

from its high-pressure layer of the outlet toward its low-pressure layer of the inlet. This axial flow is then a secondary backflow superimposed on the mean flow field: We have a strong throughflow momentum wake in the core region of the vortex “low.”

The vortex “high” is associated with a radial flow out of the core, the same as the anticyclone. The axial flow through the core is directed from the low-pressure layer of the upper atmosphere toward the high-pressure layer on the ground. For the case of the impeller, this radial flow will come from the inlet through the core of the vortex “high” toward the outlet and spread out of it. We then have here a strong throughflow momentum jet along of the vortex “high” superimposed on the mean flow field.

The local Coriolis parameter $f = 2 \Omega_n$ of the secondary flow over the cross section of the impeller-blade channel decreases downstream along the blade channel, while the pressure p increases at the same time.

According to the conservation law of the potential vorticity:

$$\Pi = \frac{\xi + f}{\rho H} = \frac{\xi + f}{p} = \text{const}$$

(Pedlosky, 1984), the relative vorticity ξ in the secondary flow will increase in this downstream direction. This indicates that the secondary vortex “low L ” (with a positive sign of ξ) will strengthen and the secondary vortex “high H ” (with a negative sign of ξ) will diminish along the blade channel in this downstream direction.

The derivation given above is verified by the experimental result given in Fig. 15 (Chen et al., 1991). The secondary vortex pair develops from the section 11 to the section 14 (i.e., the outlet) with the result that the vortex “low L ” in the corner “pressure/shroud” becomes very huge in the outlet section 14, while the vortex “high H ” in the corner “suction/hub” diminishes to a small intensity.

A further experimental result about the secondary flow of a backswept impeller obtained by Farge and Johnson (1990) is given in Fig. 16 along the blade channel in five stations. Each station consists of the secondary flows, in addition to the contours of the throughflow velocities (in the right diagram) and the dimensionless rotary stagnation pressure (in the left diagram).

At station 1 for the inlet of the blade channel, a passage vortex rotating against the rotational sense of the impeller forms the field of the secondary flow. This passage vortex keeps the absolute vorticity of the secondary flow at the zero value, because the throughflow has originated from the absolute frame with zero vorticity. This passage vortex is thus a huge “high H .” The corresponding rotary stagnation pressure remains high at 0.95 to 1 with a very uniform distribution across the section of the inlet.

This very regular passage vortex then degenerates with the throughflow traveling downstream: A low-pressure center of 0.7 near the corner “section/shroud” at station 2, followed by 0.5 and 0.45 at stations 3 and 4, respectively. The low-pressure center of 0.55 becomes very broad at station 5, i.e., at the outlet section of the impeller, while the high-pressure center of 0.95 reduces to a smaller size in the corner region of the “suction/hub.” The corresponding secondary velocity field is quite similar to that in Fig. 15.

The difference in the arrangements of the vortex pairs in the two experiments given in Figs. 15 and 16 is caused by the different shapes of the blade channels investigated. Thus these two experiments bear the evidence for the validity of the conservation of the potential vorticity along the blade channel.

The secondary vortices L and H in Fig. 14(b) correspond very well to those given in Figs. 15 and 16 over the outlet section of the impeller. Then, the vortex L is a pressure “low” centered on the throughflow momentum wake and the vortex H is a pressure “high” centered on the throughflow momentum jet, as given in Fig. 6.

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Authors’ Closure

The authors wish to thank Dr. Chen for the comment and the kind attention to the results shown in the paper.

Dr. Chen has developed an original theory based on the analogy between geophysical and turbomachinery flows, which is useful to help interpret the complex secondary flow pattern in centrifugal turbomachinery rotors. Most secondary flow fields seem to be explainable in terms of a pair of counterrotating vortices, which verify the conservation law of the potential vorticity. The two vortices generate flow along their axis: One against the primary flow gives rise to the throughflow wake, the second in the opposite direction determines a momentum jet superimposed on the main flow field.

Compared with the cases mentioned in the discussion, the present impeller geometry represents a limiting case, as the blades are set in the wholly radial part of the meridional channel. In this case the component of the rotational speed vector normal to the inlet cross section tends to zero and therefore should not be responsible for the “low” vortex identified by Dr. Chen in the secondary flow field.

It is the authors’ opinion that the position and the intensity of the low-momentum throughflow wake are strongly determined in the unshrouded impellers by the tip clearance effects. Evidence of that can be found in the experimental results and numerical predictions of Hathaway et al. (1993), in the computational investigation of Moore and Moore (1993) performed on the same impeller, without tip clearance and with different tip clearance gaps, and in the experimental data and computations of Hah and Krain (1990).

The authors are more familiar with secondary flow explanation based on the equilibrium of the fluid dynamic forces in the relative frame of reference and on the unbalance due to the presence of boundary layers near blades and endwall surfaces or to the tip clearance. However, they think that the two approaches are complementary and that the use of both may allow a more refined analysis and better understanding of the phenomena.

References

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