NASA Technical Memorandum 107463

Flow Analysis of the Cleveland Clinic Centrifugal Pump

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Prepared for the
43rd Annual Conference
sponsored by the American Society for Artificial Internal Organs
Atlanta, Georgia, May 1–3, 1997

National Aeronautics and
Space Administration

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Abstract:
An implantable ventricular assist blood pump is being developed by the Cleveland Clinic Foundation in cooperation with the NASA Lewis Research Center. At the nominal design condition, the pump provides blood flow at the rate of 5 liters per minute at a pressure rise of 100 mm of mercury and a rotation speed of 3000 RPM. Bench testing of the centrifugal pump in a water/glycerin mixture has provided flow and pressure data at several rotative speeds. A one-dimensional empirical based pump flow analysis computer code developed at NASA Lewis Research Center has been used in the design process to simulate the flow in the primary radial pump stage. The computer model was used to size key impeller and volute geometric parameters that influence pressure rise and flow. Input requirements to the computer model include a simple representation of the pump geometry. The model estimates the flow conditions at the design and at off-design operating conditions at the impeller leading and trailing edges and the volute inlet and exit. The output from the computer model is compared to flow and pressure data obtained from bench testing.

Introduction:
The Cleveland Clinic Foundation (CCF) has had a long involvement with non-pulsatile ventricular assist blood pumps (Reference 1) and is currently developing an Innovative Ventricular Assist System (IVAS), which has been previously reported in Reference 2. Continued development of the IVAS has resulted in a pump with improved performance over earlier prototypes. The cross section of the current IVAS configuration is shown in Figure 1. The new IVAS pump configuration contains a new primary impeller featuring a reduced axial height blades. The axial height of the impeller blade has been reduced from previous builds in order to increase the average velocity, and to reduce the spanwise velocity profile at the impeller exit (Figure 2). The flowpath at the impeller shroud has been modified to increase the local radius of curvature near the leading edge. The new shroud contour provides a gradual transition from axial flow near the impeller inlet, to radial flow within the blades. The blade number has been increased from six to

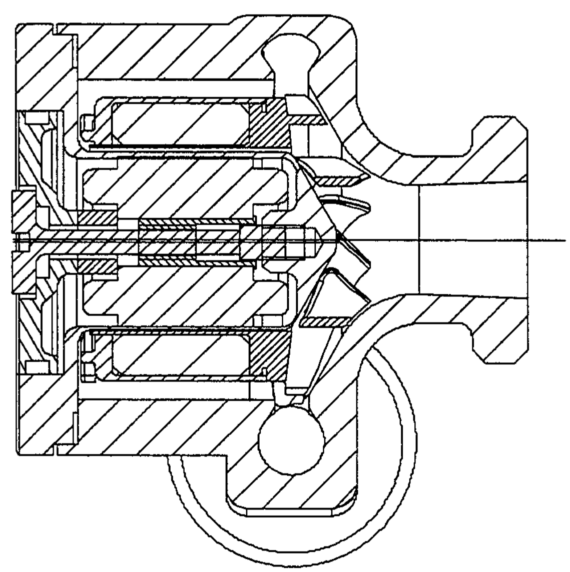

Figure 1. IVAS pump assembly featuring new primary impeller, shroud flowpath and volute.

seven blades in order to increase the work performed by the centrifugal impeller. The blade number increase reduced the flow deviation from the exit blade angle. The new impeller also features blades with reduced normal thickness.

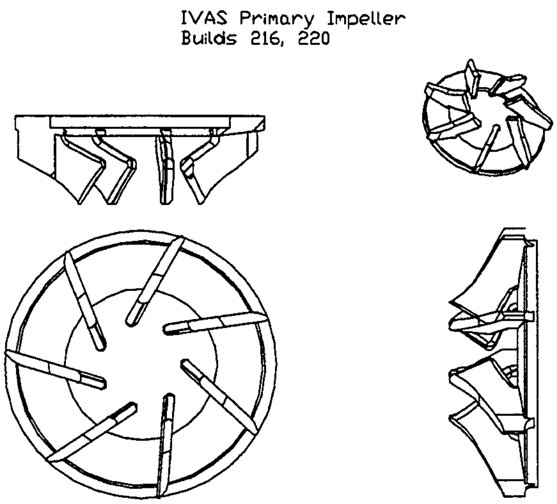

Figure 2. Centrifugal pump impeller with reduced axial height and blade thickness.

A new volute housing has also been designed to match the new impeller exit geometry. The new volute tongue, or cutwater, has been designed to have reduced levels of incidence with the flow exiting the impeller. Figure 3 shows the new volute housing with additional pressure taps located near the impeller shroud region of the housing for data taking purposes. Pressure taps number 1 to 6 are on the primary impeller inlet end of the pump at three radial locations located 180 degrees apart. Pressure taps number 7 to 10 are on the secondary impeller end of the pump at two radial locations.

Methods:

Bench testing of the current IVAS pump configuration in the water/glycerin mixture has provided flow and pressure data at several speeds.

Data from the pressure taps located within the pump housing show the radial pressure gradient in the primary and the secondary impellers at off-design flows (Figure 4). The pressure rise in the volute is greatest near the

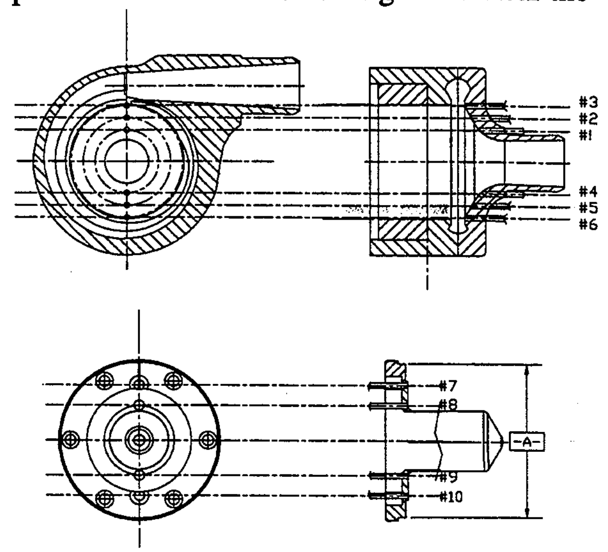

Figure 3. Pump housing with volute scroll and exit diffuser. Also shown are the pressure tap locations in the housing.

nominal design condition of 3000 RPM and 5 LPM, as can be seen in Figure 4. The highest pressure rise from the impeller exit to the volute discharge indicates that the cutwater angle and the area distribution within the volute are matched at the design operating condition.

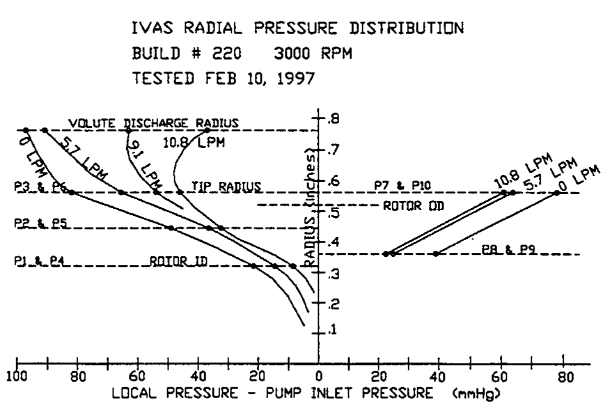

Figure 4. Test data taken at the primary and secondary impeller shrouds showing the radial pressure gradients.

To assist in the design and development process, a one-dimensional computer model was created of the pump primary impeller using the PUMPA flow code (References 3, 4, 5). The PUMPA code was developed at the NASA Lewis Research Center to provide a rapid analytical capability of pump configurations for a variety of aerospace applications. The pump code is based on the Euler equation with empirically derived values of rotor slip factor and efficiency. The code can be used to estimate the relative and absolute velocities, flow angles and static and total pressures at the rotor leading and trailing edges. It models head, flow, speed and power and creates performance maps. The map generation capabilities of the PUMPA code provides the information needed for interfacing with a concurrently developed system model.

The Innovative Ventricular Assist System (IVAS) pump is analyzed using the flow modeling code. To enable modeling the IVAS pump, the fluid properties of a mixture of glycerin and water were added to the pump code. The application of the pump code to the IVAS required a validation phase. IVAS pump test data was obtained at the Cleveland Clinic, using a water/glycerin mixture as a surrogate fluid in place of blood. Key parameters within the pump code were validated and post-test analysis of the data yielded the key parameters of slip factor (normalized value of flow deviation angle), impeller efficiency and volute loss coefficient. The pump flow model with the modified parameters matched the head-flow-speed and power maps that were obtained from laboratory testing.

The overall pump performance in Figure 5 shows the pressure rise versus flow that was achieved at 3500, 3000 and 2500 RPM for a range of flow conditions. Figure 5 also

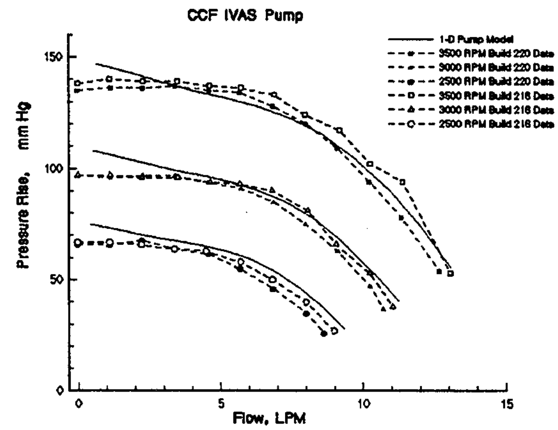

Figure 5. IVAS pump test data at 3500, 3000 and 2500 RPM, compared to values obtained from the computer flow model.

illustrates the sensitivity of the pump performance to the shroud clearance at the primary impeller face. The difference in axial running clearance between builds 216 and 220 was 0.004 inches. Varying the value of shroud clearance did not significantly affect high system efficiency.

Figure 5 also shows the comparison between the one-dimensional flow model and the test data, for a range of flow conditions at three speeds. The pump pressure rise is influenced mainly by the primary impeller, the volute and exit diffuser. The secondary impeller does not contribute significantly to the overall pressure rise, since the flow through it is relatively low, compared to the primary impeller. The flow model compares closely to the test data for most flows, except near the regions of low flow, where there is some difference between the model and the data.

The pump overall efficiency of the IVAS is shown in Figure 6. The efficiency is defined as the output hydraulic power divided by the electric power required to drive the pump. The overall efficiency includes the hydraulic losses through the primary and the secondary impellers, as well as the volute, bearing and the annular duct formed by the rotor outer diameter and the casing. Electrical losses within the motor and motor driver are also included in the overall efficiency parameter.

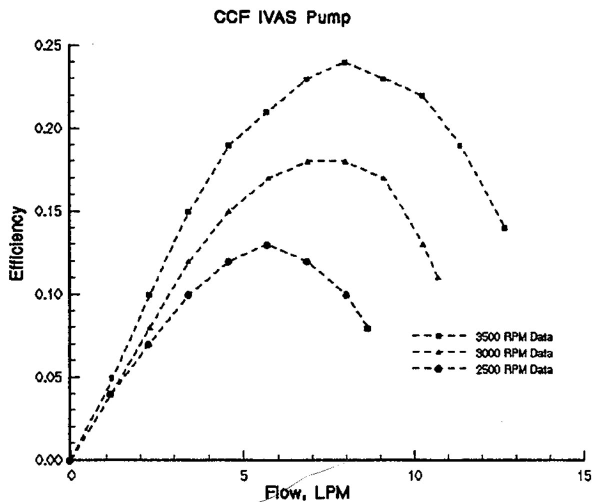

Figure 6. IVAS pump overall efficiency of pump, bearing and motor.

The input electric power required to drive the pump is shown in Figure 7.

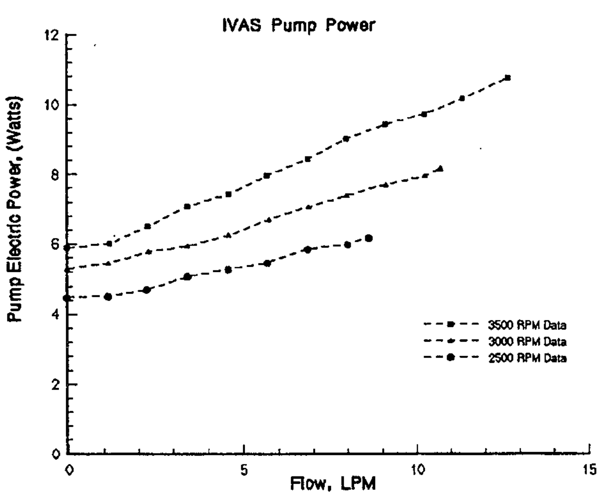

Figure 7. Electric power required to drive the IVAS pump.

Results:

The calculated values of velocity and flow angles near the impeller leading edge, during

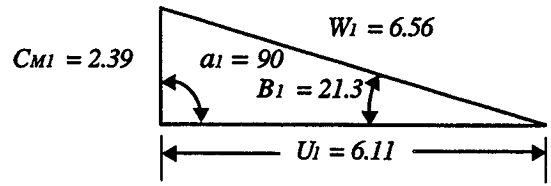

Figure 8. Absolute and relative velocities at the primary impeller leading edge, from the pump flow model.

pump operation at the nominal design point (3000 RPM and 5 LPM) are shown in Figure 8. The flow calculations are performed at the root-mean-square radius. The pump flow model is based on the prewhirl at the inlet to the impeller of zero degrees, resulting in the inlet absolute flow angle (*a*) of 90 degrees and a relative flow angle of 21.3 degrees from the tangential direction. On tests of early prototype configurations, there was evidence of prewhirl at the pump inlet. Planned large scale tests with visualization techniques will determine the impeller inlet prewhirl at a range of flow and speed conditions to confirm a reduced level of prewhirl.

The flow conditions at the impeller trailing edge were likewise calculated by the computer model. Figure 9 shows the velocities and angles as calculated by the pump flow code.

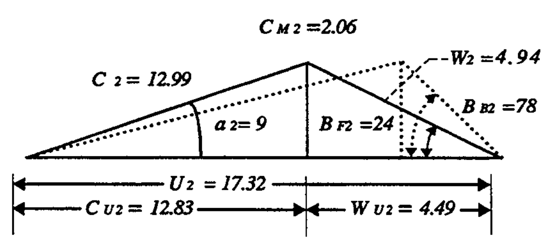

Figure 9. Absolute and relative velocities at the primary impeller trailing edge, from the pump flow model.

Discussion:

The impeller exit velocity vector triangles illustrate the difference between the ideal and the actual velocity vectors. This difference at the impeller exit results in the deviation of the flow angle (78 degrees) from the blade angle (24 degrees). There is flow deviation at the exit of all centrifugal pumps and its magnitude is influenced by key parameters such as the number of impeller blades and the exit blade angle. A reduced level of deviation has the effect of increasing the pressure rise in the pump. Future research will focus on further design improvements to the impellers, including quantifying the inlet prewhirl and reducing the levels of impeller incidence and deviation. To realize further improvements in pump performance, analysis with higher fidelity flow codes will be done at the Ohio State University College of Engineering, as well as at NASA Lewis Research Center.

Conclusion:

The hydraulic performance of the IVAS pump (build #220) has been characterized by bench testing with a water/glycerin mixture in a laboratory environment. The present pump configuration has met the performance design goals established by the Cleveland Clinic Foundation and the data has confirmed the computer flow model of the primary impeller, as well as the match between the impeller and volute.

Acknowledgments:

Funding for the IVAS program has been provided by the National Institute of Health, and the National Heart, Lung and Blood Institute under NIH contract NHLBI-HV-94-25. Support for the work at NASA Lewis Research Center has also been provided by the High Performance Computing and Communication Program (HPCCP). The success of the IVAS program can be attributed to the efforts of all the members of the IVAS design team which also includes the Ohio State University College of Engineering, Mechanical Technologies Incorporated, Smith & Nephew Richards and the Ohio Aerospace Institute (References 6, 7).

Symbols:

a = Flow angle in absolute frame of reference, degrees
B = Flow angle in relative frame of reference, degrees
C = Fluid velocity in absolute frame of reference, ft/sec
U = Blade tangential velocity, ft/sec
W = Fluid velocity relative to the blade, ft/sec
Deviation = Blade angle (B_{B2}) - flow angle (B_{F2})
RPM = rotations per minute
LPM = liters per minute

Subscripts:
1 = Impeller leading edge (inlet)
2 = Impeller trailing edge, (exit)
3 = Vaneless diffuser exit
4 = Volute exit diffuser exit
U = Tangential component of velocity
M = Meridional component of velocity

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1997	Technical Memorandum

4. TITLE AND SUBTITLE

Flow Analysis of the Cleveland Clinic Centrifugul Pump

5. FUNDING NUMBERS

WU–509–10–1A

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–10749

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–107463

11. SUPPLEMENTARY NOTES

Prepared for the 43rd Annual Conference sponsored by the American Society for Artificial Internal Organs, Atlanta, Georgia, May 1–3, 1997. Joseph P. Veres, NASA Lewis Research Center; Leonard A.R. Golding, William A. Smith, David Horvath, and Alexander Medvedev, The Cleveland Clinic Foundation, Department of Biomedical Engineering, Cleveland, Ohio (work funded under IAA YI-HV-7016-02). Responsible person, Joseph P. Veres, organization code 2900, (216) 433–2436.

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Unclassified - Unlimited
Subject Category 34

This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS

Centrifugal; Pump; Flow; Analysis; Blood; Ventricular assist; Model; Volute; Water; Meanline

15. NUMBER OF PAGES

7

16. PRICE CODE

A02

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	