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Inlet and Outlet Devices for Rotary Blood Pumps

*Xinwei Song, *Houston G. Wood, *Paul E. Allaire, †James F. Antaki, and ‡Don B. Olsen

**Department of Mechanical and Aerospace Engineering, University of Virginia, Charlottesville, VA; †Department of Biomedical Engineering, Carnegie Mellon University, Pittsburgh, PA; and ‡Utah Artificial Heart Institute, Salt Lake City, UT, U.S.A.*

Abstract: The purposes of inlet and outlet devices for rotary blood pumps, including inducers and diffusers for axial pumps, inlet and exit volutes for centrifugal pumps, and inlet and outlet cannulas, are to guide the blood into the impeller, where the blood is accelerated, and to convert the high kinetic energy into pressure after the impeller discharge, respectively. The designs of the inlet and outlet devices have an important bearing on the pump performance. Their designs are highly dependent on computational fluid dynamics (CFD) analysis, guided by intuition and experience. For inlet devices, the design objectives are to eliminate separated flow, to minimize recirculation, and to equalize the radial components of velocity. For outlet devices, the design goals are to reduce speed, to minimize energy loss, and to avoid flow separation and whirl. CFD analyses indicate the velocity field and pressure distribution. Geometrical optimization of these components has been implemented in order to improve the flow pattern.
Key Words: Inlet and outlet devices—Rotary blood pumps—Computational fluid dynamics.

The impeller is the main component in a rotary blood pump (RBP). The inlet and outlet devices take no part in the generation of head. These devices, such as, inducer and diffuser for axial RBPs, inlet and exit volutes for centrifugal RBPs, and inlet and outlet cannulas for all kinds of RBPs, do not consume external energy. For inlet devices, including inlet cannulas, inducers for axial blood pumps, inlet elbows or inlet volutes for centrifugal blood pumps, which are upstream of the impeller, their functions are to guide, straighten, and equalize the incoming flow for the impeller. Therefore, design objectives for them are to eliminate separated flow and to minimize recirculation and prerotation. For outlet devices, including diffusers for axial blood pumps, exit volutes for centrifugal blood pumps, and dischargers, which are downstream of the impeller, the design goals are to reduce the velocity, minimize the energy loss, and avoid flow separation and whirl. Unlike the impeller, most of these parts have no closed-form analysis approach for their design. Their configurational designs are highly dependent on computational fluid dynamics (CFD) analysis, guided by intuition, and probably numerical configuration optimization. CFD analyses can indicate fluid velocity and pressure distribution in these devices.

In this article, some examples of RBP inlet and outlet devices are illustrated and design techniques for these components are examined using CFD.

INLET DEVICES

Inlet elbow versus inlet volute

The shape of the inlet device has an important influence on the velocity distribution immediately ahead of the impeller and in this way it affects the hydraulic and mechanical performance of the pump. A straight, area-converging inlet pipe is best from a turbomachinery point of view. Such a pipe, whose area gradually reduces toward the impeller eye, has a definite steadying effect on the flow and assures a uniform fluid feed to the impeller. However, in order for the flow to be straight, uniform, and steady that pipe would have to be approximately 20 times longer than its diameter. In the case of blood pumps, the effective pipe length would have to be approximately

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Address correspondence and reprint requests to Dr. Xinwei Song, Mechanical & Aerospace Department, University of Virginia, P.O. Box 400746, Charlottesville, VA 22904, U.S.A. Tel.: 01-434-924-7574; E-mail: xs8d@virginia.edu
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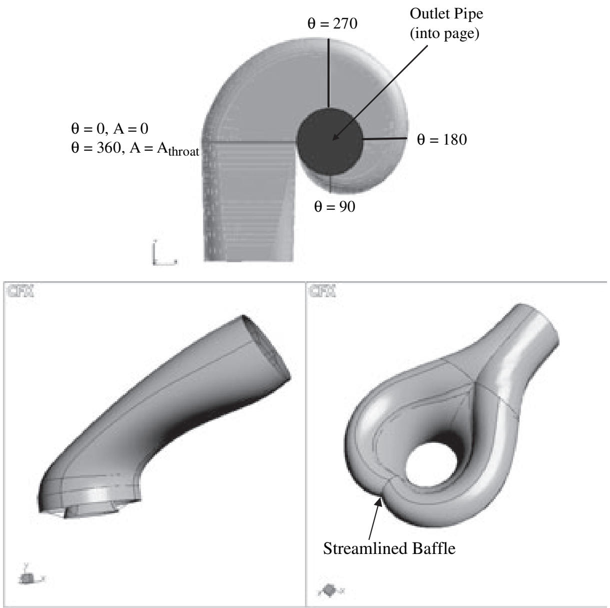

FIG. 1. The geometries of different inlet devices for centrifugal blood pumps.

10 inches. Though this is possible on the test stand or in computer models, the pump will eventually have to be inserted in the human body, which has no room for such a long pipe.

The majority of industrial single-stage impellers are equipped with volutes. In the inlet volute design, parameters such as the cross-sectional geometry, throat area, and overall height will have to be addressed and examined (Fig. 1). The selection of these parameters is governed by theoretical considerations (1), but their actual optimization has been established experimentally for both pump application and fluid performance. An inlet volute was adopted for the HeartQuest CF3, which was developed as a concept demonstrator to test fluid features, magnetic bearing designs, and control algorithms (2). The main drawback of an inlet volute is the swirling characteristics generated because of the spiral flow path (Fig. 2). The circumferential component of velocity is as high as 2.5 m/s. The interaction of this flow and the impeller will raise quite a challenge to the impeller design and negatively affect the overall pump performance. Secondly, the inlet volute was revealed to generate high stress that would be harmful to the blood.

An inlet elbow, which is considered to be equivalent hydraulically to a straight pipe for low specific speeds, is a bent and area-converging pipe. It is specially designed to link to the impeller eye and feed the impeller with a wash of vertical and spatially uniform flow. This configuration was substituted for the inlet volute in the HeartQuest CF4b, which is the first actual prototype of the clinical version of the HeartQuest products. CF4b is approximately 20% smaller than CF3, and incorporates successful technologies of the CF3 model and eliminates problems and optimizes the design (3). The CFD results for the inlet elbow demonstrated that the pressure loss and the stress are small due to the simplicity of the geometry. However the velocity and pressure distributions at the outlet of the pipe are highly nonuniform (Fig. 3). The flow favors the further side of the pipe. Recirculation flow even exists at the near side of the pipe.

A flat inlet elbow is designed to eliminate the problems of the inlet elbow. A flat inlet elbow has a converging area. A gradually accelerating flow can suppress the tendency toward velocity distortion due to a double turn just in front of the impeller eye. In order to avoid stagnation regions or collisions around the reuniting region, a streamlined baffle is designed at the further side of the flat inlet elbow. CFD simulations show that the flat inlet elbow gives the best performance for a centrifugal blood pump (Fig. 4). Smooth flow is guided into the impeller, and more

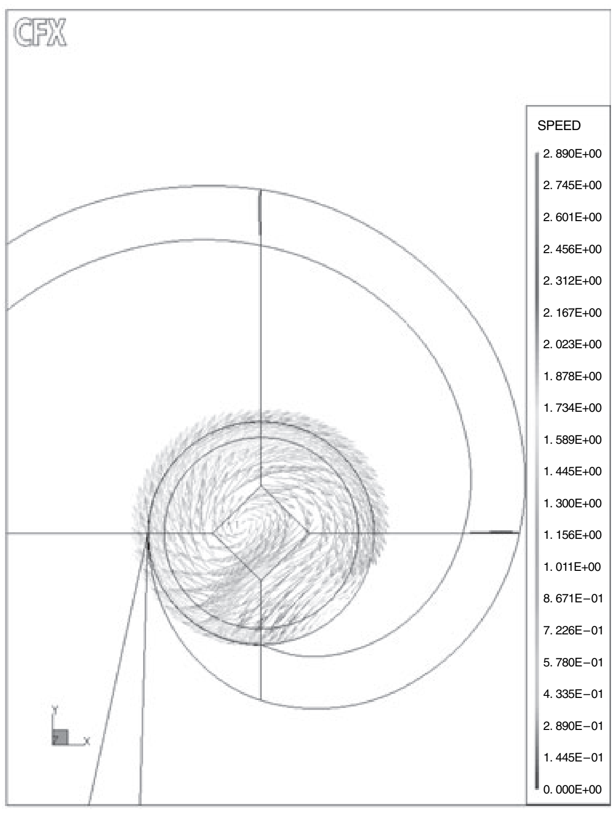

FIG. 2. The velocity profile at the outlet of the inlet volute.

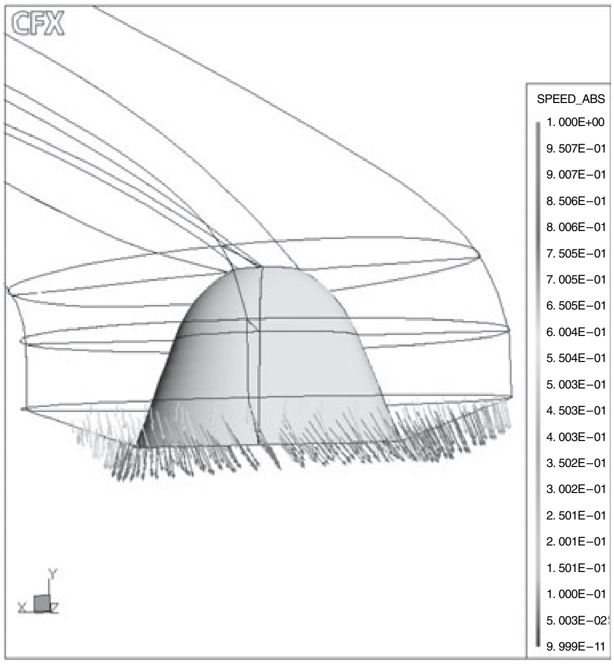

FIG. 3. The velocity profile at the outlet of the inlet elbow.

uniform distribution of flow and pressure is obtained at the outlet. Flow separation has been avoided successfully. Pressure loss is greater than for the inlet elbow, but still very small in real terms. The circumferential velocity is minimized and the swirls are almost totally removed at the feed to the impeller.

Inducer

The configuration of inducer, impeller, and diffuser has been adopted in many axial blood pumps. An inducer is not necessary for an axial blood pump, but it helps the impeller design by straightening the fluid feed. As well as straightening the flow the inducer removes prerotation of the fluid before the fluid reaches the impeller region. The design of the inducer is relatively simple, since its blades are parallel and straight axially. The number of blades is chosen to be from four to six.

OUTLET DEVICES

Exit volute

For centrifugal blood pumps, an exit volute is a necessary device to collect the flow at the trailing edge of the impeller and to convert radial velocity to tangential velocity gradually. The cross-sectional area in the exit volute is gradually increased from cut-water toward the volute nozzle to accommodate discharge along the impeller periphery. To avoid separation and losses, the volute angle at cut-water should correspond to the direction of the absolute velocity vector at the trailing edges of the impeller blade.

The design of the exit volute preferably starts with the calculation of the area of the throat. The calculation of the throat area can be aided by initially assuming a throat velocity. There are some theoretical or empirical references for different sizes and pump speeds (4). The minimum gap between the exit volute and the impeller exists at the cut-water. If this gap is too small, the impeller could touch the exit volute while spinning, and so the pump may become noisy and the efficiency may be impaired. On the other hand, an unnecessarily large gap reduces the pump optimum efficiency as extra power is required to circulate the fluid through the gap between the cut-water and the impeller. Once the diameters of the cut-water and the throat are decided, a gradually expanding base circle can be drawn. Figure 5 shows the geometry and velocity profile of the exit volute that is used in the HeartQuest CF4b. The next part after the throat is an area-diverging pipe, in which the diverging angle can be taken from 6° to 10°, in order to further slow down the speed and increase the pressure.

The exit volute causes radial thrust (4), small at the design point but increasing at larger or smaller capacities. Radial thrust is an important parameter for the design and lifetime of all kinds of bearings for rotary blood pumps, including magnetic, mechanical, and hydrodynamic bearings.

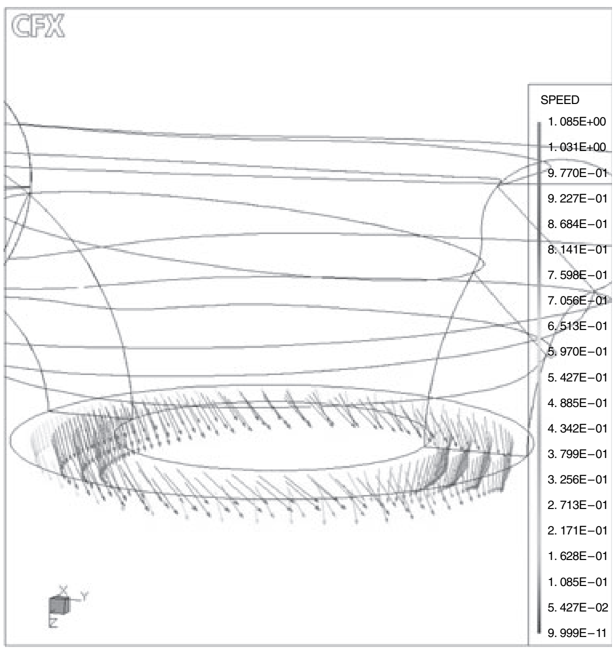

FIG. 4. The velocity profile at the outlet of the flat inlet elbow.

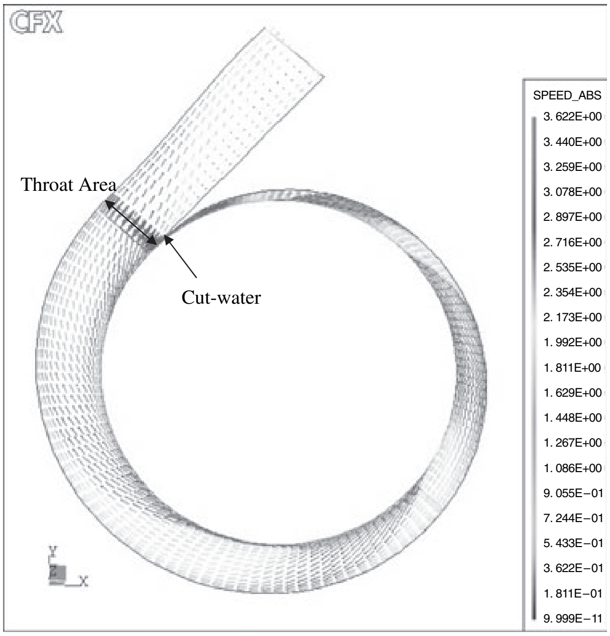

FIG. 5. Velocity profile in the exit volute.

Diffuser

The purpose of the diffuser is to convert the tangential component of the absolute velocity into pressure. This is accomplished by straightening the flow as it leaves the pump and by reducing the velocity. The diffuser blade curvature is selected so that the fluid enters the diffuser with a minimum loss and leaves the pump axially. At the interface between the impeller and the diffuser, the blade angle at the leading edges of the diffuser blades is adjusted so that the flow is tangential to the shape of the diffuser blade. The value of the blade angle decreases until all the tangential component of velocity is taken out of the flow. In addition to the reduction of the tangential velocity component, the axial velocity component is also reduced by increasing the cross-sectional area along the flow direction.

The number of blades in the diffuser varies from five to eight, a smaller number of blades being used for smaller pumps. From the point of view of fluid dynamics, more blades in the diffuser would be helpful to constrain the fluid and therefore to avoid flow separation and vortexes, but more blades may increase the head loss. Also, they increase the possibilities for structural failure and difficulties of manufacture. A comparison between three and six blades has been plotted in Figs. 6 and 7. The six-blade diffuser has a smoother fluid field than the three-blade diffuser. The pressure gain is larger in the six-blade diffuser, since it successfully avoids abnormal flow patterns, such as recirculation and separation, which waste energy.

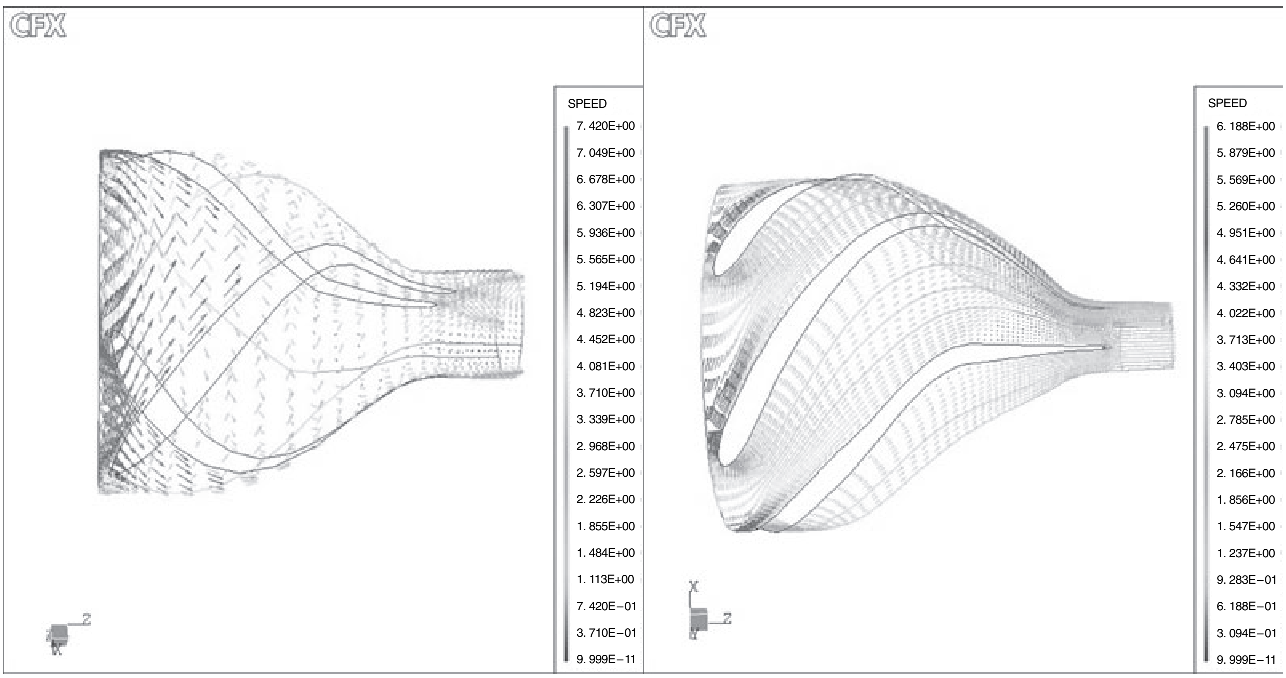

FIG. 6. The comparison of velocity profile in diffusers with different blade numbers.

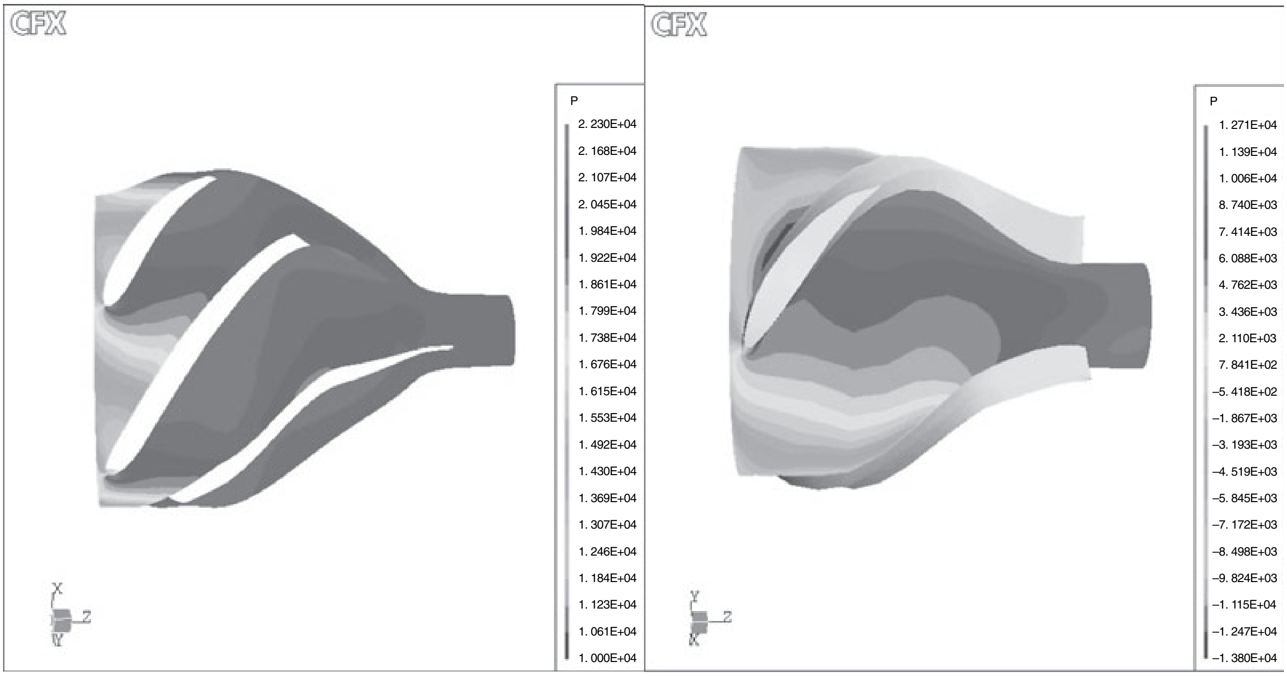

FIG. 7. The comparison of pressure distribution in diffusers with different blade numbers.

CANNULAS

There are always inlet and outlet cannulas as accessories to blood pumps. The inlet cannula is attached to a sewing cuff that is sutured into a coring punch at the apex of left ventricle. The outlet cannula connects the blood pump to the ascending aorta where a coated vascular graft section of the cannula is trimmed to length and sewn in place via an end-to-side anastomosis. An acute bend angle may result in stagnant flow regions and recirculation (5).

TABLE 1. *Design guidelines for inlet and outlet devices*

Device	Functions	Concerns
Cannula	Connect the pump to left ventricle and aorta	Stagnation and recirculation
Inducer/ Inlet volute/ Inlet elbow	Guide the flow to impeller Provide uniform and straight flow	Nonuniform flow distribution High stress Whirl
Exit volute	Collect flow Decelerate spinning velocity	Flow separation Energy lost
Diffuser	Convert velocity to pressure	Head lost Flow separation and whirl

CONCLUSIONS

Flow patterns have been investigated and analyzed in the inlet and outlet devices of rotary blood pumps by means of CFD simulations. Flow irregularities have been studied in order to optimize the geometry and configuration of these devices. Issues of inlet and outlet device design are discussed and guidelines and main concerns are summarized in Table 1.

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