Proc. 7th Int. Symp. Flow Visualization, Sep. 11-14, 1995, Seattle, Washington,USA

Investigation of the Relative Flow in Low Specific Speed Model Centrifugal Pump Impellers Using Sweep-Beam Particle Image Velocimetry

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Introduction

Detailed knowledge of flow patterns occurring in impeller passages is of cardinal importance in the design of centrifugal pumps and for the prediction of their hydraulic behaviour. To that end numerous theoretical and experimental studies have been conducted in the past. The theoretical investigations in this field mainly involved analytical studies and numerical computations on individual components and simplified configurations (see for instance Visser et al. 1994 and Badie et al. 1994), whereas experimental work concerned for most cases the study of hydraulic behaviour and performance of complete machines. Experiments on the individual components, in particular, visualization studies on impeller passage flows, have thus far been limited to a few studies only: Fisher & Thoma (1932, dye injection technique), Fister (1966, spark tracer method), Lennemann & Howard (1970, hydrogen bubble technique) and Ohki et al. (1983, spark tracer method) are notable papers in this field.

In the current work, a particle image (displacement) velocimetry study of the flow in *rotating* impeller passages is reported, which preceded laser doppler velocimetry flow measurements (Visser & Jonker 1995). The particle image technique was utilised in such a way that the passage flows could be observed and recorded directly, that is without the employment of an image-derotator device (unlike e.g. Fisher & Thoma 1932 and

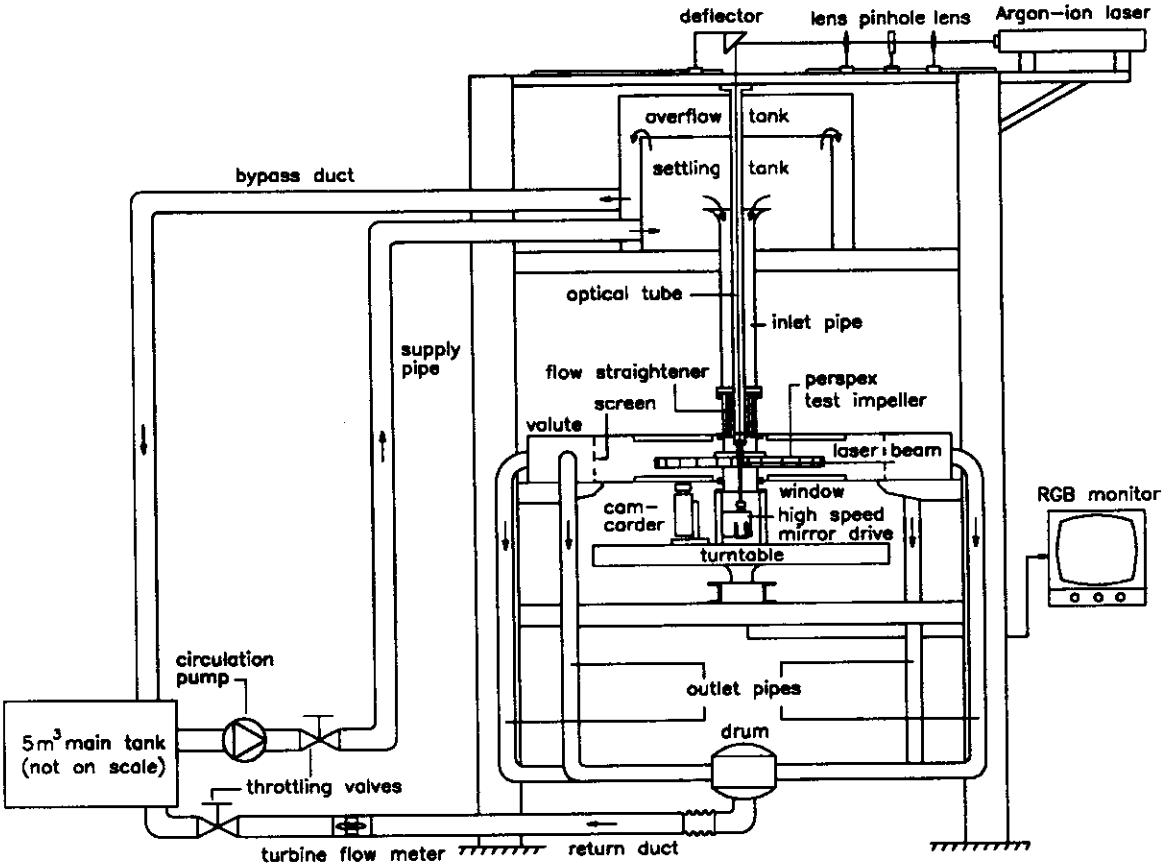

Figure 1. Diagram of test rig.

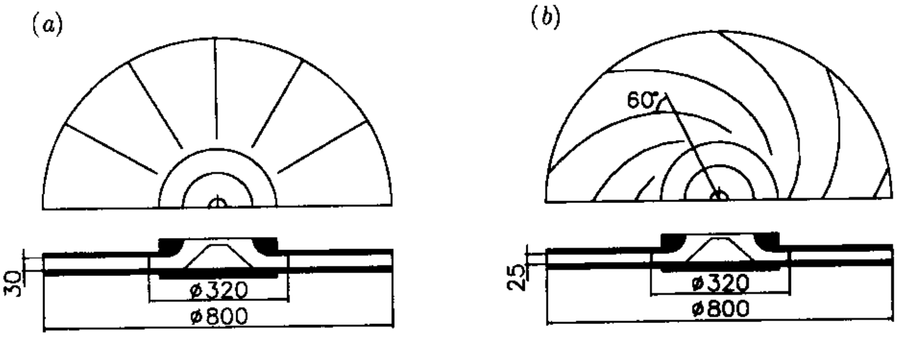

Figure 2. Twelve-bladed radial test impeller (a) and nine-bladed test impeller (b) with sixty-degree logarithmic spiral blades (dimensions in mm).

Fister 1966). To that end the equipment co-rotated with the impellers. This way we readily obtained clear pictures of the flow patterns with respect to the rotating frame of reference.

Experimental Technique

Seeding

Since particle image velocimetry (PIV) is based on measuring the motion of (seed) particles it is important that these particles follow the fluid without significant slip. For the present work we used polystyrene microspheres of 100 and 300 micron with a specific gravity of 1.0 ± 0.02, while water was the working fluid. From the expression given by Adrian (1991) the slip of these particles was estimated to be less than 0.5 and 2.5 per cent for the 100 and 300 micron grade tracers respectively.

Illumination

In order to illuminate the particle-laden flow field a sweep-beam technique was employed. The beam of a 3.5 Watt (output power) continuous wavelength Argon-ion laser was directed onto a rapidly rotating single-facet inclined mirror, which reflected the beam so that in the fluid the plane of observation was scanned periodically, with a frequency equal to the angular frequency of the rotating mirror (0-250 Hz). This way of illumination was highly efficient and extremely profitable because of the high (laser-light) energy density, which made it possible to image small particles with limited scatter efficiency that would have remained undetected if the beam was expanded into a light sheet.

Recording

To record the images a domestic (interlaced) Sony CCD-TR8E video camera-recorder with a spatial resolution of 470.000 pixels was used. The camcorder was equipped with a F1.4-2.2 zoom lens, and minimally required only 3 lux illumination (at F1.4). The images were stored on standard 8 mm video tape.

Processing

In order to get the velocity information desired a video frame was first digitised into an eight-bit 640×480 pixel array. Next, the digitised frame was processed by image analysing software (so-called PIVware), developed at Delft University of Technology - The Netherlands, which we ran on a HP9000/700-series workstation. The PIVware computed the (most probable) map of displacement vectors, which were multiplied (at a later stage) by the scanning frequency of the sweep beam and the length-per-pixel factor in order to obtain velocity vectors. The length-per-pixel factor, linking bitmap and real scene dimensions, was computed directly from the digitised frame. Furthermore, statistical tests implemented in the PIVware were employed to detect invalid vectors (see also Westerweel, 1994).

Experimental Facility

Test Rig

The experiments were performed in the test rig illustrated schematically in Figure 1. This open-loop test facility was designed such that throughput and impeller speed could be set independently, which enabled a

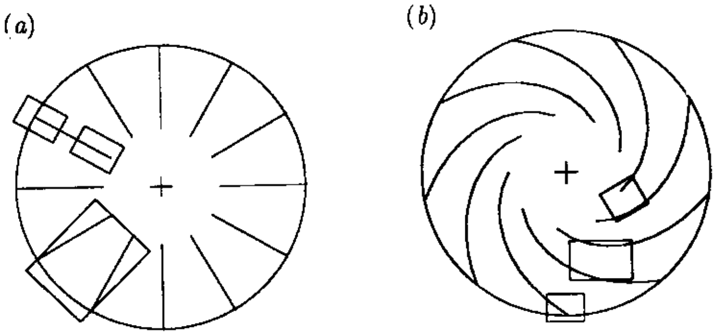

Figure 3. Location of images recorded in (a) radially bladed and (b) logarithmically bladed test impeller.

wide range of operating points.

The horizontally mounted impeller was fixed rigidly on the turntable, which had a 0-100 rpm angular speed range. The volume flow rate through the impeller was controlled by means of a throttling valve in the return duct and could be set from 0 to 20 l/s.

The impeller discharged in an oversized volute, which was equipped with special hardened glass windows and four symmetrically arranged outlets. Downstream disturbances were stemmed by a screen with 1.6 per cent opening, placed around the impeller at the outer periphery of the test section. A flow straightener was installed in the impeller inlet pipe.

A frequency-controlled circulation pump fed the settling tank, such that the test rig operated under overflow conditions; that is, the settling tank was flooded and a small flux of water was bypassed to the main tank. The settling tank was open to atmosphere.

The camcorder that recorded the flow was mounted on the turntable, and co-rotated with the impeller. The video signal of the camera was transmitted through a slip-ring arrangement so that the flow could be monitored. Recording was controlled remotely by infra-red light.

The scanning frequency of the sweep beam was adjusted remotely, over the slip-ring arrangement, by means of voltage control of the mirror drive. The plane of observation could be set from hub to shroud by vertical adjustment of the rotating mirror. A spatial filter was used to give the laser beam a diameter of 2 mm in the plane of observation. Furthermore, an air-filled optical tube was installed in the inlet pipe to get a short water-travelled optical path, so that the high energy density of the laser beam was retained.

Test Impellers

The experiments were conducted on two shrouded impeller configurations of simple two-dimensional design. Successively, we tested a twelve-bladed model fitted out with straight radial blades (Figure 2*a*), and a nine-bladed model equipped with sixty-degree backward-leaning logarithmic spiral blades (Figure 2*b*).

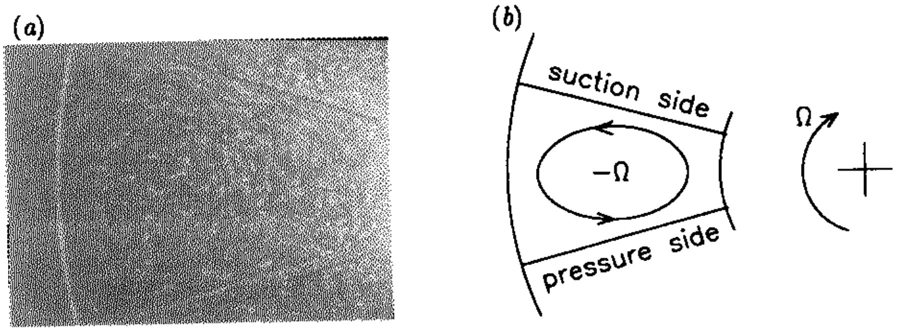

Figure 4. Flow pattern in rotating radially bladed impeller passage at zero throughput. (*a*) PIV image at $\Omega = 30$ rpm; (*b*) schematic representation.

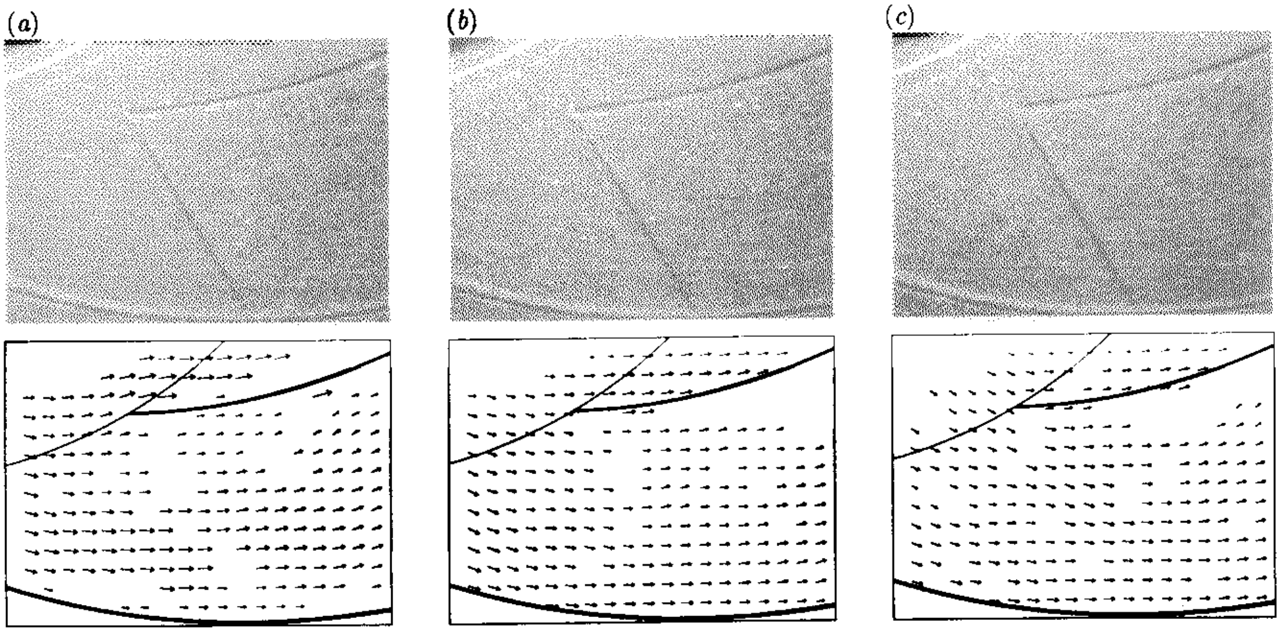

Figure 6. Images and PIV measurement results of the flow near the leading edge at (*a*) $\Phi = 0.063$; (*b*) $\Phi = 0.095$; (*c*) $\Phi = 0.117$.

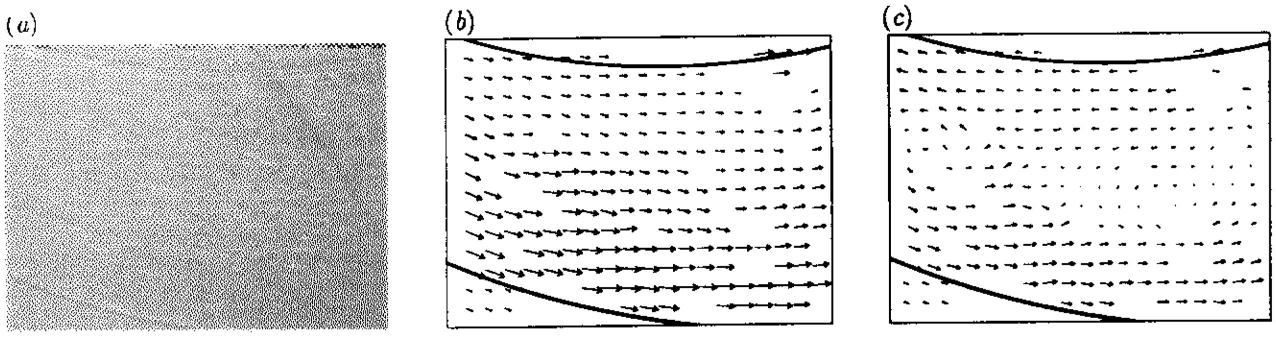

Figure 7. Passage flow at $\Phi = 0.095$ in nine-bladed test impeller. (*a*) PIV image; (*b*) PIV measurement result; (*c*) mean-throughput-subtracted result.

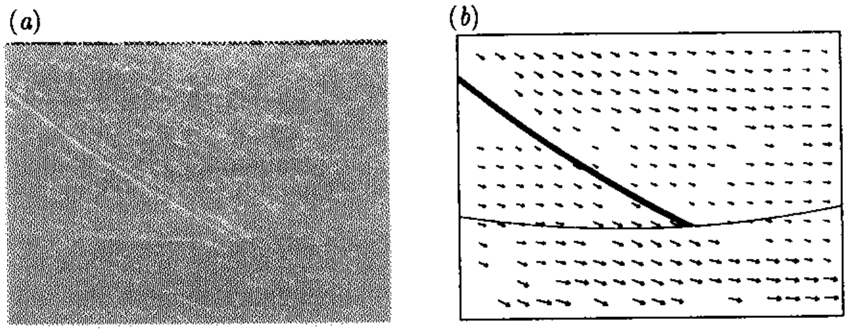

Figure 8. Flow near the trailing edge at $\Phi = 0.095$. (*a*) PIV image; (*b*) PIV measurement result.

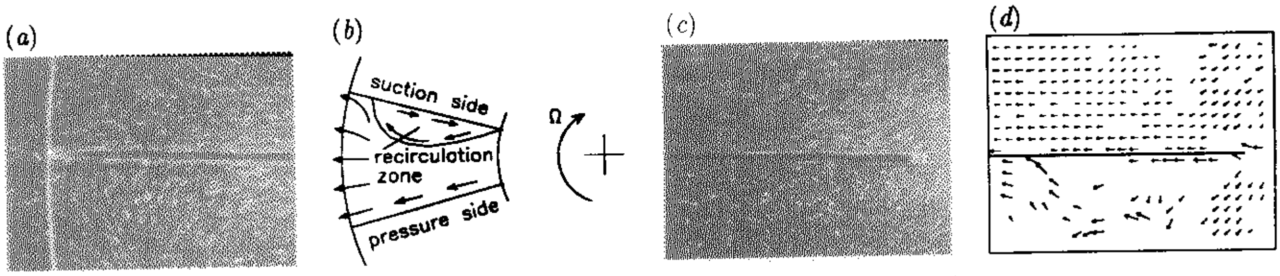

Figure 5. Flow pattern in radial impeller passage at $\Phi = 0.16$. (a) image at trailing edge; (b) overall schematic representation; (c) image at leading edge; (d) PIV measurement result (leading edge).

The impellers were made entirely of perspex to meet the demand of optical accessibility, and they were both designed to run at 32 rpm. At this angular speed, the Reynolds number based on the impeller outlet diameter and tip speed equals 10^6.

Results

Twelve-Bladed Radial Test Impeller

The experiments with this impeller were all performed with the 300 micron grade particles. Images at zero and non-zero throughput were recorded. Their locations are indicated in Figure 3(a).

Figure 4 shows the motion encountered at zero throughput. A PIV measurement result could not be obtained because of velocity direction ambiguity. Nonetheless, we clearly detect a (potential flow) relative eddy, generated between the blades. Basically, this eddy originates from the irrotationality of the flow in the absolute (non-rotating) frame. In the relative or rotating frame the (potential) flow possesses a constant vorticity, equal to -2Ω; i.e. $\nabla \times w = -2\Omega$, in which w is relative fluid velocity and Ω is angular speed.

Figure 5 illustrates the flow pattern at non-zero ($\Phi = 0.16$) throughput.[¶] In the PIV measurement result approximately 15 per cent of the vectors generated was detected as outlier, which vectors have been removed. The image of Figure 5(a) could not be (PIV) analysed because of the directional ambiguity.

With reference to Figures 5(c) and 5(d) it is seen that the flow separates immediately from the suction side near the leading edge, due to the high incidence angle. For the image shown the incidence angle equals 45°, which is readily computed from the flow rate coefficient Φ on the basis of simple Eulerian flow theory. The computed incidence angle complies nicely with the angle observed under which the flow separates.

Figure 5(a) shows that the separated flow reattaches near the trailing edge. A stagnation point is found on the suction side of the blades, and a recirculation zone results. Furthermore, it is seen that the flow runs smoothly off the suction and pressure side trailing edges. The overall flow pattern observed in the passage at non-zero throughput is illustrated schematically in Figure 5(b).

Nine-Bladed Logarithmic Spiral Test Impeller

The experiments with this impeller were conducted with the 100 micron grade tracers. The locations of the PIV images recorded are shown in Figure 3(b). The respective results are displayed in Figures 6, 7 and 8. Presented are the original images and maps of displacement vectors. In each frame approximately 15 per cent of the PIV vectors generated was detected as being spurious. The maps show the results of the PIV analyses with spurious vectors removed. Deleted vectors *were not* replaced by interpolated vectors since, mathematically speaking, we have cuts in each image (namely the blades) and, hence, discontinuities in the fluid velocity; a (straight-forward) interpolation algorithm would have generated false vectors.

Figure 6 shows the flow near the leading edge at low ($\Phi = 0.063$), medium ($\Phi = 0.095$) and high ($\Phi = 0.117$) volume flow rate. At medium flow shockless entry was clearly observed. The high flow rate resulted in the formation of a pressure-side leading-edge separation bubble. The low flow rate yielded suction-side leading-edge separation.

Figure 7 displays the passage flow at $\Phi = 0.095$. With reference to Figure 7(b), we clearly observe higher values of the tangential velocity on the suction side of the blades and near stagnation flow close to

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[¶] $\Phi = Q_v/(2\pi\Omega r_2^2 h)$ where Q_v is volume flow rate, r_2 is impeller outer radius, and h is axial depth of the impeller.

the pressure side of the blades, confirming the presence of the relative eddy. Figure 7(*c*) distinctly visualises this presence of the relative eddy. This map has been obtained from Figure 7(*b*) by subtracting the mean throughput velocity.

Figure 8 shows the flow near the trailing edge at $\Phi = 0.095$. The PIV measurement result unequivocally demonstrates that the flow runs off the trailing edge smoothly, exemplifying Zhukovski's hypothesis.

Concluding Remarks

A scanning-beam particle image velocimetry method has been used to study the flow in the passages of low-specific-speed model centrifugal pump impellers of simple two-dimensional design. Strong point of the method was that it presented an instantaneous and quick survey of velocity distributions in the plane of flow. The method proved to be extremely valuable for exploratory investigation and, moreover, provided a quantitative bases for interpretation.

In the test rig, a twelve-bladed radial impeller and a nine-bladed sixty-degree logarithmic-spiral-blade impeller have been tested, which revealed interesting phenomena concerning impeller passage flow. In particular, the presence of the relative eddy - predicted by potential flow theory - has been corroborated.

Acknowledgements

The authors gratefully acknowledge the support by SHELL The Netherlands, and the cooperation with Dr. J. Westerweel (Delft University of Technology - The Netherlands). The software for the digital PIV analysis (PIVware) originated from the Laboratory for Aero and Hydrodynamics, Delft University of Technology, The Netherlands.

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