Prerotation

Perhaps no aspect of turbomachinery flow is more misrepresented and misunderstood than the phenomenon of "prerotation". While this belongs within the larger category of secondary flows (dealt with in section (Mbdf)), it is appropriate to address the issue of prerotation seperately, not only because of its importance for the hydraulic performance, but also because of its interaction with cavitation.

It is first essential to distinguish between two separate phenomena both of which lead to a swirling flow entering the pump. These two phenomena have very different fluid mechanical origins. Here we shall distinguish them by the separate terms, "backflow-induced swirl" and "inlet prerotation". Both imply a swirl component of the flow entering the pump. In fluid mechanical terms, the flow has axial vorticity (if the axis of rotation is parallel with the axis of the inlet duct) with a magnitude equal to twice the rate of angular rotation of the swirl motion. Moreover, there are some basic properties of such swirling flows that are important to the understanding of prerotation. These are derived from the vorticity transport theorem (see, for example, Batchelor 1967). In the context of the steady flow in an inlet duct, this theorem tells us that the vorticity will only change with axial location for two reasons: (a) because vorticity is diffused into the flow by the action of viscosity, or (b) because the flow is accelerated or decelerated as a result of a change in the cross-sectional area of the flow. The second mechanism results in an increase in the swirl velocity due to the stretching of the vortex line, and is similar to the increase in rotation experienced by figure skaters when they draw their arms in closer to their body. When the moment of inertia is decreased, conservation of angular momentum results in an increase in the rotation rate. Thus, for example, a nozzle in the inlet line would increase the magnitude of any preexisting swirl.

For simplicity, however, we shall first consider inlet ducting of uniform and symmetric cross-sectional area, so that only the first mechanism exists. In inviscid flow, it follows that, if there is a location far upstream at which the swirl (or axial vorticity) is zero, then, in the absence of viscous effects, the swirl will be everywhere zero. This important result, which is a version of Kelvin's theorem (Batchelor 1967), is not widely recognized in discussions of prerotation. Moreover, the result is not altered by the existence of viscous effects, since purely axial motion cannot generate axial vorticity. However, there are two common circumstances in which prerotation can be generated without violation of the above theorem, and these give rise to the two phenomena named earlier.

The first of these common circumstances arises because of one of the most important secondary flows that can occur in pumps, namely the phenomenon of "backflow". This is caused by the leakage flow between the tip of the blades of an impeller (we consider first an unshrouded impeller) and the pump casing. The circumstances are depicted in figure 1. Below a certain critical flow coefficient, the pressure difference driving the leakage flow becomes sufficiently large that the tip leakage jet penetrates upstream of the inlet plane of the impeller, and thus forms an annular region of "backflow" in the inlet duct. After penetrating upstream a certain distance, the fluid of this jet is then entrained back into the main inlet flow. The upstream penetration distance increases with decreasing flow coefficient, and can reach many diameters upstream of the inlet plane. In some pump development programs (such as the Rocketdyne J-2 liquid oxygen pump) efforts have been made to insert a "backflow deflector" in order to improve pump performance (Jakobsen 1971). The intention of such a device is to prevent the backflow from penetrating too far upstream, to reduce the distortion of the inlet flow field, and to recover, as far as is possible, the swirl energy in the backflow. More recently, a similar device was successfully employed in a centrifugal pump (Sloteman *et al.* 1984).

Some measurements of the axial and swirl velocities just upstream of an axial inducer are presented in figure 2. This data is taken from del Valle *et al* (1992), though very similar velocity profiles have been reported by Badowski (1969, 1970) (see also Janigro and Ferrini 1973), and the overall features of the flow

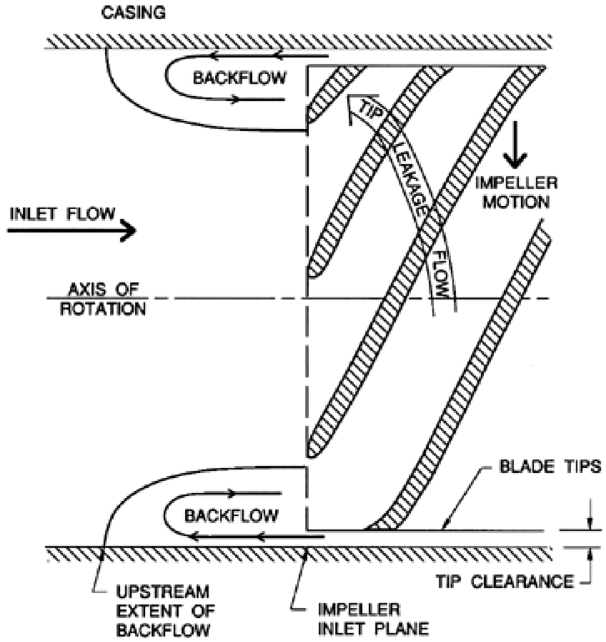

Figure 1: Lateral view of impeller inlet flow showing tip leakage flow leading to backflow.

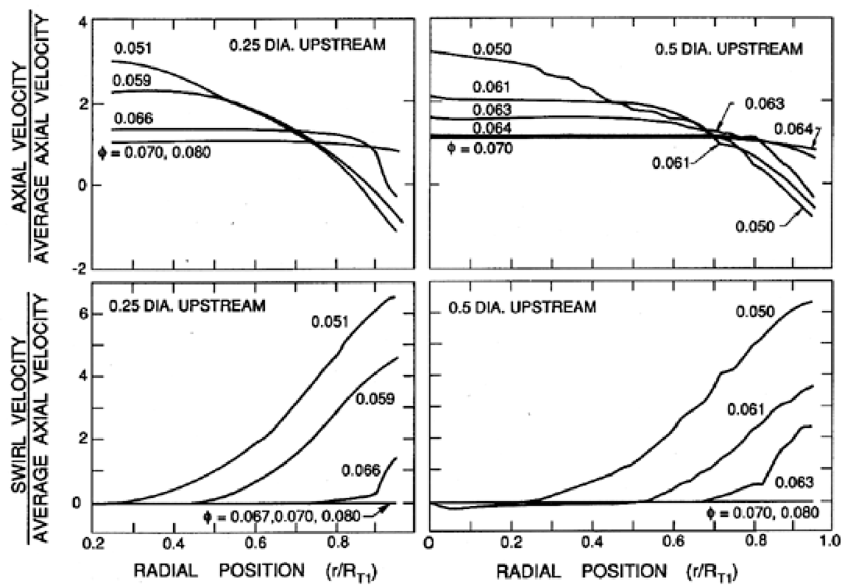

Figure 2: Axial and swirl velocity profiles in the inlet duct 0.25 diameters (left) and 0.5 diameters (right) upstream of the inlet plane of an inducer (Impeller VI) for various flow coefficients as shown (from del Valle, Braisted and Brennen 1992).

are similar whether the pump is shrouded or unshrouded, axial or centrifugal (see, for example, Stepanoff 1948, Okamura and Miyashiro 1978, Breugelmans and Sen 1982, Sloteman *et al.* 1984). Measurements are shown in figure 2 for two distances upstream of the inlet plane (half a radius and one radius upstream), and for a number of flow coefficients, ϕ. Note from the axial flow velocity profiles that, as the flow coefficient is decreased, the backflow reaches a half radius upstream at about $\phi \approx 0.066$, and one radius upstream at about $\phi \approx 0.063$. The size of the backflow region grows as ϕ is decreased. It is particularly remarkable that at $\phi \approx 0.05$, nearly 30% of the inlet area is experiencing reverse flow! We can further observe from the swirl velocity data that, in the absence of backflow, the inlet flow has zero swirl. Kelvin's theorem tells us this must be the case because the flow far upstream has no swirl.

Obviously the backflow has a high swirl velocity imparted to it by the impeller blades. But what is also remarkable is that this vorticity is rapidly spread to the core of the main inlet flow, so that at $\phi = 0.05$, for example, almost the entire inlet flow has a nonzero swirl velocity. The properties of swirling flows discussed above are not violated, since the origin of the vorticity is the pump itself and the vorticity is transmitted to the inflow via the backflow. The rapidity with which the swirl vorticity is diffused to the core of the incoming flow remains something of a mystery, for it is much too rapid to be caused by normal viscous diffusion (Braisted 1979). It seems likely that the inherent unsteadiness of the backflow (with a strong blade passing frequency component) creates extensive mixing which effects this rapid diffusion. However it arises, it is clear that this "backflow-induced swirl", or "pre-rotation", will clearly affect the incidence angles and, therefore, the performance of the pump.

Before leaving the subject of backflow, it is important to emphasize that this phenomenon also occurs at flow rates below design in centrifugal as well as axial flow pumps, and with shrouded as well as unshrouded impellers (see, for example, Okamura and Miyashiro 1978, Makay 1980). The detailed explanation may differ from one device to another, but the fundamental tendency for an impeller to exhibit this kind of secondary flow at larger angles of incidence seems to be universal.

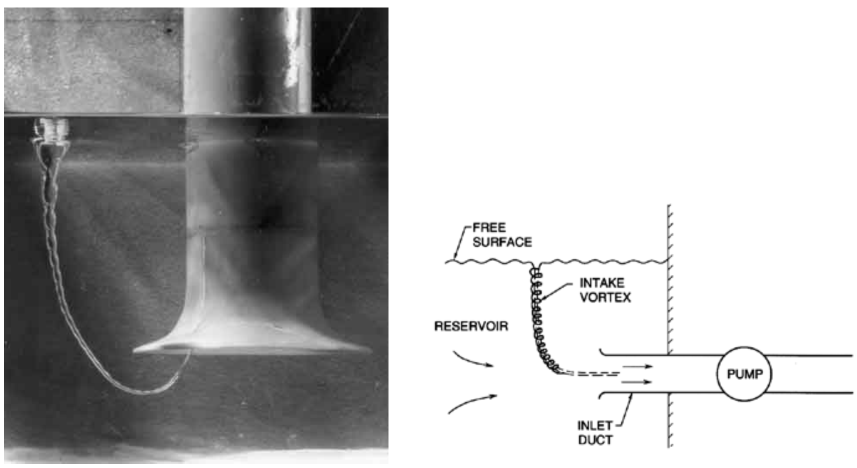

Figure 3: Right: sketch of a typical inlet vortex associated with prerotation. Left: Photograph of an air-filled inlet vortex from Wijdieks (1965) reproduced with permission of the Delft Hydraulics Laboratory.

But there is another, quite separate origin for prerotation, and this is usually manifest in practice when the fluid is being drawn into the pump from an "inlet bay" or reservoir with a free surface (figure 3). Under such circumstances, it is almost inevitable that the large scale flow in the reservoir has some nonuniformity that constitutes axial vorticity or circulation in the frame of reference of the pump inlet. Even though the fluid velocities associated with this nonuniformity may be very small, when the vortex lines are stretched as the flow enters the inlet duct, the vorticity is greatly amplified, and the inlet flow assumes a significant preswirl or "inlet prerotation". The effect is very similar to the bathtub vortex. Once the flow has entered an inlet duct of constant cross-sectional area, the magnitude of the swirl usually remains fairly constant over the short lengths of inlet ducting commonly used.

Often, the existence of "inlet prerotation" can have unforeseen consequences for the suction performance of the pump. Frequently, as in the case of the bathtub vortex, the core of the vortex runs from the inlet duct to the free surface of the reservoir, as shown in figure 3. Due to the low pressure in the center of the vortex, air is drawn into the core and may even penetrate to the depth of the duct inlet, as illustrated by the photograph in figure 3 taken from the work of Wijdieks (1965). When this occurs, the pump inlet suddenly experiences a two-phase air/water flow rather than the single-phase liquid inlet flow expected. This can lead, not only to a significant reduction in the performance of the pump, but also to the vibration and unsteadiness that often accompany two-phase flow. Even without air entrainment, the pump performance is almost always deteriorated by these suction vortices. Indeed this is one of the prime suspects when the expected performance is not realized in a particular installation. These intake vortices are very similar to those which can occur in aircraft engines (De Siervi *et al.* 1982).