# Numerical Simulation of the Ultra-high-speed Low-specific-speed Impeller Pump and Application Research in Hydraulic System

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**Abstract.** The numerical simulation on total range of rotational speed of an Ultra-high-speed low-specific-speed impeller pump which can be applied to the liquid propellant rocket have been performed, obtained some outer characteristics of the impeller pump. Compared the outer characteristics from the numerical simulation with that from the experimentation on low rotational speed, the outer characteristic curves on Ultra-high-speed have been predicted. Research on the application of impeller pump in hydraulic system, analysed the working of the impeller pump and the common displacement pump in a hydraulic system.

**Keywords:** Low-specific-speed impeller pump, Ultra-high-speed, Numerical simulation, Hydraulic system.

## 1. Introduction

This research aimed at an Ultra-high-speed Low-specific-speed impeller pump which can be applied to the liquid propellant rocket, the impeller pump is often used for fluid delivery, in this research, and it works as energy source in a hydraulic system. Constructed the completed three-dimensional flow field model, the numerical simulation on total range of rotational speed have been performed by CFDesign, obtained the flow field distribution, come with some outer characteristics of the impeller pump, we mainly research the outer characteristics and its application in hydraulic system. The working of the impeller pump is different from the common displacement pump in hydraulic system, the working of both pumps in a hydraulic system were analysed.

## 2. Modeling and the numerical simulation

### 2.1. Description and modeling

The impeller of the Ultra-high-speed Low-specific-speed impeller pump is shown in Fig 1.a, according to the definition in reference [1], this pump is a mixed-flow pump with fully open impeller. Its maximum working speed of revolution is 150000r/min, the working pressure is 28MPa, the working flow rate is 200L/min, to perform the unit conversion, the working flow rate is 12m3/h, the pump head (transfer to water medium) is 2427.6m, and the specific speed is 60. On the base of these specifications, it is called as the Ultra-high-speed low-specific-speed impeller pump, the impeller pump for short.
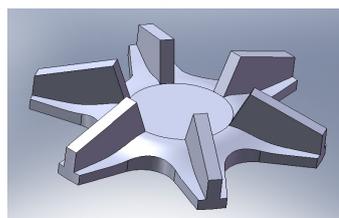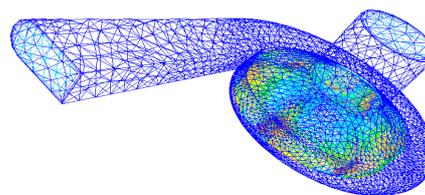


a. The impeller                        b. Completed flow field model

Fig. 1: Structure and flow field model of the impeller pump.

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In this research, we constructed the three-dimensional model for each part of the impeller pump by SolidWorks, after some necessary Boolean operation, deduced the whole flow field model from the impeller pump inlet to the impeller pump outlet, lead the model to CFdesign for numerical simulation. In CFdesign, the mesh is constructed by the non-structure tetrahedron, the meshed flow field model is shown in Fig 1.b, and there are 86209 cells, 28369 nodes.

## 2.2. The numerical simulation

The condition of the impeller pump inlet: the fluid direction is perpendicular to the inlet end plane, and the inlet gauge pressure is zero. The condition of the impeller pump outlet: the fluid direction is perpendicular to the outlet end plane, and the outlet gauge pressure is zero. Set the outlet gauge pressure is zero, which means the liquid from the impeller pump outlet to the atmosphere directly, this flow rate is the maximum flow rate on this rotational speed, it is called the idle flow rate. Set the outlet gauge pressure is a certain value, which means there is a certain load on the impeller pump outlet, the flow rate of pump will decrease. Set the discharged flow rate is zero, the outlet gauge pressure can be simulated, this pressure is the maximum pressure on this rotational speed, and it is called the shut off head.

The velocity and the pressure field distribution of pump on all working conditions under the rotational speed of 150000r/min have been obtained, come with the shut off head, the idle flow rate, and the pressure-flow curve. The rotational speed 20000r/min can be reached easily in the testing, to revise the simulation result under 150000r/min, we can deduce the predictive outer characteristic.

## 3. Research of the outer characteristic

### 3.1. The shut off head curve

The shut off head curves under 20000r/min are shown in Fig 2.a, the solid line is the numerical simulation result, and the dashed line is the testing result. The shut off head curves under 150000r/min are shown in Fig 2.b, the solid line is the numerical simulation result, and the dashed line is the predictive result.

In Fig 2.a, there have parabolic relation between the shut off head of numerical simulation and the impeller pump rotational speed, it is $P'_{close} \propto n^2$, of which, $P'_{close}$ is the numerical simulation head, $n$ is the impeller pump rotational speed. To fitting the numerical simulation curve under 20000r/min:

$$P'_{close} = 0.0026n^2 \qquad (1)$$

In this formula, $P'_{close}$ is the shut off head of numerical simulation, MPa. $n$ is the impeller pump rotational speed, 1000r/min.



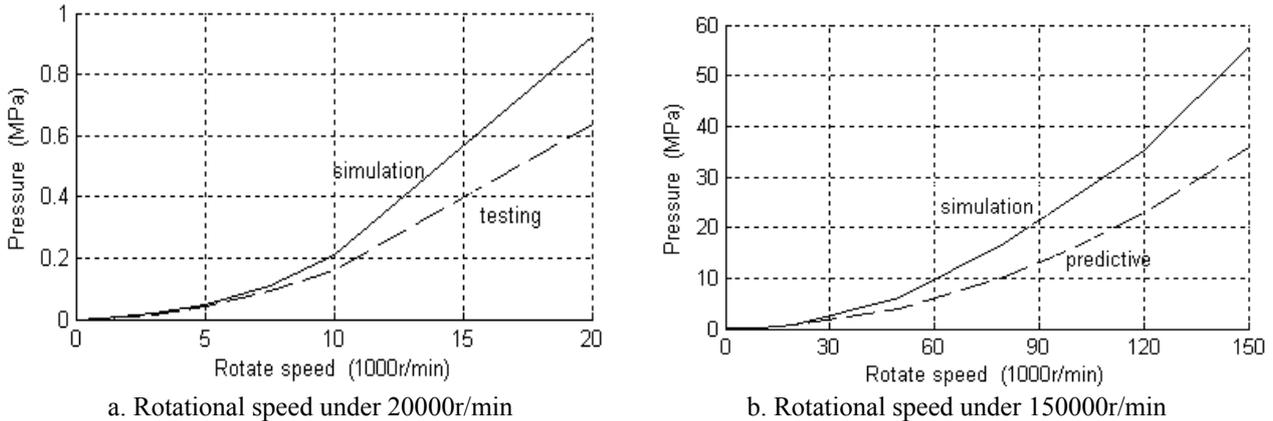a. Rotational speed under 20000r/min        b. Rotational speed under 150000r/min

Fig. 2: Shut off head curves.

According to centrifugal pump theory[2-3], there have parabolic relation between the shut off head and the impeller pump rotational speed, same as numerical simulation under 150000r/min in Fig 2.b. The testing result of shut off head under 20000r/min is lower than the numerical simulation result in Fig 2.a, to fitting the testing result of shut off head:

$$P_{close} = 0.0016n^2 \qquad (2)$$

In this formula, $P_{close}$ is the testing result of shut off head, MPa. $n$ is the impeller pump rotational speed, 1000r/min.

Comparing the formula (1) and (2), the numerical simulation result is higher. These two formulas are base on numerical simulation and testing, they are decided by pump structure, and they are not general formula. According to formula (2) and the simulation result in Fig 2.b, we can deduce the predictive shut off head curve under 150000r/min, the dashed line in Fig 2.b, the shut off head on 150000r/min is 36MPa.

## 3.2. The idle flow curve

The idle flow curves under 20000r/min are shown in Fig 3.a, the solid line is the numerical simulation result, and the dashed line is the testing result. The idle flow curves under 150000r/min are shown in Fig 3.b, the solid line is the numerical simulation result, and the dashed line is the predictive result.

In Fig 3.a, there have proportion relation between the idle flow rate of numerical simulation and pump rotational speed, it is $Q'_{free} \propto n$, of which, $Q'_{free}$ is the numerical simulation flow rate, $n$ is the impeller pump rotational speed. To fitting the numerical simulation curve under 20000r/min:

$$Q'_{free} = 10n \qquad (3)$$

In this formula, $Q'_{free}$ is the idle flow rate of numerical simulation, MPa. $n$ is the impeller pump rotational speed, 1000r/min.

According to centrifugal pump theory[2-3], there have proportion relation between the idle flow rate and the impeller pump rotational speed, same as numerical simulation under 150000r/min in Fig 3.b. The testing result of idle flow rate under 20000r/min is lower than the numerical simulation result in Fig 3.a, to fitting the testing result of idle flow rate:

$$Q_{free} = 6n \qquad (4)$$

In this formula, $Q_{free}$ is the testing result of idle flow rate, MPa. $n$ is the impeller pump rotational speed, 1000r/min.
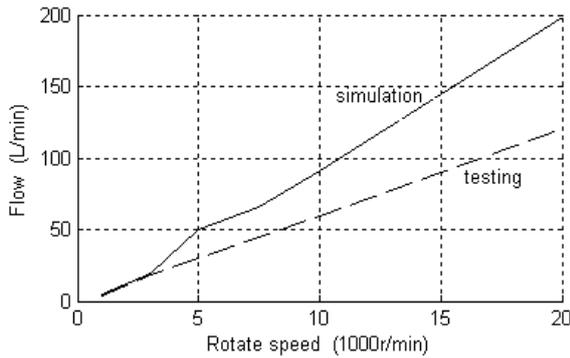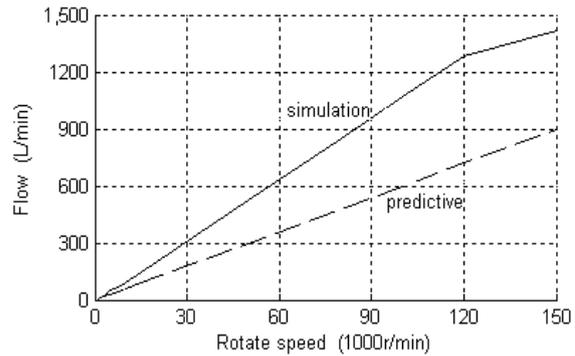


a. Rotational speed under 20000r/min        b. Rotational speed under 150000r/min

Fig. 3: Idle flow curves.

Comparing the formula (3) and (4), the numerical simulation is higher, same as formula (1) and (2). According to formula (4) and the simulation result in Fig 3.b, we can deduce the predictive idle flow curve under 150000r/min, the dashed line in Fig 3.b, the idle flow rate on 150000r/min is 900L/min.

## 3.3. The pressure-flow curve

The pressure-flow curve is the main outer characteristic of the impeller pump[2-3]. In the domain of fluid machine, the pump always works on rated speed, or the rotational speed changes a little, only need to research the pressure-flow curve on a certain rotational speed. In this research, the rotational speed changes in a wide range, we need to run the numerical simulation on many rotational speeds. We have already obtained the shut off head and the idle flow rate, they are the starting point and end point of the pressure-flow curve along the flow axis. The pressure-flow curve and the output power curve on 10000r/min are shown in Fig 4.a, the solid line is the numerical simulation result, and the dashed line is the testing result. The pressure-flow curve and the output power on 150000r/min are shown in Fig 4.b, the solid line is the numerical simulation result, and the dashed line is the predictive result.

According to the numerical simulation pressure-flow curve on 150000r/min, and the predictive maximum pressure 36MPa on 150000r/min, and the maximum flow rate 900L/min on 150000r/min, and the formulas (2)(4), we can deduce the predictive pressure-flow curve and the predictive output power curve on 150000r/min, as shown in Fig 4.b. From the predictive curve, we can obtain the outlet pressure on a certain

flow rate on 150000r/min, such as, the outlet pressure is 32MPa correspond to the flow rate 300L/min, the outlet pressure is 33MPa correspond to the flow rate 200L/min, then, the output power can be calculated.
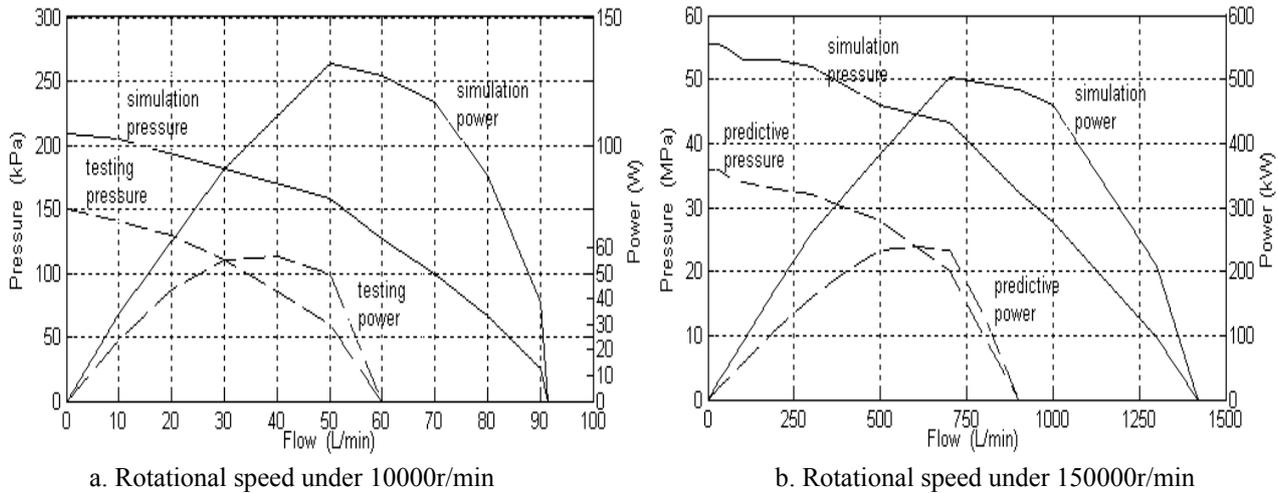


a. Rotational speed under 10000r/min          b. Rotational speed under 150000r/min

Fig. 4: Pressure-flow curves.

## 4. Application research in a hydraulic system

A hydraulic system is shown in Fig 5, two parallel servo valve work as the system load, the rated flow rate of each servo valve is 200L/min, the rated pressure is 21MPa, then, and the rated point of two valves is 400L/min, 21MPa. There is a relief valve of 25MPa which have been built in system.
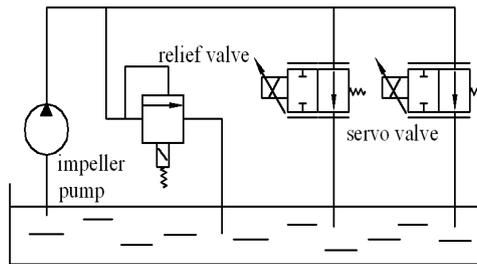


Fig. 5: Hydraulic system circuit.

The system working curves are shown in Fig 6.a. The dashed line is the pressure-flow load curve of two servo valves, the two solid lines are predictive pressure-flow curves of pump on 100000r/min and 150000r/min, the dashed dot line is the pressure-flow curve of relief valve.

As shown in Fig 6.a, when the driving rotational speed is 100000r/min, the system works on point A1, which is the intersection point of the predictive pressure-flow curve on 100000r/min and the pressure-flow load curve. If the flow rate had been disturbed, the system works on the high flow rate point E1 or the low flow rate point D1, when there is no change of the outer load and the driving speed of impeller pump, the system will come back to point A1 along with the predictive pressure-flow curve. If the rotational speed of impeller pump increase to 150000r/min, the system working point will go up along with the pressure-flow load curve, restricted by relief valve, the system will work on point C1, that is the intersection point of the relief valve pressure-flow curve and the pressure-flow load curve, if we cancel the relief valve in Fig 5, the system will work on point B1, that is the intersection point of the predictive pressure-flow curve on 150000r/min and the pressure-flow load curve.

From above analysis, under the driving speed 150000r/min, the system working point must be in the region enclosing by M1, N1, P1 and the flow axis, M1 is the intersection point of the relief valve pressure-flow curve and the pressure axis, N1 is the intersection point of the relief valve pressure-flow curve and the predictive pressure-flow curve on 150000r/min, P1 is the intersection point of the flow axis and the predictive pressure-flow curve on 150000r/min.

If we replace the impeller pump to a fixed displacement pump in Fig. 5, the system working curves are shown in Fig 6.b. The two straight lines which are perpendicular to flow axis are pressure-flow curves of fixed displacement pump on different driving speed, the pressure-flow load curve and the relief valve pressure-flow curve have no change. If the flow rate of fixed displacement pump is 300L/min, the system

will work on point A2, if the flow rate had been disturbed, the system works on the low pressure point E2 or the high pressure point D2, when there is no change of the outer load and the driving speed of impeller pump, the system will come back to point A2 along with the pressure-flow curve of 300L/min. If the driving speed of fixed displacement increase, the flow rate up to 500L/min, the system working point will go up along the pressure-flow load curve, it had been restricted by relief valve, and the system will work on point C2, the intersection point of the pump pressure-flow curve on 500L/min and the relief valve pressure-flow curve. If we cancel the relief valve in Fig 5, the system will work on point B2, which is the intersection point of the pump pressure-flow curve on 500L/min and the pressure-flow load curve. So, the system working point depend on the pressure-flow curve of fixed displacement pump and the pressure-flow load curve, but, if the system working pressure higher than the setting pressure of relief valve, the pressure-flow load curve will be replaced by the relief valve pressure-flow curve.



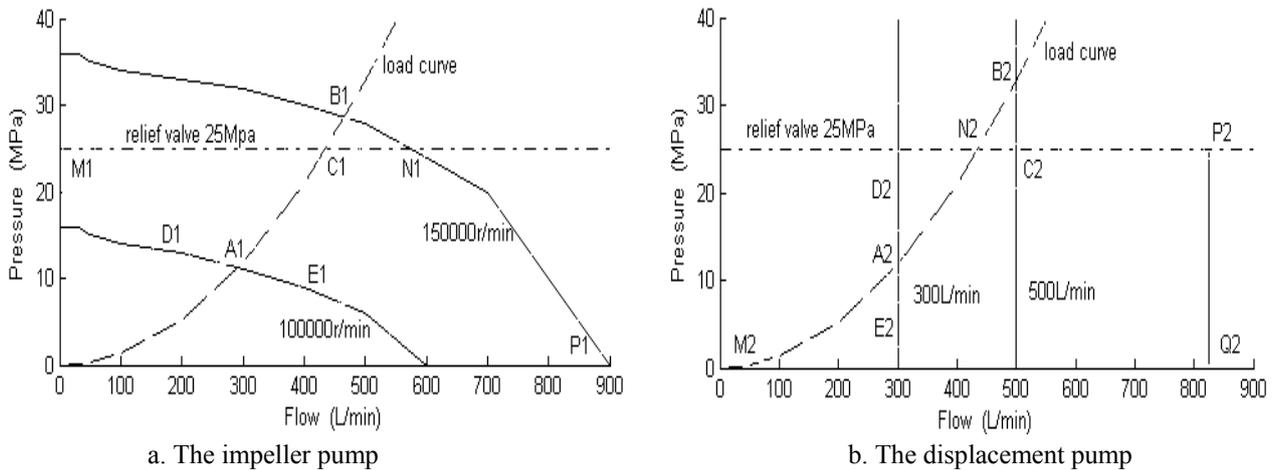a. The impeller pump      b. The displacement pump

Fig. 6: Working point of two sorts of pump.

From above analysis, under the given flow rate of the fixed displacement pump, the system working point must be in the region enclosing by M2, N2, P2,Q2 and flow axis. M2 is the starting point of the pressure-flow load curve, N2 is the intersection point of the relief valve pressure-flow curve and the pressure-flow load curve, P2 is the intersection point of pump pressure-flow curve on the highest rotational speed and the relief valve pressure-flow curve, Q2 is the intersection point of the pump pressure-flow curve on the highest rotational speed and the flow axis.

# 5. Conclusion

Research on an Ultra-high-speed Low-specific-speed impeller pump which can be applied to the liquid propellant rocket, Constructed the completed three-dimensional flow field model from the impeller pump inlet to the impeller pump outlet, obtained some outer characteristics by the numerical simulation, compared the outer characteristics from these results with that from the experimentation on low rotational speed, the outer characteristic curves on Ultra-high-speed have been predicted. Research on the application of impeller pump in hydraulic system, compared the working of impeller pump with that of the common displacement pump in a hydraulic system. This research made a foundation of the new type impeller pump designing and its application in hydraulic system.

# 6. References

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