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Studies on the Flow of Cross-Flow Impellers*

(1st Report, Experimental Study)

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An interesting flow phenomenon in a cross-flow impeller---an asymmetrical throughflow in a geometrically symmetrical impeller---has been investigated experimentally. The causes of the throughflow are explained in relation to the flow mechanisms. Flow was visualized by moire method of topography and solid particles. The transient process of the flow from the starting of an impeller until formation of a large eccentric vortex was observed in details.

If Reynolds number is larger than 250, the throughflow occurs in all the types of the impellers experimented. In the steady rotation of the impeller the eccentric vortex rotates slowly around the impeller-axis and flow pattern changes sequentially. The change of flow patterns is essential to the flow of the cross-flow impellers.

1. Introduction

A cross-flow fan has a rotating impeller with many forward-curved blades around its periphery. A rotating cross-flow impeller, in spite of its geometrical symmetry about the axis of rotation, generates an asymmetrical throughflow. The flow enters the impeller along one portion of the cascade and leaves it through another, whereas the blade cascade is uniform and identical over the whole periphery.

On the other hand, in such an impeller as axial- or centrifugal-type, a flow occurs in the axisymmetrical plane of the rotation. It can be regarded as an axisymmetrical flow if we neglect small disturbances induced periodically and locally in the flow. Although fluid machines with a cross-flow impeller belong to turbomachines in the principle of the operation, they operate in a fundamentally different way from axial- or centrifugal-fluid machines as to the axisymmetry of flow.

In 1892 Mortier(1) got a patent for the invention of the cross-flow fan. By the turn of the century its application to mine ventilation had become widely known. A cross-flow fan with a large impeller having an outer diameter of 2.8 m was then made. However, it was soon superseded by a new-coming superior Capell- and Rateau-fan. It had been almost completely forgotten except by American inventors who had eagerly been engaged in improvements of the cross-flow fans, until in 1930s Ackeret(2) suggested use of the fan to the suction of the boundary layers on airfoil wings as a possible application of it.

Ackeret worked in cooperation with Sprenger to investigate several types of the cross-flow fans. Later in 1953, Eck(1) revealed the flow within the cross-flow impeller by flow visualization, which was chara-

cterized by the formation of a line vortex eccentric to the axis of rotation of the fan. The discovery of the eccentric vortex made a great turning point in the investigation of the cross-flow fans. After Eck, numerous important developments were made, especially by Coester(3), Ikegami-Murata(4) and Porter-Markland(5). Most of these studies were concerned with the improvement of the performance of the cross-flow fans, whereas the most fundamental problems, apart from the practical ones, that is, why an asymmetrical flow occurs in a geometrically symmetrical impeller, and why the stability of the flow is achieved with the formation of the eccentric vortex, have never aroused the interest of anyone except Trampusch(6) who tried a qualitative explanation of it.

Recently, cross-flow fans as air-moving devices in air-conditioning and electronics industry are steadily gaining in importance. While the progresses in the performance and geometrical improvement of the cross-flow fans in the last decades have been quite astonishing, the mechanism and principle of the flow remain unknown.

In the present paper, the asymmetrical throughflow phenomenon and the behavior of the eccentric vortex in cross-flow impellers are investigated experimentally. In the succeeding paper, the stability of the eccentric vortex will be dealt with analytically, and the performance of a cross-flow fan with simple casings will be discussed in relation to the flow mechanisms. The research program described in this paper was conducted in two phases with a rotating cross-flow impeller in unbounded fluid. First, the incipient process of development of a flow of an impeller started suddenly from standstill until the formation of an eccentric vortex was examined, in which the flow was visualized by means of moire method of topography and/or solid particles. Then the flow field after the eccentric vortex formation was investigated in details.

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2. Experimental equipment and methods

2.1 Experimental apparatus : The working fluid is water filling an open vessel. Fig.1 shows the experimental apparatus which consists of a water table (1) with free surface, an impeller (2) immersed in the water and supported with its axis held vertically, an electric motor (3), a speed change gear (4) and a reduction gear. Rotational speed of the impeller can be smoothly varied at $N=1.8-90$ rpm. Above the bottom of the tank there is provided an intermediate flat glassy plate of acrylite resin at the same level as the base end plate of the impeller in order to reduce the secondary flow.

Fig. 1 Experimental apparatus.

2.2 Impellers : Seven models of three types of impellers are constructed and given in Table 1. These types are of a circle-, a radial- and a circular arc-impeller characterized by respective blade profiles. Although most of blade profiles of cross-flow impellers used in practice generally are a forward-curved circular arc-type, it is found by a preliminary experiment that an asymmetrical throughflow, which is characteristic of the flow of a cross-flow impeller, occurs not only in a circular arc-type, but also in a radial- and even in a circle-impeller just arranged on a periphery with small cylinders as blades. Furthermore, since flows of a circle- and a radial-impeller are simpler than that of a circular arc-impeller, these three types of impellers are determined for use in this study. Fig. 2 illustrates the blade profiles of the circular arc-impellers experimented.

Fig. 2 Blade profiles of circular arc-impellers.

Table 1 Dimensions of impellers

Blade profile	Symbol	Inner diameter D_1 mm	Outer diameter D_2 mm	No. of blades Z	Chord length b mm	Span mm	Thickness t mm
Circle	IA2	143	157	18	7.0	111	7.0
Circular arc	IB1	136	160	35	13.1	108	2.1
	IB2	125.5	160	27	19.1	105	3.2
	IB3	123.8	160	27	19.0	105	3.2
Radial	IC1	140.5	160	18	9.7	110	2.1
	IC2	124.4	160	18	17.8	110	2.1
	IC3	100.3	160	18	29.9	110	2.1

2.3 Moire method of topography : Three dimensional deformation (undulation and upheaval) of a free water surface induced by the flow of a cross-flow impeller can be visualized optically by moire topography. A simple moire topography using a master grid screen located close to an object and its shadow projected on the surface of the latter was devised by Meadows et al. (7) and Takasaki (8) independently in 1970, and has been applied to a graphic description of the three dimensional profile of a solid body to date.

Tagori-Masunaga (9) first applied this method to a fluid flow. They succeeded in the contour mapping of water waves produced by a cruising ship model. In the present study, the moire topography was applied to investigate the process of the formation of an eccentric vortex within a cross-flow impeller and to examine the unsteady behaviors of the throughflow. The flow visualization by the moire method enables precise observation and measurement of the formation process, behavior and intensity of the vortex as well as the pressure measurement in the whole flow field. In Fig. 1 instrumentations concerned with the moire topography are also indicated.

Symbol (6) in the figure denotes a master grid screen in which frosted nylon fibers of 0.23 mm mean diameter are stretched at 1 mm pitch with tension between both threaded bars supported with a square frame. Symbol (7) is a fine adjusting mechanism, (8) and (9) are a motor driven camera and a light source (24v, 300w iodine lamp), respectively. The spacing between the surface of the screen and that of the water at rest is strictly set constant throughout the screen. To generate moire fringes in good contrast with an object surface, the water surface was made reflective by scattering aluminium powder after diffusing well a small amount of kelosene on it.

2.4 Tracer method : Moire method cannot give any information about an underwater phenomenon and velocity distribution of a flow. Then polystyrene particles (specific weight 1.03--1.05 g/cm³, grain size 0.3--1 mm) are utilized to visualize the water flow. The tracer method enables velocity measurement and detailed observation of an underwater flow. In order to avoid aggregation of tracing particles, a small quantity of bubble extinctive and nonionic surface active additives is added to the water.

One of the side walls of the tank is made transparent with a plexiglass for illumination. Outside the illuminating wall, double shielding plates with a slit through which light beams illuminate a cross section of the tank, 5--7 mm width and about 30 mm below the static water level are provided. Movement of

particles suspended in the fluid at the illuminated cross section is photographed by a camera installed above the impeller.

3. The formation process of an eccentric vortex

3.1 Observation of formation process of an eccentric vortex by means of moire method : Fig. 3 shows consecutive photographs of formation process of an eccentric vortex in a radial-impeller. In each film, time (sec) indicated in the figure was measured from the starting of the impeller. Rotational sense of impellers is clockwise in all the experiments. Sequential variations of moire fringes, then flow behaviors inside and around the impeller can be observed in the films. The spacing between two arbitrary adjacent fringes is about 0.42 mm in height.

Immediately after the starting, surface waves occur in the interior and exterior of the impeller and propagate into them. Consecutively, small vortices are shed at each leading edge (the outer periphery) of the cascade. Then adjacent shed vortices two by two begin to coalesce into a larger but looser vortex. The coalesced vortices expanding and diffusing into the vast fluid with the rotation of the impeller, bring considerable portions of the stationary fluid in the outer region into motion. Shortly after the small vortex shedding at the leading edge, an

alternate vortex shedding at the trailing edge (the inner periphery) of an individual blade begins. As well as the exterior one, the interior edge itself constitutes a kind of vortex street. The arrangement of both vortex streets soon turns into regularly staggered double rows of shed vortices on both sides of the impeller.

Fig. 3 (a) shows this situation in which the surface waves remain. The vortices shed at the leading edges are inherently unstable, soon expanding and disappearing, whereas ones at the trailing edges themselves repeat to merge into larger vortices (Fig. 3 (b)). The coalescing vortices within the impeller increase their intensity and decrease the number of them at every stage of the coalescence.

The number of the vortices decreases to 4, 3, 2 and unity at last. At every stage of the evolution, the coalescing vortices are nearly equidistant from each other on a certain circle (Fig. 3 (c) and (d)). In the final stage, a larger vortex is formed inside the impeller and moves to one side. This can be clearly recognized in Figs. 3 (e) and (f) which show how the circular symmetry of the flow pattern is disturbed by an eccentric vortex. A throughflow which is characteristic of a cross-flow impeller occurs already when the number of the coalescing vortices reduces to only two. There exists a couple of an entry- and a discharge-stream for each of double vortices.

Fig. 3 Transient process of formation of an eccentric vortex. $t(s)$ indicates time (sec) passed from the starting of impeller.

When a predominant one of them absorbs the other, the former surviving vortex merges into a large solitary one which is already eccentric to the impeller-axis at the moment of the formation, as seen in Fig. 3 (e). The circulation of the eccentric vortex is not so strong immediately after the formation, accordingly the throughflow is weak. Gradually, the entry-stream into the impeller which forms the throughflow increases in succession with the emergence of the eccentric vortex, then it makes small vortex shedding at the trailing edges of the blades on the suction side grow intensively.

These small vortex rows flowing with the throughflow are induced toward the inner region of the eccentric vortex. A portion of them is involved into the eccentric vortex to increase its intensity. Consequently, the eccentric vortex evolves into a stronger vortex and augments its eccentricity as far as to the inner edge of the impeller at the extremity. Fig. 3 (f) shows the situation in which an eccentric vortex is being evolved. In the central portion (core) of the vortex several middle-size vortices merging into the core can be discerned.

Without any solid boundary such as a casing able to obstruct flow of an impeller, the eccentric vortex cannot stay at a definite position and rotates slowly around the impeller-axis. At first, the vortex rotates in a direction opposite to the rotation of the impeller. However, in the long run the reverse rotation ceases. Then the normal rotation in the same direction as that of the impeller appears. The rotational speed of the vortex around the impeller-axis, namely that of the whole flow is only several or several tenth times that of the impeller.

3.2 Limits of an eccentric vortex formation and a throughflow: Time T_0 (sec) required for completion of formation of a strong eccentric vortex and inception of normal rotation, counted from the starting of an impeller, and number of rotations M of the impeller until T_0 are measured. In Fig. 4 the relations between (M, T_0) and Reynolds number Re are shown for three types of impellers.

Where, Reynolds number Re is formed of the outer peripheral velocity U_2 , the chord length b of a blade and the kinetic viscosity ν of water. Although the magnitude of M depends on the blade geometries, it is confirmed that beyond a definite Reynolds number, in spite of rotational speed of an impeller, a throughflow is completed after the impeller has performed some rotations M . The value of M is found to be smaller for an impeller whose energy output is larger. The limits of the eccentric vortex formation which are shown also in Fig. 4 were determined from the experiments at $Re=110-250$ considering of the scattering of the measured values.

At $Re > 250$ a vortex is formed for all the types of the impellers, while it is not at $Re < 110$. In the intermediate range $Re=110-250$ the vortex once formed will disappear in a long run of rotation of the impeller and will be reformed in another run. It is, therefore, appropriate to call this region a transient one. Thus, the limit of the eccentric vortex formation is defined to lie at $Re=250$.

Now, there are two explanations about the

(a) A circle-impeller (IA2)

(b) A radial-impeller (IC1)

(c) A circular arc-impeller (IB2)

Fig. 4 Relations between (M, T_0) and Re .

occurrence of a throughflow in a cross-flow impeller. One is the so-called vortex principle by Eck, the other an explanation by Porter-Markland. According to the vortex principle, even if there exists a solitary vortex within an impeller, a throughflow may not occur without its displacement eccentric to the impeller-axis. With the vortex displacement to one side of the impeller, there will occur an asymmetrical flow, that is, a throughflow.

On the other hand, Porter-Markland insists that a throughflow precedes an eccentric displacement of a vortex. Presumably, a vortex eccentric to an impeller-axis is formed as the consequence of the occurrence of the throughflow which constitutes an entry- and discharge-stream within an impeller. They carried out an experiment on a fan with a conventional casing to examine the effect of a guiding device on the fan performance.

When a guide vane is inserted within the impeller at such a position that it produces maximum resistance, a throughflow remains although the vortex core is completely broken down. Thus, it may be said that the core exists because of the throughflow and not conversely. Energy diffuses from the throughflow into the core region, thereby maintaining the rotation.

By visualization of the flow of a cross-flow impeller performed by the present author, in which Reynolds number was adequately large and both an eccentric vortex and a throughflow occurred, the following evidences were obtained; when trials were made to break down a vortex core by inserting a solid body such as a cylinder or a flat plate into the inner- or outer-region of an impeller, (a) the eccentric vortex previously existing displaced to a location to produce lesser resistance to the flow, (b) in the case in which the vortex core was prevented from displacing or depressed with some interrupting object in the exterior of the impeller, almost all portions of the vortex core disappeared. However, the remaining flow outside the inserted solid body was nothing but a throughflow.

The latter case might be regarded to be an equivalent but simplified case of that of Porter-Markland. The core of the eccentric vortex rotates inherently as solid rotation, as confirmed later. Therefore, although the core region is displaced with a solid body, the whole flow may not be forced to provoke any change.

Thus, the conclusion can be deduced as follows: The formation of the eccentric vortex or the vortex displacement eccentric to the impeller-axis causes a throughflow. When a tentative operation to destroy a vortex core is made with insertion of a solid body in the interior or exterior of an impeller, a virtual core displaced by the body remains as it is and on the outside of the solid body a vortical flow constitutes a throughflow.

4. Flow at steady rotation of an impeller

4.1 Classification of flow patterns: At steady rotation of a cross-flow impeller in unbounded fluid, the flow rotates slowly around the axis of rotation of the impeller since there exists no preferred location. The eccentric vortex rotates nearly in proportion to rotation of the impeller. There are two ways of the vortex movements; one along the circumference and one in a radial direction of the impeller. Generally, the flow of a cross-flow impeller without a casing or a guiding device scarcely keeps the same type of flow pattern but changes it sequentially in an ordinary operation. This is very different from flows of other types of turbo-

machines. This offers an important problem relating to fundamentals of the flow of a cross-flow impeller. Flows of the impellers shown in Table 1 were investigated to examine sequential variations of flow pattern by flow visualization using polystyrene particles as tracer at Reynolds number $Re = 250-15,000$.

As a result, five flow patterns (1)--(5) were identified whose features are given in Table 2. In Fig. 5 four characteristic flow patterns (2)--(5) of a circular arc-impeller at rotational speed $N=20$ rpm are shown.

Flow pattern (1) which is an only exceptional and axisymmetrical one occurs also in a circular arc-impeller. However, it happens to appear momentarily in succession to a violent change of flow; for example, disappearance of a solitary vortex in the flow pattern (5). In the flow pattern (1) the vortex is not eccentric to the impeller-axis, hence the vortical flow is concentric with it and no throughflow occurs. In the flow pattern (2) the flow is such that the vortex in the flow pattern (1) displaces eccentric to the axis, whereby energy output from blades is small and the eccentricity is not so large.

Small vortices shed from the trailing edges of blades at the suction-side of an impeller and a throughflow increase the intensity of the eccentric vortex. Subsequently the eccentricity grows gradually, then the flow which is almost symmetrical with the center of the vortex in the flow pattern (2) gives way to the pattern (3). Yamafuji-Ohashi (10) found that the discharge-stream from the delivery-side of an impeller consists approximately of a logarithmic spiral. The growth of the discharge-stream reaching straightforward as far as the suction-side of the impeller provokes counter prerotation of the inflow. In this flow pattern (3), the rotational speed of the vortex around the axis is nearly constant so far as the eccentricity does not vary.

Increase of the eccentricity yields violent growth of the exhausting jet from the impeller and excessive counter prerotation of the flow. Consequently, both flows mentioned above build up a closed flow loop resembling a vortex which is seemingly conjugate with the eccentric vortex. We call this flow the flow pattern (4). The large conjugate vortex formed and expanding in the exterior of the impeller can be regarded as a vortex bound to the eccentric vortex. After the appearance of a bound vortex, the counter prerotation of the inflow at the suction-side is augmented, which increases the energy output from the blades exceedingly. When the bound vortex extends extremely, it is cut off from the eccentric vortex and becomes a solitary vortex. There emerges the flow pattern (5).

Table 2 Classification and features of flow patterns

Symbol of flow pattern	Location of a vortex against impeller-axis	Configuration of flow	Feature of delivery stream	Blade profile corresponding to typical flow pattern
(1)	concentric	axisymmetric	circular arc	* above limit of occurrence of throughflow ** scarcely in throughflow region
(2)	eccentric	"	"	circle, radial
(3)	"	asymmetric	logarithmic spiral	radial, circular arc
(4)	"	"	a bound vortex	circular arc, radial
(5)	"	"	a solitary vortex	circular arc, (radial)

Fig. 5 Typical flow patterns.
(IB3, $N=20$ rpm)

4.2 The throughflow mechanism : Development of flow pattern from (3) to (4) in a radial-impeller at constant rotation was visualized by moire method and shown in Fig. 6. The core of an eccentric vortex involving shed vortices to grow into a stronger vortex suffers some deformations in its configuration (Fig. 6 (a)) compared with a fully developed one (Fig. 6 (b)). The vortex core deformation corresponds to involvement of small vortices and unsteady movement of the eccentric vortex. The development and deformation

Fig. 6 Sequential variation of flow pattern.

of the eccentric vortex cause a change in flow angles at the inlet and the outlet of the cascade. In general, a flow pattern is apt to change to another which is capable of much energy output, hence an eccentric vortex is likely to move to a more favorable location to maximize the output into the fluid.

In the case of Fig. 6 (a), the eccentric vortex does not only grow with the involvement and rolling up of small vortices, but also promotes vortex shedding by providing an approaching flow to the suction-side with a favorable flow angle. Neglecting a secondary flow around an impeller, a rapid displacement of a vortex is due to the acceptance of the radial inflow by rolling up of shed vortices and to relaxation of it since there is no sink for the inflow. Throughflow is supplied continuously with output from an impeller, then angular momentum of the fluid in the direction of rotation of the impeller increases.

There is, however, a certain limit of growth of a vortex. Fig. 7 shows an example of flow pattern (5), a flow with a counter vortex formed in the outer vicinity of the suction-side. The counter vortex which rotates reversely to rotation of the eccentric vortex interferes strongly with the latter and destroys the whole flow system suddenly.

Fig. 7 Interference between a counter vortex and an eccentric vortex.

This means cutting away of a bound vortex and weakening of the eccentric vortex. A solitary vortex drifting with the discharge-flow comes out of the bound vortex. Thus the flow pattern (4) which is considered to be most stable does also transfer to another flow pattern through sudden dissipation and diminution of energy output induced by the occurrence of a counter vortex and the elongation of the bound vortex or the solitary vortex shedding. Variation of flow pattern in a cross-flow impeller is, therefore, understood to be inevitable to the rotation of an impeller in unbounded fluid.

4.3 Profile of an eccentric vortex : Ilberg-Sadeh (11) and Porter-Markland (5) measured a flow of a cross-flow fan by a Pitot-tube and a hotwire anemometer respectively. They revealed an eccentric vortex to be approximately Rankine's combined vortex. The present author examined the profile by moire method. Fig. 8 illustrates both cross-sections of an eccentric vortex in the flow pattern (4) obtained by isopachic contours of moire fringes. Thereby, the vertical difference between two adjacent fringes is about 0.49 mm.

In the figure we can observe slight deformations of the vortex profile in the portions of the cascade. In order to determine the vortex profile, the order of an arbitrary fringe is to be known at first. Then the

Fig. 8 Vortex profiles of flow pattern (4) in a circular arc-impeller. (IB2, $N=20$ rpm)

vertical difference between a fringe and an adjacent one is calculated by a formula given by Takasaki (8). It is compared with the result obtained experimentally by double level sensing probes immersed in the water. Measurement of static pressure of flow by moire fringes is executed as follows. There is a relation between the static pressure and the height of the free water surface.

If an eccentric vortex does not rotate around the center of the impeller and no sudden change of the water surface due to disturbances occurs, depression of the surface of a vortical flow is considered to denote practically a static pressure distribution of the flow. When a vortex movement occurs, its influence upon the static pressure may not be neglected because of a vertical velocity component of the flow. However, since the rotational speed of a vortex around an impeller-axis in the present study is small in comparison with that of the impeller, we can neglect the vertical component and regard the vortex to be at standstill.

4.4 Measurement of velocity and pressure :

Formerly, measurements of velocity and pressure have been carried out only about impellers with casings by the previous researchers, but not about one without a casing. When a cross-flow impeller without a casing rotates in unbounded fluid, the flow is unsteady because of rotation of an eccentric vortex, therefore a pressure pick up such as a Pitot-tube or a hotwire anemometer as a velocity probe is not adequate to measurement of a whole flow field. In this study, velocity and pressure distributions over the whole flow field are obtained by tracers and moire fringes respectively.

A combination of both methods yields energy distribution of the flow. Magnitudes of flow velocity at the inner- and the outer-periphery of an impeller are considerably different from those of the circumferential velocity of the impeller at the same places. At the mean radius of the impeller $r_a = (r_1 + r_2)/2$, however, the difference between flow- and circumferential-velocity is very small.

Flow velocity of an eccentric vortex increases linearly outward in the same way as that of a forced vortex, then a peak velocity is attained at places other than the impeller bladings. Flow velocity after reaching its peak is gradually decreased toward the outside. In every experiment conducted also for another impeller as well as that shown in Fig. 9, we can identify an actuator point in

Fig. 9 Velocity distribution of a vortical flow.

a certain portion of the impeller in every radial direction at which flow velocity becomes equal to the circumferential velocity of the impeller at that position.

A measured pressure distribution expressed in the static pressure coefficient ϕ_s is shown in Fig. 10. Where,

$$\phi_s = (P - P_a) / (\rho/2) U_a^2$$

P : static pressure of a vortical flow

P_a : static pressure of fluid at rest

and U_a : circumferential velocity of an impeller at $r_a = (r_1 + r_2)/2$

Fig. 10 Static pressure distribution.
(IB2, N=20 rpm)

A combination of the velocity profile obtained by tracer method and the pressure distribution by means of moire method is shown in Fig. 11, which can describe an unsteady flow in the whole flow field precisely. As seen in Figs. 10 and 11, the larger the eccentricity of the vortex becomes, the greater the depression of pressure at the vortex core becomes. Since the flow in the core region is a recirculating one, an increase in the eccentricity produces a steep increment in the vortical flow velocity near the bladings, which introduces a large quantity of inflow at the suction-side of the impeller.

Subsequently, it varies flow pattern by providing an increased output for the flow. In these contexts, the engineering significance of the cross-flow impeller as a unique and singular impeller is found. Thus the cross-flow fan is a dynamic pressure type, therefore in order to obtain large static pressure recovery a suitable casing must be installed at the delivery-side as well as the suction-side of it.

Fig. 11 Static pressure and velocity distributions of flow pattern (5) in a circular arc-impeller. (IB2, N=20 rpm)

5. Conclusions

From the investigations of the cross-flow impellers in unbounded fluid, the following conclusions were reached:

(1) After the starting of an impeller small vortices are shed from the inner- and outer-edges of the cascade. Then they begin to coalesce with each other and merge into a large eccentric vortex.

(2) A throughflow comes out of the formation of the eccentric vortex.

(3) At a Reynolds number greater than 250, an eccentric vortex is formed in a circle- and a radial-impeller as well as in a circular arc-impeller, hence a throughflow occurs in all the types of the impellers experimented.

(4) In steady rotation of an impeller, flow pattern varies sequentially by itself.

(5) There exists an actuator point within each radial portion of the impeller bladings, where the flow velocity is equal to a circumferential velocity of the impeller there.

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