impeller near the walls is far from potential, and this analysis could result in bad approximations.

On the other hand, Pfleiderer [4] developed a method to calculate the slip assuming a uniform distribution of the pressure around the blade. This method was strongly influenced by the type of diffuser. Another well-known expression for calculating the slip factor is provided by Stodola [2], who assumed a rotating cylinder of fluid at the end of the inter-blade channel as the cause of the slippage. Later, Stanitz [3] proposed a slip factor correlation derived from the analytical model of two-dimensional fluid flow.

Even though there are some results for backward-curved vanes, most of the work is related to radial blades.

In 1967, Wiesner [7] carried out a comprehensive review of the literature available up until that time regarding the slip factor. In his classical paper, Wiesner concluded that the Busemann's method was still the most accurate one. Furthermore, the author proposed a correlation fitting the Busemann data extremely well up to a limiting inlet-to-outlet impeller radius ratio. All the same, an empirical correction factor for conditions beyond this limiting radius factor was presented.

In 2006, von Backström [8] proposed a simple analytical method to derive the slip velocity in terms of a Single Relative Eddy (SRE). He tried to unify the other prediction methods. However, none of the proposed methods are general and they produce different results even when applied to the same impeller.

Stiefel [9] has proposed, for compressors, calculation charts and tables which are useful for practical applications. Here, we propose similar tables for centrifugal pumps in their design-point conditions. Various experimental tests have been done on centrifugal pumps. In most cases, the tested models are especially designed for research purposes (very long diffusers, specially profiled inlets, etc.). The results of such experiments cannot be generalized for industrial pumps where the fluid normally passes directly from the impeller into the volute which has significant influence on the flow regiment.

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Nomenclature

AN	flow distortion coefficient, dimensionless
b	impeller width, m
C	absolute velocity, m/s
CM	radial (meridional) component of C, m/s
CU	peripheral component of C, m/s
D	impeller diameter, m
g	gravitational acceleration, m/s^2
m	meridional coordinate
R	radius of impeller, m
P_S	static pressure, m H_2O
U	impeller peripheral speed, m/s
W	relative velocity, m/s
Z	number of blades
Greeks	
α	absolute flow angle, degree
β	relative flow angle, degree
β'	blade angle, degree
Φ	circumferential angle, degree
μ	slip factor, defined by Eqs. (1) and (2)
ϕ	impeller discharge flow coefficient, dimensionless $\equiv \overline{Cm_2}/U_2$
ω	angular velocity
Subscripts	
1	at the impeller entry
2	at the impeller exit
i	along stream line, blade-to-blade plane
j	along width, meridional plane
R	real or effective
Th	theoretical
Superscripts	
* (asterisk)	non-uniform flow
′ (prime)	infinite number of blades

The experimental part of this research consists of testing five industrial pumps over the whole range of their working conditions using only directional probes.

Analysis of the results reveals that there are some other factors that affect the slip phenomenon in off-design conditions. These factors include the pre-rotation phenomenon caused by the back flow, the outlet non-axisymmetric, and the non-uniform flow. Therefore, the slip factor table can be used only in design point.

1.2. The slip phenomenon

Theoretical blade-to-blade analysis and experimental measurements at the outlet of radial and mixed-flow impellers have shown a difference between the exit flow angle β_2 and the geometrical blade angle β'_2. This angular difference corresponds to an absolute-tangential velocity difference ΔCU_2 and characterizes the slip phenomenon in the flow. The local slip factor at point *i* along a streamline, at the impeller outlet (Fig. 1), is defined by:

$$\mu_i \equiv CU_{2i}/CU'_2. \quad (1)$$

The mean slip factor (called simply "slip factor") can be written as:

$$\mu \equiv \Sigma\left(CM_{2ij} \cdot CU_{2ij}\right)/\left(CU'_2\right) \cdot \Sigma CM_{2ij} = \overline{CU_2}/CU'_2. \quad (2)$$

In which $\overline{CU_2}$ is a mass-average value. Its value depends on the calculation method (two-or three-dimensional calculation).

Now, we consider the difference between the theoretical slip factor μ_{TH} and the real one μ_R. The theoretical slip factor is affected by the inevitable slip of the non-viscous flow in the impeller channel. This slip in return depends only on the geometrical parameters of the impeller (blade number *Z*, outlet angle β'_2, radius ratio, etc.) and is calculated only for the design point. We obtain μ_R from experimental measurements. It is a function of the flow parameters (viscosity effects, flow rate, and the Reynolds number) as well as μ_{TH}.

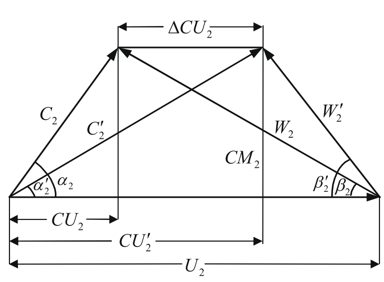

Fig. 1. Impeller discharge velocity diagram.

2. Slip factor table

2.1. Theoretical slip factor table

There are many theoretical or empirical methods currently being used to predict the slip factor of a centrifugal impeller from the geometry of the impeller. Each of these methods is valid only for some particular cases, i.e. applying different methods; result in different slip factors for the same impeller case. Experimental measurements are necessary to define the ranges of validity of different proposed formulae. For example, Table 1 shows that Stanitz's equation [3] can give large errors on the slip-factor value when considering impellers with few blades and small outlet angles (less than 50°), while the same formula is one of the most suit-

Table 1
Section a: comparison of experimental and predicted slip factors at the design point. Section b: geometry items of test impellers.

	Item (1)		Impellers				
			A	B	C	D	E
Slip factor (Section a)	Experiments		0.77	0.80	0.74	0.82	0.72
	Wiesner		0.82	0.85	0.80	0.84	0.76
	Stodola		0.79	0.84	0.74	0.83	0.68
	Fujie		0.77	0.80	0.77	0.77	0.72
	Stanitz		0.67	0.75	0.67	0.67	0.51
	S.R.E. (2)		0.73	0.78	0.73	0.73	0.64
	T.S.F. (3)		0.79	0.83	0.78	0.82	0.71
		Uncertainly					
Geometry (Section b)	Z	–	6	8	6	6	4
	β'_2	±0.5°	24°	24°	30°	18°	24°
	D_1/D_2	±0.1%	0.46	0.46	0.46	0.46	0.46
	b_2/D_2	±0.6%	0.28	0.28	0.28	0.28	0.28
	β'_1	±0.5%	30	30	30	30	30

(1) Other definitions for slip factor, such as $\mu \equiv 1 - \Delta CU_2/U_2$ used in the paper are specified in the proper context.
(2) Single Relative Eddy method, $Slip - Factor \equiv 1 - 1/(1 + 5(1 - D_2/D_1)^2/2\pi(\cos\beta'_2)^{0.5})$.
(3) Theoretical slip factor table ($Slip - Factor \equiv 1 - \overline{\Delta CU_2}/U_2$).