# An Investigation on Occurrence of Backflow Phenomena Caused in Axial Flow Pump, Part. II: Upstream Backflow

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*Abstract:* - It is not possible to say that the condition of upstream backflow affect to the condition of downstream backflow and the condition of downstream backflow affects to the condition of upstream backflow. Their conditions are due to the interrelation between the geometrical shape of impeller blades and the average velocity across the flow passage between impeller blades in the rotating flow passage of axial flow pump. Because internal flow condition is formed by the action of impeller blades to the fluid flow at each of flow rates in the flow passage of impeller blades.

*Key-Words:* - Axial flow pump, upstream backflow phenomena, and Off design condition

## 1. Introduction

The maximum overall pump efficiency of axial flow pump of which we can accomplish at the design flow rate in our today's best practical design technique is very poor compared with those of centrifugal, mixed flow and semi mixed flow pumps. It is the lowest. And ratios of shut off head and shut off horsepower against those at the design flow rate are very large. In addition, cavitation performance characteristics are also very poor [1].

Because of these, many researchers, engineers, and pump users have put their remarkable attention on the design method of the axial flow pumps to improve their overall pump efficiency for many years. One of today's most trustful theoretical design method on the axial flow pump is the design method due to application of aerofoil theory to the fluid flow in the rotating flow passage between impeller blades.

This theoretical design method is established basically upon the application of lift and drag interrelationship to the fluid flow caused in the rotating flow passage of axial flow pumps. Fluid particles are forced to rotate together with impeller blades in the rotating flow passage by the impelling action of impeller blades and the fluid particles flow condition, that is, internal flow condition is formed with the vortex motion in the rotating flow passage. Therefore, at a first glimpse it seems that forced vortex motion is formed naturally between impeller blades. However, theoretical vortex motion, which is applied to the fluid flow to establish the theoretical design method, is not the forced vortex motion, but the free vortex motion for some reason. That is, uniform distribution of axial component of velocity is assumed between hub and casing wall across the flow passage for the fluid flow in the rotating flow passage of impeller blades. Hence, as a result, effect of centrifugal forces due to impeller blades rotational motion is not considered at all in the theory and neglected from the discussion in the theoretical process of development [1,2].

While, in the theoretical design method of centrifugal pump, the effect of centrifugal force is fully introduced in the theory and discussed, and succeeded to accomplish practical high overall pump efficiency at the design flow rate. In addition, some of investigators have reported that the background of design method of which aerofoil theory is applied to the fluid flow between blades of axial flow pump is not reasonable both theoretical considerations and experimental viewpoints [3,4].

From these viewpoints, basic reasons of occurrence of upstream and downstream backflow phenomena are investigated theoretically and experimentally in this study because they are the typical of internal flow condition of axial flow pumps. Therefore, it is expected that the result of these investigations might bring us some significant and useful information on this problem. From these viewpoints, the reasons of occurrence of upstream backflow are merely discussed in this paper. The reasons of occurrence of downstream backflow are reported in part I.

## 2. General Expression on the Occurrence of Upstream Backflow Phenomena

Upstream backflow is caused near the casing wall in the flow passage at the location of boundary between upstream and leading edge of impeller inlet. The reason of occurrence of upstream backflow is usually explained as that: It is caused by the effect of downstream backflow, which is occurred before the occurrence of upstream backflow at a large flow rate. Downstream backflow is caused near the hub in the flow passage at the location of boundary between trailing edge and downstream of the flow passage.

If the downstream backflow is caused near the hub at the trailing edge of impeller discharge at a large flow rate, and if it increases its rotational flow region radially outward toward casing wall and axially toward upward leading edge of impeller inlet in the rotating flow passage with the decrease in flow rate, fluid flow at the upstream flow passage, especially that at the boundary between upstream and leading edge of impeller inlet is effected by the flow condition at the downstream of impeller discharge.

Circular rotational motion due to downstream backflow phenomenon makes not only the main flow's flow passage narrow at the impeller discharge, but also radial outward component of velocity is induced on the fluid flow at the region of upstream of it. Hence the fluid flow entering the narrow flow passage at the impeller discharge is constructed from those entering axial direction due to main flow and those entering radial outward, which is supplementary caused in the flow passage because of the effect of rotational motion of downstream backflow. Therefore, upstream flow condition; especially flow condition near casing wall is affected at the boundary between upstream and leading edge of impeller inlet by the fluid flow condition in the rotating flow passage of downstream backflow.

Total amount of axial component of velocity across the flow passage decreases with the decrease in flow rate. Therefore, fluid flow condition across the flow passage between hub and casing wall is affected at the outside radius near the casing wall by the radial outward component of velocity caused at inner radius near the hub due to the effect of downstream backflow. The fluid flow at the upstream of rotational region of downstream backflow has radial outward component of velocity although it has radial inward component of velocity at the downstream of rotational region. Its magnitude increases with the decrease in flow rate and its rotational region expands axial direction toward upstream flow passage and radial outward toward casing wall in the rotating flow passage because effect of expanded downstream backflow increases with the decrease in flow rate.

Then, fluid flow between hub and casing wall across the flow passage shifts its flow direction radial outward in the impelling section of rotating flow passage, and the fluid flow at the upstream of impeller inlet decreases its axial component of velocity at the outer radius near the casing wall at the leading edge of impeller inlet. While fluid particle increases its radial outward component of velocity at the inner radius near the hub with the decrease in flow rate. And if this tendency becomes strong with the decrease in flow rate, upstream backflow is induced at the outer radius near the casing wall in the flow passage at the location of boundary between upstream and leading edge of impeller inlet. This is one example of expressions generally made on the occurrence of upstream backflow phenomenon.

However, this expression is not correct..

## 3. Physical Source on the Occurrence of Upstream Backflow Phenomena

True physical source of occurrence of upstream backflow is not due to existence of downstream backflow in the flow passage at the downstream of impeller discharge. It is due to the grade of separation of fluid particles from the blade surfaces at the leading edge of impeller inlet for the unit decreases in flow rate. In other words, upstream backflow is caused at the leading edge of impeller inlet due to the poor designing and production of the impeller blades.

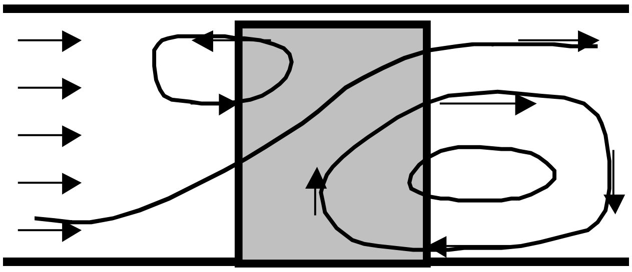

Fig.1 Illustration of upstream and downstream backflows caused in the rotating flow passage.

If the impeller blades design and production are made very poor, fluid particles collision with the blade surfaces due to disagreement of fluid particles flow direction with the impeller blades blade angle and the separation of fluid particles from the balde surfaces are obviously caused towards the flow passage between blades in the rotating flow passage of impeller blades at and around the leading edge of impeller inlet. This separation of fluid particles from the blade surfaces becomes large especially at outer radius near the casing wall at the location of boundary between upstream and leading edge of impeller inlet, because fluid particles flow condition is very complicated at that section of the flow passage of the impeller inlet. This is experimentally confirmed by many investigators.

Generally speaking, fluid particles flow condition at and near the casing wall is unstable at the boundary between upstream and leading edge of impeller inlet because fluid particles flow condition at that flow passage is not only effected by the collision of fluid particles with the blade surfaces and the separation of fluid particles from the blade surfaces due to disagreement of fluid particles flow direction with the impeller blades blade angle, but also effected by the boundary layer, which is developed axial direction along the casing wall and the clearance flow formed between casing wall and impeller blades blade tip surfaces.

They form complicated flow condition at that flow passage. Therefore, fluid particle, which is flowing at outer radius near the casing wall, is very easy to loose its axial component of velocity at the boundary between upstream and leading edge of impeller inlet more than that at inner radius near the hub for the unit decrease in flow rate. In addition to these, if the flow rate decreases, remaining time of fluid particles in the rotating flow passage, that is, amount of rotational motion of fluid particles together with impeller blades increases in the flow passage, which results to cause radial outward movement in the flow passage due to rotational motion of the impeller blades. Therefore, radial outward component of velocity is induced in the rotating flow passage with the decrease in flow rate.

All these are the terms to increase the possibility to cause the upstream backflow in the rotating flow passage. If the impeller blades blade designing and the production of impeller blades are made very poor, in no doubt, these terms to cause the upstream backflow maght be fully guaranteed. Therefore, it might be possible to say that these are the pure sources of occurrence of upstream backflow phenomenon.

## 4. Practical Experimental Data on the Occurrence of Upstream Backflow

Experimental performance characteristic curves for five axial flow pumps tested and their flow rates at which upstream and downstream backflows occurred are shown in Fig. 3 [5].

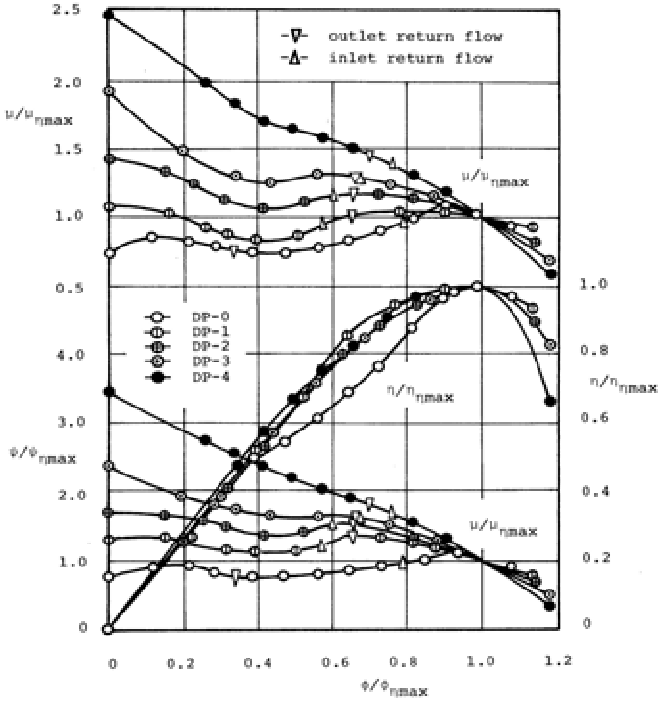

Fig.2. General performance characteristic curves of five semi-mixed flow type axial flow pumps tested and flow ratios at which upstream and downstream backflows started by T. Tanaka [5].

Fig. 2 indicates that geometrical formation of overall efficiency curve for DP-0 pump was the worst of the five. It formed a very reduced poor efficiency curve at off design flow rate. DP-4 pump had a reduced efficiency curve at off design flow rate. DP-3 pump had a poor overall efficiency curve. Overall efficiency curve for DP-2 pump was rather average. Geometrical formation of overall efficiency curve for DP-1 pump was the best of the five. Overall efficiency curve was the flattest of the five.

The ratios of flow rate at which upstream backflow was observed to that at the design flow rate for DP-0, DP-1, DP-2, DP-3, and DP-4 pumps were 0.790, 0.573, 0.603, 0.672, and 0.762, and those at which downstream backflow was observed were 0.341, 0.653, 0.655, 0.667, and 0.698, respectively. The difference of flow ratios between the flow ratios at which upstream backflow occurred and that at which downstream backflow was observed are 0.449, -0.080, -0.052, 0.005, 0.064 for DP-0, DP-1, DP-2, DP-3, and DP-4 pumps, respectively.

This experimental data indicate that upstream backflow was occurred at a large flow ratio before the downstream backflow occurred at a small flow ratio for DP-0, DP-4, and DP-3 pumps. On the DP-0 pump, upstream backflow occurred first at a fairly large flow rate. It occurred at a high flow rate just after a slight decrease in flow rate from the design flow rate. And the downstream backflow occurred at a small flow rate with a further decrease in flow rate. The flow rate at which upstream backflow occurred was the largest and that of downstream backflow occurred was the smallest of the five. The upstream backflow for DP-4 pump appeared sometime before the downstream backflow occurred. Upstream backflow occurred just before the downstream backflow occurred and at approximately the same flow rate for DP-3 pump.

On the other hand, upstream backflow occurred afterward at a smaller flow rate after the downstream backflow appeared for DP-1 and DP-2 pumps. DP-1 pump had occurred upstream backflow at a fairly small flow ratio after the downstream backflow occurred. It had the smallest flow rate at which the upstream backflow appeared of all the tested five. The occurrence of upstream back flow for DP-2 pump was larger than that of DP-1 pump. While, the occurrence of downstream backflow for DP-2 pump was the largest of the five.

These indicates that occurrence of upstream backflow is strongly related to grade of overall pump efficiency. If the occurrence of upstream backflow is caused at a fairly small flow ratio compared with that of occurrence of downstream backflow, geometrical formation of overall pump efficiency curve becomes a flatter one. Overall pump efficiency curve for DP-1 pump might be the example for this case. However, overall pump efficiency curve becomes a reduced one with the occurrence of upstream backflow becomes first. That is, if the flow rate at which upstream backflow occurred becomes large compared with that of downstream backflow, overall pump efficiency becomes a reduced one. Overall pump efficiency curve for DP-2 pump might be the example for this case.

The occurrence of downstream backflow for DP-2 pump was the firstest of the five. It occurred at a large flow rate. However, upstream backflow was caused very quickly at a large flow ratio (0.603) slightly afterwards the downstream backflow had started. Downstream backflow was occurred at flow ratio 0.655. The difference of flow ratios between the flow ratios at which upstream backflow occurred and that at which downstream backflow was observed are -0.052 for DP-2 pump and -0.080 for DP-1 pump. Same could be said for the cases when the upstream backflow had started first at a large flow rate and the occurrence of downstream backflow became very late to a small flow rate. Geometrical formation of efficiency curve becomes a reduced one as it is seen in DP-3, DP-4, and DP-0 pumps.

## 5. Pure Reasoning of Occurrence of Upstream Backflow at Off Design Flow Rate

Let us consider two different kinds efficiency pumps. One has a very good flat overall pump efficiency curve and the other had a very poor reduced one at off design flow rate. To simplify the discussion their overall pump efficiencies are assumed equivalent at the design flow rate. Now let us consider the operating condition at off design flow rate $Q_X$.

From previous discussion, it is clear that discharge valves valve opening for poor efficiency pump is larger than that of good efficiency pump at off design flow rate $Q_X$. Velocity distribution for poor overall efficiency pump shifts radial outward less than that for good efficiency pumps at outer radius near the casing wall. That is, if the pump efficiency is worse, the axial component of velocity becomes less larger at outer radius near the casing wall but the axial component of velocity becomes less smaller at the inner radius near hub than those for good efficiency pump at an equivalent off design flow rate.

That is, if the pump efficiency is worse, the amount of fluid particles, which flows at outer radius near the casing wall, becomes less large and that, which flows at inner radius near the hub, becomes less small. By shifting the amount of fluid particles flow rate radial outward near the casing wall less than that for good overall efficiency pump, flowing fluids are obtaining less stronger effect of impeller blades centrifugal forces and less high pressure head in the rotating flow passage of impeller blades. Therefore, in the rotating flow passage of worse efficiency pump, radial outward forces act on fluid particle less than that for good efficiency pump.

These indicate that the occurrence of downstream backflow is caused in the flow passage near the hub at a larger flow rate less than that of good efficiency pumps at off design flow condition. Therefore, if the pump efficiency is worse, increasing rate of axial component of velocity is less larger at outer radius near the casing wall and less smaller at inner radius near the hub compared with those of good efficiency pumps for the unit decrease in flow rate. Therefore, it could be said that not only expanding speed of rotational region of downstream backflow becomes less faster than that of good efficiency pump in the rotating flow passage, but also its strength becomes less stronger than that of good efficiency pump for the unit decrease in flow rate. That is, the worse the overall pump efficiency becomes, not only the flow rate at which downstream backflow occurred becomes less larger at high flow rate, but also the expanding speed of rotational region of downstream backflow becomes less larger and its strength becomes less strong in the rotating flow passage. That is, the worse the overall pump efficiency becomes, the downstream backflows rotational region becomes less large.

In this discussion, although the maximum overall pump efficiencies are assumed equivalent at the design flow rate, geometrical formation of overall pump efficiency curve for poor efficiency pump is assumed as a very reduced one at off design flow rate. This indicates that impeller blade is designed so that it keeps low efficiency and a reduced efficiency curve even at a very large flow rate near the design flow rate. That is, the separation of fluid particles from the blade surfaces is easily caused in the flow passage if the operating condition moves from the flow rate at the design flow rate to that at off design flow rate. In other words, fluid particle separates easily from the blade surfaces for a slight change in operating condition. Hence, for the slight change in operating condition, even at the high flow rate near the design flow rate, impeller blade cannot keep its strong impelling action on the fluid flow and cannot push the fluid particles behind the impeller blade at high efficiency compared with those of good efficiency pump.

From these discussions, it would be clear that the grade of overall pump efficiency is strongly interrelated with the flow rate of occurrence of upstream backflow, expanding speed of upstream backflow for the unit decrease in flow rate, and the strength of rotational motion of upstream backflow. If the pump efficiency is worse than the others, it indicates that its downstream backflow might not be caused at a high flow rate compared with those of good efficiency pumps. And the expanding speed for the unit decreases in flow rate and the strength of rotational motion of downstream backflow are smaller than those of good efficiency pumps. On the other hand, upstream backflow might be caused at a high flow rate compared with those of good efficiency pumps. And the expanding speed for the unit decreases in flow rate and the strength of rotational motion of upstream backflow are larger than those of good efficiency pumps.

From these viewpoints, it could be said that upstream backflow phenomenon could be understood as the barometer of overall pump efficiency to classify the pumps grade. From above discussion it might be possible to say that if the flow rate at which upstream backflow has started is larger than the others at off design flow rate, it indicates that the overall pump efficiency is worse than the others.

## 6. Pure Observation of Upstream and Downstream Backflows Occurrence at Off Design Flow Rate

Relationship between upstream and downstream backflows is discussed in many literatures. Most of those explanations are not made sufficiently. In strictly speaking their expressions are as follows: The upstream backflow is caused by the effect of downstream backflow and the downstream backflow is caused by the effect of upstream backflow. In other words, if the reasoning of occurrence of upstream backflow is described first in detail in the literature, the reasoning of occurrence of downstream backflow is explained as that it is induced by the effect of upstream backflow [2]. If the reasoning of occurrence of downstream backflow is described first in detail, the reasoning of occurrence of upstream backflow is explained as that it is induced by the effect of downstream backflow [6]. These are not correct.

Experimental data, shown in Fig. 3 and other experimental data introduced in other literatures, strictly show practical reasoning on the occurrence of upstream and downstream backflow phenomena. It is obvious that some of impeller blades caused upstream backflow phenomenon first at a large flow rate after a short decrease in flow rate from that at the design flow rate [2,5]. For example, on the DP-0 pump, the domain of rotational motion of upstream backflow has expanded rapidly radial inward towards inner hub radius with a decrease in flow rate. Its expanding speed for the unit decreases in flow rate was very large. However, it did not induce the downstream backflow in the downstream flow passage of impeller discharge. Occurrence of downstream backflow was very late at off design flow rate. The flow rate at which downstream backflow was induced in the rotating flow passage was very small. It was the smallest of tested impeller blades. Downstream backflow was caused after a far decrease in flow rate from that at the design flow rate. See Fig. 3.

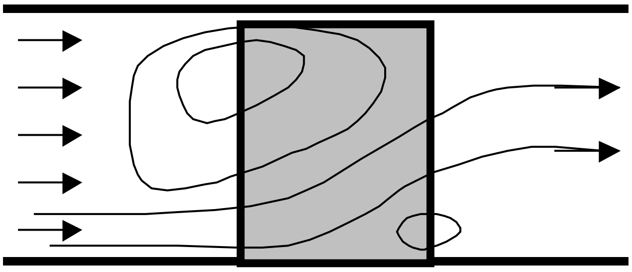

Fig.3 . Illustration of backflow phenomenon of which upstream backflow occurred at high flow rate.

Conversely, some of the impeller blades caused downstream backflow phenomenon first at a large flow rate after a short decrease in flow rate from that at the design flow rate [5,6]. For example, on the DP-1 pump, the domain of rotational motion of downstream backflow expanded rapidly radial outward towards casing wall with a decrease in flow rate. Its expanding speed for the unit decreases in flow rate was very large. However, it did not induce the upstream backflow in the upstream flow passage of impeller inlet. Its occurrence of upstream backflow was very late at off design flow rate. The flow rate at which upstream backflow was induced in the rotating flow passage was very small. It was the smallest of tested impeller blades. Upstream backflow was caused after a far decrease in flow rate from that at the design flow rate. See Fig. 4.

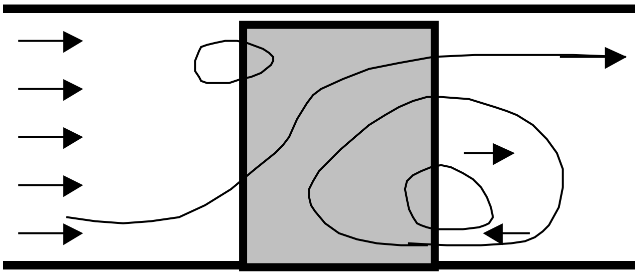

Fig. 4. Illustration of backflow phenomenon of which downstream backflow occurred first at high flow rate.

In addition to these, some of the impeller blades induced upstream and downstream backflows at an approximately same flow rate at off design flow rate [5]. Dp-3 pump might be the example for this case. These indicate that it is not possible to say that one backflow phenomenon, which was caused at a high flow rate, induces the other backflow phenomenon, which is caused later on at a small flow rate in the rotating flow passage. See Fig. 5.

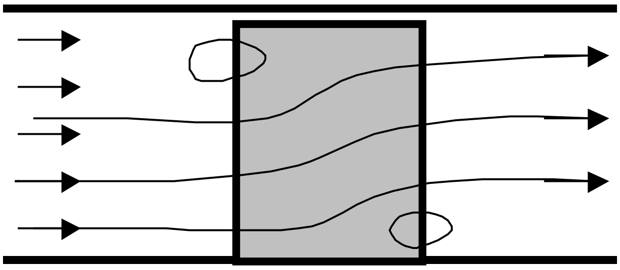

Fig.5 Illustration of backflow phenomenon of which upstream and downstream backflows occurred at and about the same flow rate.

## 7. Conclusion

It is not possible to say that the condition of upstream backflow affect to the condition of downstream backflow and the condition of downstream backflow affects to the condition of upstream backflow. Their conditions are due to the interrelation between the geometrical shape of impeller blades and the average velocity across the flow passage between impeller blades in the rotating flow passage of axial flow pump.

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