한국동력기계공학회지 제10권 제4호 pp.153~158 2006년 11월

Estimation of Blood Flow in a Double Output Centrifugal Blood Pump
원심 혈액 펌프에서의 혈액의 흐름 평가

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Key Words : Centrifugal blood pump(원심 혈액 펌프), Computational fluid dynamics(CFD), Leakage flow (누혈량), BiVentricular Assist Device(BVAD), Thrombosis(혈전증)

Abstract : 최근 임상용 LVAD의 계속된 발전으로 인해 환자들의 삶이 연장되었다. 그러나 LVAD가 환자의 삶을 연장하였지만, 우심실 심부전증을 야기 시켰고, 결론적으로 환자들은 RVAD가 필요하게 되었다. 이러한 이유로 장시간 사용할 수 있는 BVAD의 도입이 요구 되어졌다. 최근 BVAD에 관련된 연구들을 보면 장시간 사용을 위한 원심 BVAD의 디자인과 BVAD에서의 누수 정도를 파악하는데 목적을 두고 있다. 따라서 본 논문에서는 BVAD의 누수를 파악하기 위한 속도 데이터와 용적당 흐름 비율의 계산을 CFD를 사용하여 해석적으로 조사하고자 하였다. CFD의 해석 결과 틈새부위의 회전수가 증가 할수록 혈액의 흐름을 방해하는 역류가 증가하고, 유량도 줄어들어, 틈새부위의 누수량이 회전속도의 변화에 의존된다는 것을 확인 할 수 있었다.

1. Introduction

Currently, implantable LVAD using centrifugal blood pumps are being developed and are seeing clinical use in many institutions, but LVAD implantation may cause liver dysfunction and multiple organ failure. To prevent liver dysfunction and multiple organ failure, maintaining the central venous pressure as low as possible is imperative. Early right ventricular assist device (RVAD) implantation has been shown to decrease right-sided pressure, alleviate liver congestion, although it is difficult to predict whether the patient requiring a LVAD will also need a RVAD[1]. Therefore, an implantable BVAD should be developed to deal with longer term bridging to transplantation. The current research focus is in the development of a BVAD.

Mock circulation loop[2),3)] (Fig. 1) and scaled-up centrifugal VAD[4)] (Fig. 2) have been developed in our laboratory.

Many current mock circulation systems concentrate solely on left ventricular assist device evaluation, and may not incorporate pulsatile flow. However, this mock circulation loop was developed to imitate the needed features of the systemic and pulmonic circulatory systems, designed to function under the conditions of rest, exercise and heart failure. This rig provides the ability to estimate the hemodynamic effect of LVAD, RVAD, and BVAD in vitro.

The scaled-up centrifugal VAD provided valuable insight into the internal flow patterns within the centrifugal blood pump design. In the development of centrifugal VADs for medium term use, perhaps longer then 6 months, it is especially important to eliminate blood stagnation at the back gap of the impeller [5),6)]. Flow stagnation

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접수일 : 2006년 10월 13일, 채택확정 : 2006년 11월 9일

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within the gap region between the rotating impeller and casing may lead to thrombus formation.

To overcome stagnation of secondary flow, certain centrifugal blood pumps have washout holes located in the impeller to generate circulatory blood flow inside the pump5),7). However, excessive leakage flow will lead to low pump efficiency8).

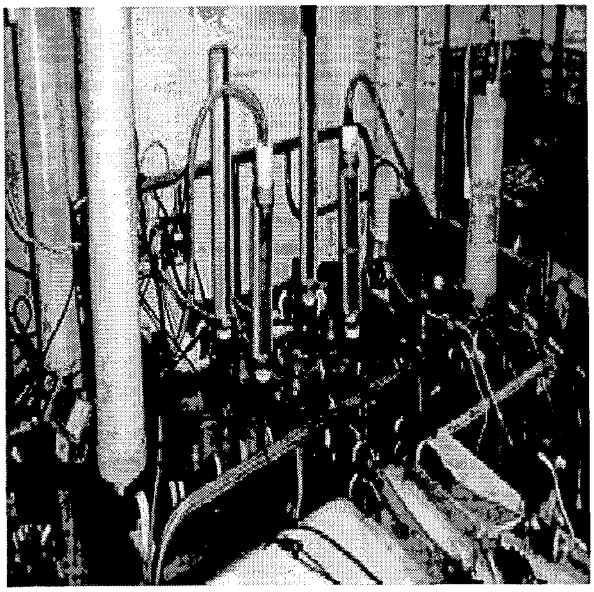


Fig. 1 Systemic and pulmonary mock circulation loop

The flow behaviour in the narrow clearance of BVAD can be analysed through experimental technique, but the flow field occurs in a small area and constructing the entire flow field requires a lot of time, although the results are reasonably reliable9).

A computational Fluid dynamics(CFD) provides an effective method in order to investigate the geometric parameters of the newly developed pump and possible thrombus formation sites10).

The objective of the preliminary study is to predict volumetric flow rates and velocity profiles in the gap region of BVAD at different rotational speed. A new BVAD design is presented to relate the leakage flow in the gap with the pump geometry shown in Fig. 2. A functional relationship of the leakage flow in terms of the rotational speed can help to predict the leakage flow rate at other operating conditions.

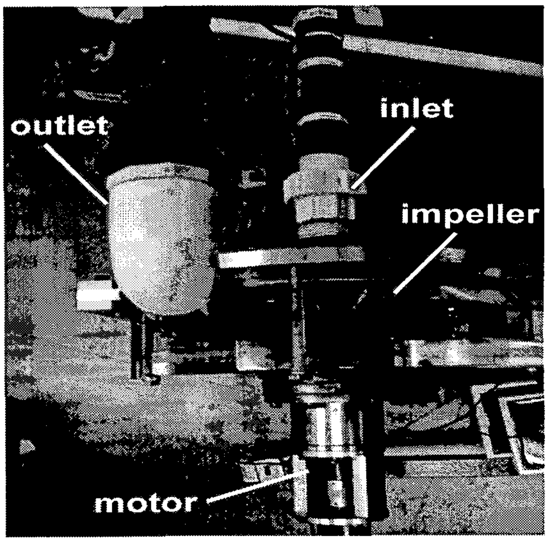


Fig. 2 Scaled-up centrifugal VAD

2. Materials and Method

2.1 Pump Structure

The current technique used to address biventricular assistance involves the implantation and operation of two separate pumps. This results in increased size and control complexity arising from the need to control two independent pumps for left and right assistance. Hence the pump shown in Fig. 3 has a single rotational speed and the difference in pressure is achieved by incorporating different impeller vane diameters and profiles on the left and right sides. To obtain low thrombogenicity, the design should avoid low flow areas as they typically appear at critical regions in terms of washout and risk of thrombus formation. Therefore, suitable flow patterns have to be generated within the BVAD11).

The double-sided impeller configuration also eliminates areas of low flow or stagnation often found beneath conventional single-sided centrifugal blood pumps, significantly reducing the potential for thromboembolic events12).

This article attempts to model leakage flow path between the rotating impeller and stationary housing. Leakage flow is due to pressure difference fluid leaving the impeller trailing edge of a LVAD and returning to a RVAD via the leakage flow path.

The pump specifications are shown in Table 1 and Fig. 3 shows the schematic view of a BVAD.

The gap between impeller hub and the pump casing is fundamental importance to determine the flow structure within the gap. In addition, the bigger gap may lead low thrombus formation. However, the gap is also maintained as small as possible so that the power required to drive the impeller can be kept to a minimum, and pump efficiency should be a maximum. The initial radial and axial clearance was selected as 0.5 *mm* for the preliminary result.

Table 1 Design constants for the Bi-VAD, magnetic-suspension blood pump

	LVAD	RVAD
Parameter	Design values	
Design pump Head	H = 100 mmHg (13.3 kPa)	H = 20mmHg (2.66 kPa)
Design flow rate	Q = 5 L/min	Q = 5 L/min
Impeller diameter	D = 50 mm	D = 22.5 mm
Design impeller speed	N = 1,800~2,200	N = 1,800~2,200
Number of vanes	n = 6	n = 6
Impeller /casing gap	0.5 mm	0.5 mm

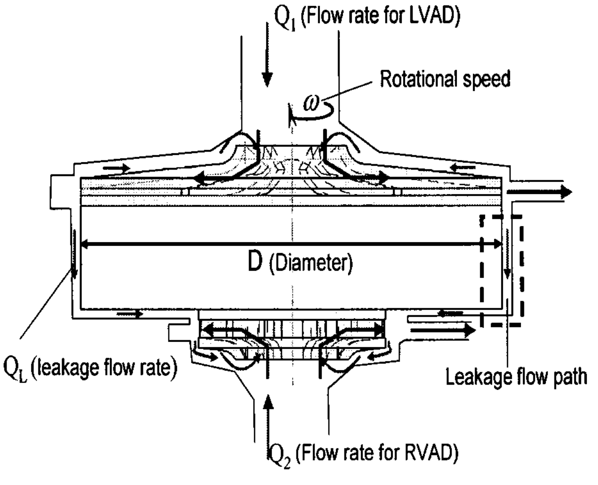


Fig. 3 The schematic of the BVAD and the passage of the washout flow

2.2 CFD model

With centrifugal blood pumps, design of the impeller suspension system is as important as the impeller design in order to avoid thrombus formation[13]. The CFD model therefore consisted of the region around the gap between the impeller hub and the pump housing. The simplified model contains a rotating wall, which has angular velocity ω, and a stationary wall. The walls have an inner radius and an outer radius. They are separated by a distance h. The pump driving condition are a flow rate of 5 l/min and supply pressures of 100 and 20 *mmHg* for the LVAD and RVAD, respectively. Therefore, a pressure difference is 80 *mmHg* between the volute of the LVAD and RVAD. The CFD model was generated using GAMBIT, and the model contained about 160,000 cells. For calculation of the flow field, the commercial CFD code FLUENT was employed to solve the Reynold-averaged Navier-Stokes equations. In this study, blood was assumed to be Newtonian with a viscosity of 0.0036 *Pas* and a density of 1059 kg/m^3[10]. In addition, the blood through the pump was assumed to be steady state. No-slip condition was applied to the walls. Furthermore, maximum $Re_{gap} = \omega r d/v$ turn out to be 863.9 at rotational speed 2200 *rpm*(where r is the radius, ω is the rotating speed of the impeller, d is the width of the gap, and ν is the kinematics viscosity). Since this value was smaller then 1500, the flow was thus assumed to be laminar in the gap[14,15,16].

2.3 Data analyses

One of the new features of the Bi-VAD model is leakage flow path between an impeller hub and the pump housing. Enhancement of washout effect due to pressure difference generated between LVAD and RVAD. A schematic diagram of the flow path is shown in Fig. 4.

The main focus of this study was to assess the effects of variations in impeller rotational speed on the leakage flow, thus, volumetric flow rates and velocity profiles in the gap region was analysed at 1800 *rpm*, 2000 *rpm*, and 2200 *rpm*.

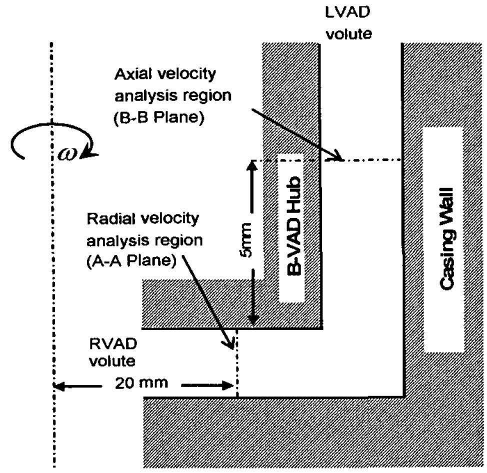


Fig. 4 Enlarged leakage flow path.

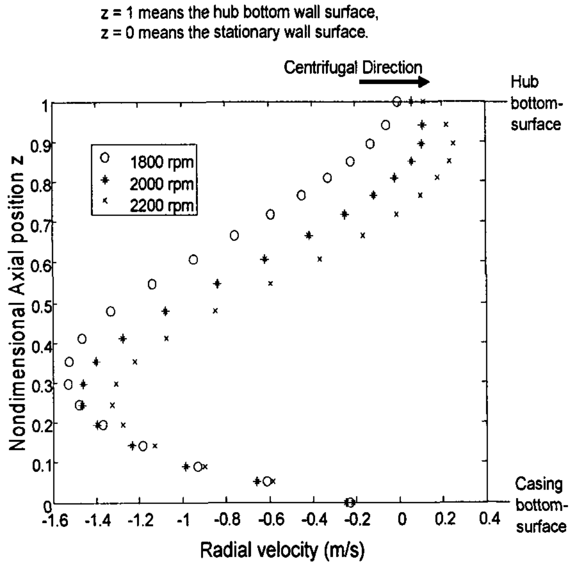
3. Results and Discussion

3.1 Velocity distribution / Leakage flow rates

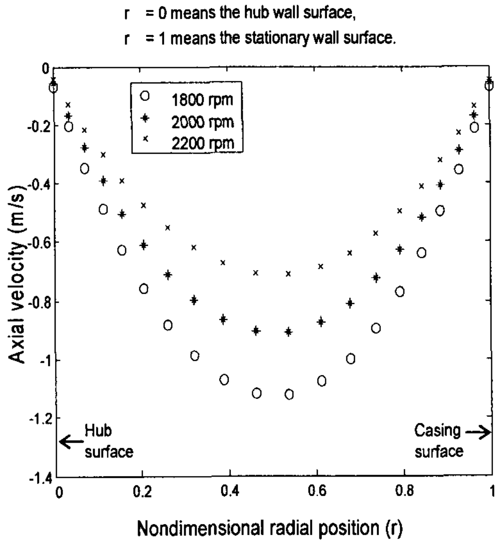
Fig. 5 presents radial and axial velocity distributions plotted as a function of the gap distance at leakage flow path. Velocity profiles against different rotational speeds. The values of the radial velocity component were about -1.5 *m/s*near the housing and about 0.1 *m/s* near the impeller at A-A plane under 2000 *rpm*. Within the axial clearance, there are 2 major opposing forces present. The pressure differential between a LVAD and a RVAD tries to push the blood from the LVAD to the RVAD while the hub surface of RVAD rotating effect tries to push the blood toward the outer radius.

In the plane close to the rotating hub surface of RVAD, the centrifugal effect is predominant. This causes an outward velocity near the hub surface. By contrast, the pressure difference drives the flow inward at near the stationary casing surface.

To have a good washout it is essential to have relative motion between fluid particles and the rotating hub surface, and that flow reversals be avoided[17]. The most important concern on the gap between the impeller hub and the pump housing is the secondary flow should be enough to avoid blood coagulation or thrombus formation[18]. If the inertia factor is large, flow reversal, due to centrifugal forces, occurs at the rotating hub surface of the BVAD; a lower inertia factor is a sign that the pump is more efficient in ensuring a better washout[8].



(a) Radial velocity distribution(A-A plane)



(b) Axial velocity distribution (B-B plane)

Fig. 5 Velocity distribution in the leakage flow path.

The volumetric leakage flow rates through the leakage flow path under different rotational speeds are presented in Fig. 5 (b). The flow rate through the leakage flow path depends on the variation in rotational speed because high rotational speed increase flow reversals which may block blood flow in flow path. Therefore, the flow rate decreases as the rotational speed increases. The ratio of leakage flow and inlet flow rate is presented in Fig. 6.

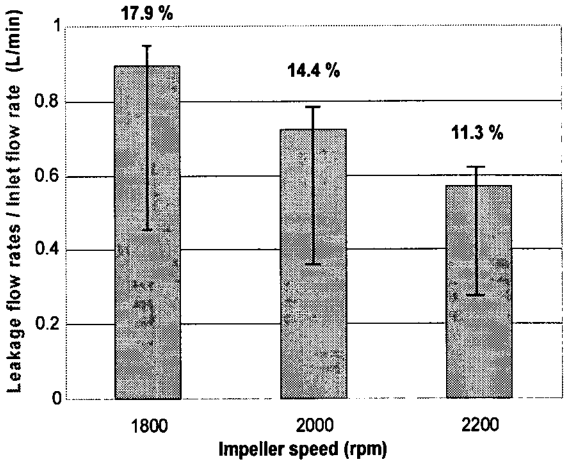


Fig. 6 Ratio of Leakage flow and inlet flow rate.

4. Conclusion

In this article, numerical analysis is used to determine the functional relationship between leakage flow rate and rotational speed. It was found that the leakage flow rate varies almost linearly with the rotational speed. The CFD analysis was carried out to analyse the secondary flow in terms of velocity profiles and flow rates through the narrow clearance region.

The volumetric leakage flow rate was found to be approximately 14.4 % of the inlet flow at 2000 *rpm*. The leakage flow path is designed to provide a washout mechanism that reduces the recirculation duration of the blood in the gap between impeller hub and casing for a double output centrifugal artificial heart pump for use as a BVAD.

The present numerical calculations of leakage flow have revealed that leakage flow rate of the BVAD is dependent on the rotational speed, and a low inertia factor of is more efficient in ensuring a better washout. In order to achieve a good washout effect and establish anti-thrombogenicity, it is necessary that the operating speed should decrease in the magnetically suspended BVAD blood pump system.

Acknowledgement

This is supported by Second-phase Brain Korea 21 project and New University for Regional Innovation project in 2006 years.

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