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A Method of Measuring Velocity Distribution of Flow in Runners

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In this paper, a photographic method of measuring velocity distribution of flow in rotating runners or impellers is reported. In the introduction, the present status of measuring technique and merits and defects of some existing methods are described. In chapter 2, the behavior of strings and particles in the flow and their phots with stationary or moving camera are written. In chapter 3, the author's method which consists mainly of taking stroboscopic photos of strings fastened both to runners and casing walls, is explained. Some errors which may occur in this method and their calibration or method of elimination are discussed in chapter 4. In the last chapter, the range of adaptability, comparison or joint use of this method with others etc. are treated.

1. Introduction

The measurement of velocity distribution of flow in runners, espeically in the circumferential direction, is one of the most important problems in the study of hydraulic machines, but, at present, accurate and simple methods are not known.

Pitot tube which rotates with the runner is useless unless it can be adjusted with respect to its axial position and nose direction.

Automatic recording method of spherical pitot tube with five pressure holes fixed to the runner may be used for the same purpose[1] but requires axial adjustment also to measure at least along a line.

These methods need very complicated constructions and moreover the measurable range by one tube is restricted.

Hot wire anemometer[2] which rotates with the runner has similar defects.

Particles in the flow (or colored fluid) injected into the flow show interesting properties when photographed by stationary or moving camera. Strings fastened to runners or stationary walls show analogous properties. They can be used for flow measurement and are discussed in detail in chapter 2. The author's method is a special case in this category.

By pitot tubes set to the casing wall near a runner, the time mean value of velocity head and direction of maximum momentum and also the pressure of the flow at corresponding points can be measured. Similarly, mean velocity and its direction are measured by hot wire apparatus.

Both these methods are simple but adaptable only to measure time mean value at inlet or exit or outer space of the runner.

If hot wire apparatus with more than two wires is sensitive enough and indicates readings without lag, it may be used for measuring instantaneous velocity conditions, but the sensitivity against direction of flow is generally poor.[3]

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2. Motion of strings or particles in the flow and their photos

A short string which is fastened to a point of rotating runner or impeller indicates the direction of relative flow, if the effects of bending resistance and inertia of the string, gravity force acting on it, inequality of the direction of flow along the string or turbulence produced by the wire or other medium to which the string is fastened are negligible.

Therefore, photos taken by camera stationary or rotating with the runner show the direction of relative flow, assuming the time of exposure is short enough.

With longer exposure, fixed camera gives relative stream lines shifted in the direction of rotation, i. e. a band with corresponding breadth. while rotating camera gives a bundle of stream lines passing a point.

On the other hand, photos of strings fastened to the stationary casing give the direction of absolute flow, irrespective of the duration of exposure and whether the camera is rest or in motion, although moving camera gives band form of absolute stream lines corresponding to the camera speed and exposure.

Small particles (or colored liquid and the like) issuing continuously from a small tube (fixed to the runner or casing wall) into the flow and moving with it without slip indicate similar but slightly different attitude as that of a string fastened to that tube end. One of the differences is that, a string shows a curve passing the point of fixation at every instant or a sort of instantaneous mean stream line while small particles show the loci of fluid parts that have passed the tube end and so diffuses generally wide into the flow. In spite of such differences, both curves coincide in the vicinity of the tube end if the string is not too long.

In the case above mentioned, if each particle is traceable, these particles may be treated as independent ones and the motion of flow can be analyzed as in the following case. When small particles are mixed with the flow suspended in it and moving without slip, instantaneous photos of them show merely so many scattered points while photos taken with adequate exposure show loci of their motion during that time, i. e. segments of absolute stream lines by stationary camera and those of relative stream lines by the camera rotating with the runner.

Velocity distribution of flow can also be obtained from three or four consecutive figures, each taken instantaneously with short intervals on a same film. High speed camera gives similar but more detailed results.

In general, the photographic method is simple and practical if errors due to aberration, refraction and those originated from the properties of particles and strings are eliminated.

The method using particles is simpler compared with that of strings but location of particles in the direction of camera axis is difficult. To overcome this difficulty some cumbersome measures must be taken such as adoption of light through slit or short depth of focus.

There are some ingenious applications of this method. The following is one of such examples.

The flow in a runner with homogeneously mixed particles is photographed by both stationary and rotating cameras. From these photos, directions of absolute and relative flows are obtained and velocity triangles are drawn at each point and then velocity distribution is determined.[4]

In this method, stream lines are apt to confuse because of the variation of velocity (both in magnitude and direction) in the direction of camera axis and the shift of absolute stream lines due to the time of exposure. Such confusion is especially marked at exit and inlet of the runner and near the blade surface.

Another example is the adoption of the method of injection of white colored liquid into the flow from a small tube fixed to the casing[5]. In this case the diffusion of colored mass is not in excess and white colored absolute path, when it reaches blade inlet, is cut by the blade and moves with different relative speed along the blade making discontinuity or slip of absolute path between front and back surfaces of the blade. This slip serves as a measure of velocity difference and consequently pressure difference on both sides of blade.

3. Author's method

From the necessity to measure circumferential distribution of velocity in impellers of centrifugal pumps, the author devised a method[6] which consists mainly of taking stroboscopic photos of strings fastened both to the impeller and the casing.

At exit and inlet of the impeller or runner the direction of relative flow is obtained from strings on the impeller and that of absolute flow from strings attached to the casing side.

From these directions and the known peripheral speed, the velocity triangle is constructed and the magnitude of relative or absolute velocity of the flow is determined as shown in Fig. 1 (a). Thus velocity distributions on inlet and exit surfaces are obtained.

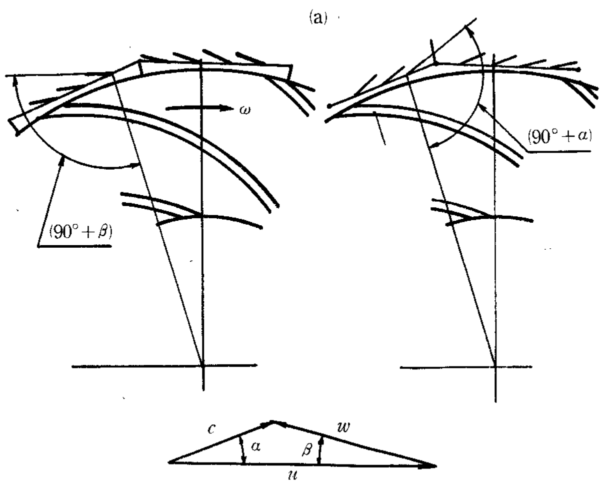

Fig. 1 (a)

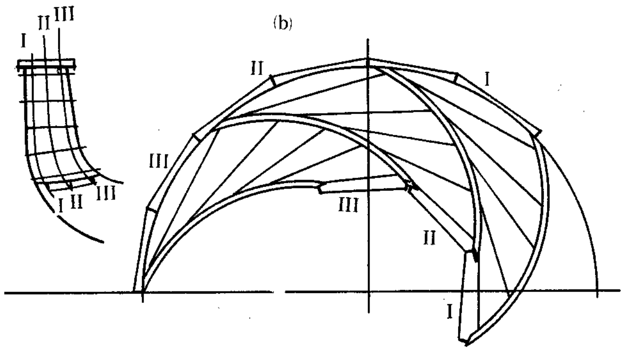

Fig. 1 (b)

In the impeller, relative stream lines are drawn from the direction of strings fastened to thin wires which are fixed to blades at both ends. Extending these lines to inlet and exit surfaces (where velocity is known) the magnitude of velocity between relative stream lines in the impeller and therefore the velocity distribution is determined. Similarly, for the outer space of the impeller, absolute flow is acquired from absolute stream lines starting from inlet or exit surface of the impeller.

The wires, to which strings are fastened, are stretched between blades of the impeller, sufficiently in number to obtain relative stream lines. For example, five to seven in the direction of flow or m-direccion and three to four in n-direction (perpendicular to the wall or shroud surface as in Fig. 1 (b).

Assuming the flow condition at points similarly situated between blades is identical when the impeller comes to the same position (relative to the casing), these wires are distributed properly in the impeller so as each wire is distinguishable when photographed. Fig. 1 (b) and Fig. 2 are such examples.

The number of strings is chosen from the same consideration (i.e. enough to obtain stream lines), say, five to seven between two blades according to the number of blades and length of strings.

The length of strings are taken about $(0.5 \sim 1.2) \times$ (distance between two adjacent fastening points) according to the turbulence of flow to avoid entanglement and must be long enough to eliminate the effect of fastening conditions and in the same order as the length of flow which moves approximately in the same direction at any instant.

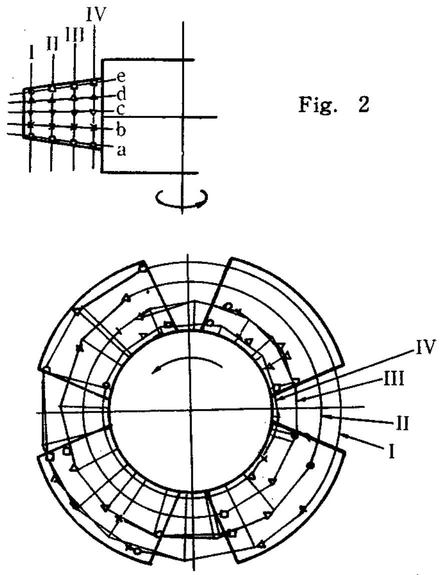

Fig. 2

At exit or inlet of the impeller or

runner, the wires to which strings are fastened must be projected out some distance l so that after the measurement of the relative flow they are shifted in n or m direction or completely removed and strings connected to the casing are inserted in the same position. To avoid this, the direction of absolute or relative flow at these surfaces are estimated from extrapolation of values obtained at inside or outside of them but it may bring some errors.

The string connected to the casing is fastened to the tip of a small rod which is set movable in its axial direction or n-direction of flow. Several strings fastened to a wire stretched in circumferential direction may also be used and this wire is fixed to a small rod or frame which is movable in n direction. In the latter case caution must be paid that the wire does not deform.

Photos are taken by a stroboscope. A metal piece is fixed to the rotating shaft and its tip sweeps the pick up coil once in one revolution cutting the magnetic lines and stirs the lamp to flash.

If the position of pick up coil is made adjustable in circumferential direction, then photos of different phase of impeller can be taken with stationary camera. To take photos at different position referred to the casing the camera must be displaced.

Time mean value of direction of flow can be obtained with suitable exposure of film.

A photo with exposure not longer than one revolution (or single flash photo) gives instantaneous state of flow and from sufficient number of such photos some characters of flow may be analized.

Plate 1 shows an example of photos taken in the preliminary test. In this case, the impeller is of pure radial type with exit diameter 444 mm, distance between front and back shrouds 29 mm, number of revolutions per minute 1800 and is driven in the open air. (1), (2) are taken with 1/15 sec exposure while others are taken with 1/8 sec. (1), (3), (6) are photos at middle section, (5) and the left half of (2), (4) are those near the back shroud (about 3 mm from the shroud) and (7) and right half of (2), (4) are near front shroud (about 3 mm from the front shroud). The diameter of wire is about 0.6 mm while the string is No. 50 count thread with 1/3 polypropylene and 2/3 cotton.

To confirm or check the results obtained by photographic method, pitot tube or hot wire inserted through casing wall at exit and inlet side of impeller may also be used. They can indicate circumferential mean value of absolute velocity head and pressure or absolute velocity.

If the velocity fluctuation outside the impeller, where method of rotating string is of no use (for example, near the tongue of spiral casing), is to be measured, photos of stationary strings by stationary camera and those of moving particles by moving camera may be useful.

When the rotation of camera around the shaft is impossible some substitute but approximate method may be used. One of such simple method is shown in Fig. 3

The camera is pivotted to a small rotating shaft (not the impeller shaft) at O and rotates with the shaft with constant angular velocity ω. AB is the plane of light which comes through a slit and A is the point to be photographed.

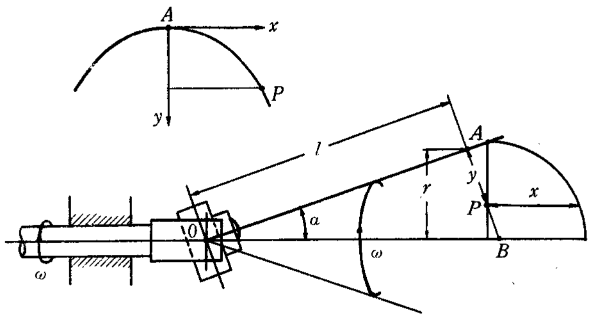

Fig. 3

The lamp is synchronized to flash a short duration when the axis of camera passes A. Then the co-ordinates of any point P on the locus of camera axis on AB plane is easily determined graphically as indicated and the locus is determined. The speed of camera axis at A is $r\omega$. Adjusting α and l in such a way that AO becomes perpendidular to AB plane, direction of motion of particles near A relative to that of camera axis is obtained.

4. Errors and their estimation

Errors come about from several causes in the author's method.

Errors due to the effects of gravity force, bending resistance and fastening conditions on the direction of a string can be calibrated in a parallel flow with varying magnitude and direction of velocity, from which the range of applicability of this method is estimated. Such calibration must be done for each case if any of the factors, say, string, fluid, method of fastening etc. are changed. These errors become negligible as velocity increases.

Errors due to inertia of the string is also tested by stationary jet and moving string or vice versa. These errors become marked when density of string is larger than that of the fluid and for strings connected to the casing (for they are exposed to highly fluctuating velocity compared with those connected to the runner). These errors become negligible for strings in a flow of liquid.

Errors due to the refraction of light at casing wall and aberration may be calibrated by putting graduated scale or plate and the like into the casing (runner being removed) filled with the fluid to be tested and taking photos of the plate set at various positions.

For example, in the case of an axial flow pump shown in Fig. 2, only cylindrical transparent casing filled with water is taken and a rectangular plate painted white with equally spaced and crossing black lines is placed in it set at various meridian sections with one side of the square figure parallel to the axis of the cylinder and photographed with axis of camera directed to the axis of cylinder. The direction θ of crossing lines or diagonals at any nodal point of the lattice figure on the film is compared with that of the corresponding theoretical direction θ' and θ-θ' curve is drawn for that point.

Angles θ, θ' are measured from the direction of the axis of the cylinder.

These curves are prepared for sufficiently large number of points on surfaces a, b,$\cdots$ in Fig. 2 and the direction θ of string on photos may be corrected by these charts assuming the relative position of camera to the cylinder is the same as in the calibration and the position of impeller referred to camera is known.

Flow in runners is generally three dimensional, so photos of strings taken from only one side can not indicate true direction of flow and this tendency is marked for impellers with high specific speed.

In such cases photos from two directions are needed. The directions of the same string of photos from two sides are corrected by the method mentioned above. Then, three dimensional direction is obtained as follows.

In Fig. 4, P is the point where a string is fastened, PS is the string, AP, BP are the directions of camera axis (when two photos are taken). PE is perpendicular to the plane containing AP, BP. Directions AP, BP are known, from which PE is determined. Let surfaces perpendicular to AP, BP be $(A'PE)$, $(BP'E)$. On these surfaces corrected photos of the string PS_A, PS_B, taken from directions A and B are given. Then, from graphical method shown in Fig. 5, angles between planes EPA and EPS or α_A and between planes EPB and EPS or α_B and angle between PS, PE or α are known and the direction of string is given.

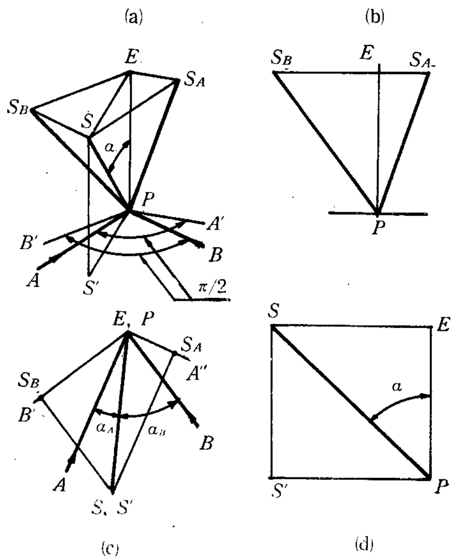

Fig. 4

Inequality of physical properties of fluid is another cause of photographic error. Caution must be paid to keep the properties of fluid unchanged and uniform.

Most of the errors mentioned above are common for photographic method in general.

5. Conclusion

In the above articles, a photographic method of measuring velocity distribution of flow in runners or impellers is explained and probable errors and their calibrations are discussed.

As mentioned above, this method has some defects, for example;

Photos of strings fastened to the runner and casing at inlet or exit surface can not be taken simultaneously ; for gaseous flow with small velocity the effect of the gravity on the string is not negligible ; in some cases time mean direction of absolute and relative flow at a point on the exit surface is hard to estimate from the photos, consequently the magnitude of velocity also.

For the last mentioned, photos with short time exposure may be useful and from several such photos the time mean value can be determined. Photos with long time exposure show the range of variation of flow direction and general tendency of flow can be seen from them.

On the other hand this method has several merits, for example ;

Velocity distribution in circumferential and other directions can be determined by comparatively simple method ; position of string can be traced exactly and so reliable to measure three dimensional flow, etc. Adaptable range of this method depends on the properties of the string, the fluid, the form of runner and casing etc. and should be studied on each occasion.

By combined use of this method with others the measurable range of flow may be increased and studies on such problems will be continued.

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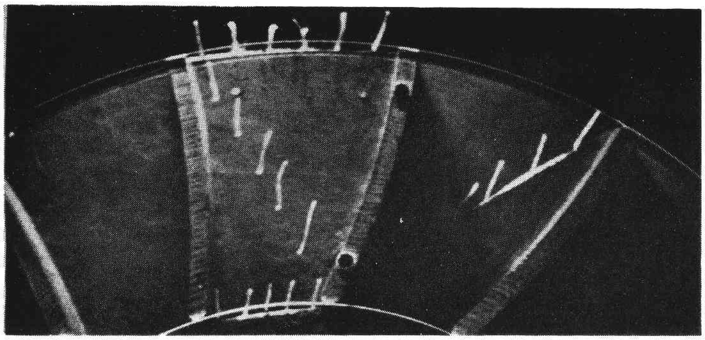

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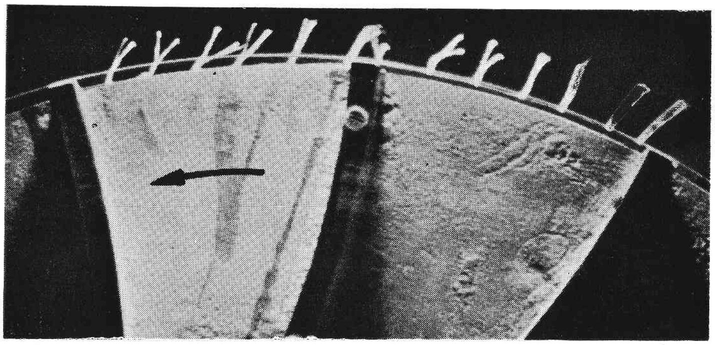

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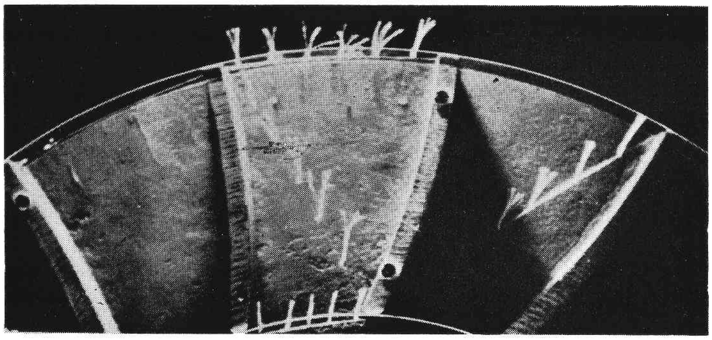

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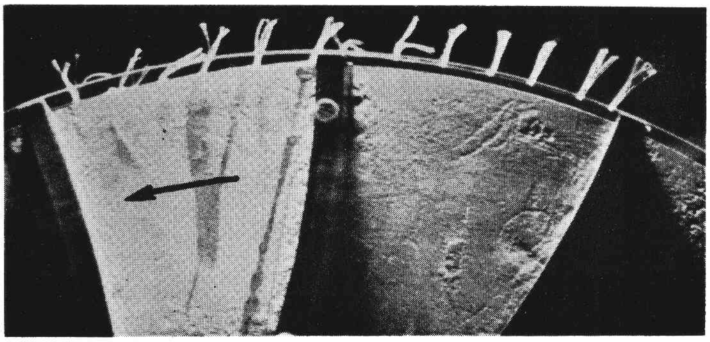
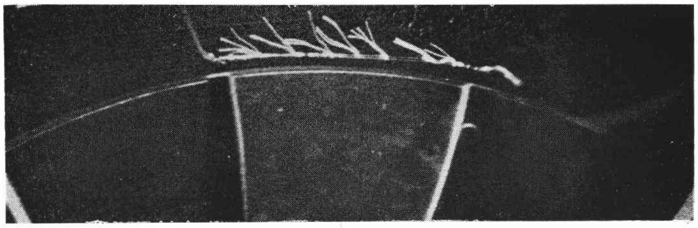


Plate 1-1



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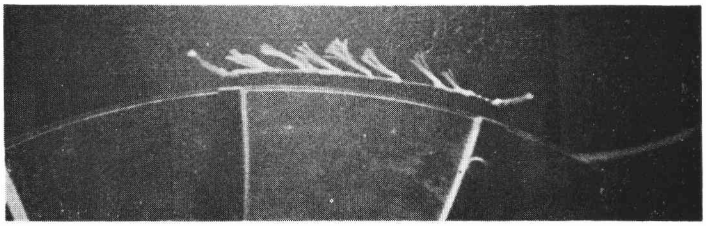

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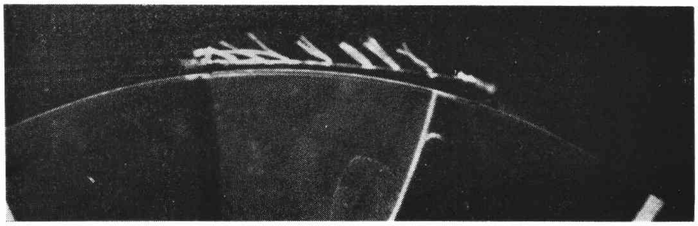

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Plate 1-2