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Numerical study of unsteady flow in centrifugal cold compressor

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Abstract

In helium refrigeration system, high-speed centrifugal cold compressor is utilized to pumped gaseous helium from saturated liquid helium tank at low temperature and low pressure for producing superfluid helium or sub-cooled helium. Stall and surge are common unsteady flow phenomena in centrifugal cold compressors which severely limit operation range and impact efficiency reliability. In order to obtain the installed range of cold compressor, unsteady flow in the case of low mass flow or high pressure ratio is investigated by the CFD. From the results of the numerical analysis, it can be deduced that the pressure ratio increases with the decrease in reduced mass flow. With the decrease of the reduced mass flow, backflow and vortex are intensified near the shroud of impeller. The unsteady flow will not only increase the flow loss, but also damage the compressor. It provided a numerical foundation of analyzing the effect of unsteady flow field and reducing the flow loss, and it is helpful for the further study and able to instruct the designing.

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Keywords: unsteady flow; centrifugal cold compressor; surge; CFX

1. Introduction

A large cryogenic helium refrigeration system is the supporting technology of advanced science and technology and is mainly composed of compressors, oil removal system, heat exchangers, turbo-expanders and control valves. With the development of accelerator technology and requirement of higher beam energy and luminosity, the

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cryogenic and superconducting technology is applied widely to the accelerator construction and lots of large helium cryogenic systems were established successively.

The large cryogenic helium refrigeration system for the Large Hadron Collider (LHC) and the International Thermonuclear Experimental Reactor (ITER) shows the highest level of the world [1, 2]. The superfluid helium with high thermal conductivity and low viscosity is ideal coolant. In the 1980's, a superfluid helium cryogenic system at 1.8 K was firstly used in the TORE SUPRA. Thereafter, CEBAF was the first accelerator project using this technology for cooling superconducting RF cavities.

The LHC project makes use of a large cryogenic capacity at 1.8 K for cooling superconducting high-field magnets. Future accelerator projects like TESLA are also based on superfluid technology [3]. The centrifugal cold compressor is the key equipment of the superfluid helium cryogenic system. The saturated helium bath is evacuated by the cold compressor, from 120 kPa (4.4 K) to 1.5 kPa (1.8 K) [4].

Generally speaking, cold compressors enter the surge region in the case of low mass flow or high pressure ratio, while they enter the choke region in the case of high mass flow or low pressure ratio[5]. Since a surge causes an intense oscillation of pressure, it is dangerous in particular.

With the development of computer technology, numerical simulation technology has become an important and effective tool for studying the internal flow of centrifugal compressor. In order to obtain the installed range of cold compressor, unsteady flow in the case of low mass flow or high pressure ratio is investigated by the ANSYS CFX.

2. CFD model of cold compressor

In order to obtain high efficiency, backward-skewed blades consisting of main and split blade were used in the impeller of the cold compressor such as shown in Fig. 1. The impeller diameter is 100 mm and the rotating speed is 44 krpm. Based on the ANSYS Workbench, a 3D design and simulation of the cold compressor was implemented. The 3D design model was accomplished by Blade-Gen and the computational grid was made by Turbo-Grid as shown in Fig. 2. The number of nodes is 300000. After that, the CFD analysis was solved by ANSYS CFX software. In the CFX, the blades, hub and shroud were defined as adiabatic walls with the appropriate rotational velocity. The boundary condition at the inlet was always set as the total pressure and total temperature and the boundary at the outlet was set at the mass flow rate accordingly. The cryogenic helium below the atmospheric pressure was used as the refrigerant gas.

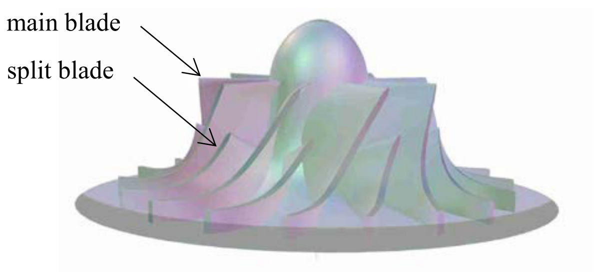

Fig. 1. Model of impeller.

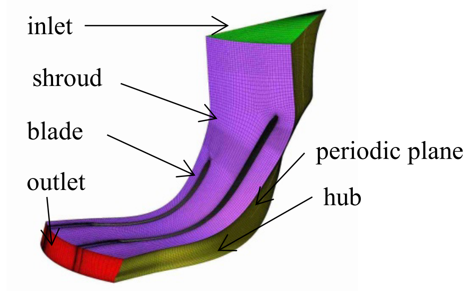

Fig. 2. Meshing of periodic channel.

3. Results and discussion

Simulation of the off-design performance of the centrifugal cold compressor was considered for six off-design reduced mass flow: 30, 40, 60, 70, 80 and 110% under the design speed 44 krpm. The reduced mass flow Mr is defined as follow:

$$Mr = \frac{M}{M_{ref}} \cdot \frac{P_{ref}}{P} \cdot \sqrt{\frac{T}{T_{ref}}}, \quad (1)$$

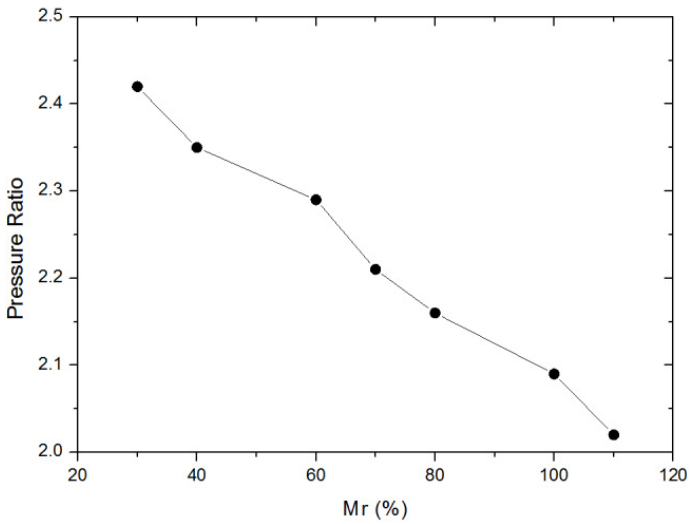

Fig. 3. Total pressure ratio of impeller under the different reduced mass flow conditions.

where M , P and T are mass flow, inlet pressure and inlet temperature of impeller and M_{ref} , P_{ref} and T_{ref} are corresponding parameters at design condition. Each cold compressor has its individual working field indicating the combination of rotating speed, mass flow, pressure ratio and suction conditions. Under the design speed, as the reduced mass flow reduces, the total pressure increase of impeller from 2.09 to 2.41 as shown in Fig. 3.

The CFD results are showing a reverse trend which is unlikely to occur in the cold compressor. When the centrifugal compressor is working in different conditions, the internal flow of impeller is different. At the design condition, the relative velocity of inlet is the same direction as the leading edge of the blade and helium stream enters the impeller passage smoothly. But when the inlet mass flow is less than the design mass flow, the helium stream enters the impeller passage at positive angles of attack and it causes flow separation on the back of the blade. Due to the inertia force, the flow separation is increased and it will not only increase the flow loss, but also damage the compressor.

The surge occurs in the centrifugal compressor at a small flow rate. Such unsteady flows which often represent the backflow and vortex are intensified near the shroud of impeller.

As shown in Fig. 4, when the reduced mass flow is reduced to 80%, backflow is produced on the back of the main blade and near the split blade. With the further decrease of mass flow, backflow and vortex continue to increase and extend to the leading edge of the blade even to the inlet of compressor.

Fig. 5 shows the vector of area averaged on meridional surface (Cm) under the different reduced mass flow conditions. When the reduced mass flow is reduced to 60%, anti-clockwise backflow is produced near the shroud of impeller. With the further decrease of mass flow, back flow is increased in the strength and influence area. The largest influence area is close to 40%.

4. Conclusion

The numerical analysis has been done to understand the effect of mass flow on the performance of the centrifugal cold compressor.

From the results of the numerical analysis, it can be deduced that the pressure ratio increases with the decrease in reduced mass flow.

With the decrease of the reduced mass flow, backflow and vortex are intensified near the shroud of impeller. The unsteady flow will not only increase the flow loss, but also damage the compressor.

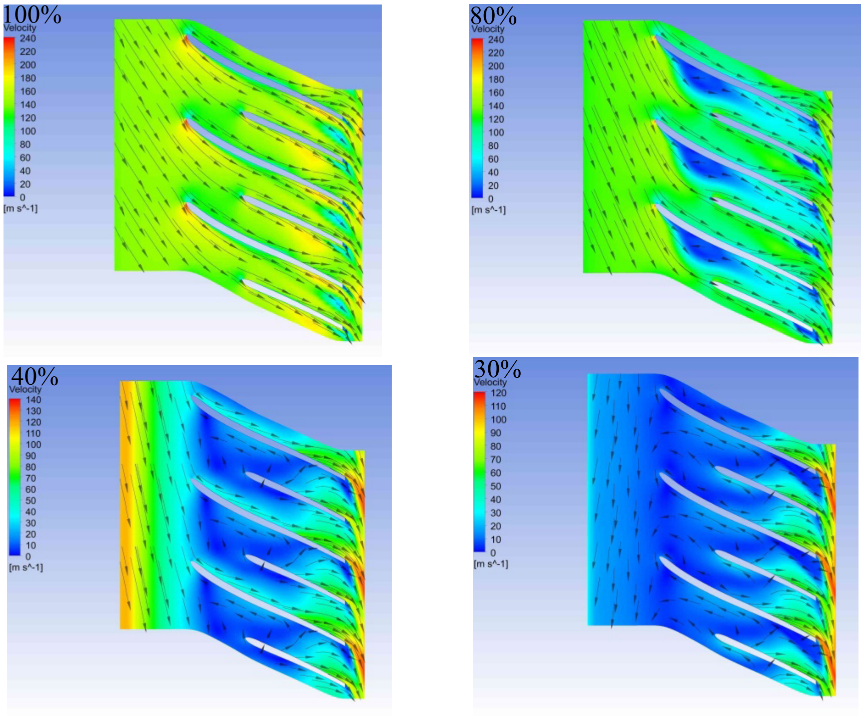

Fig. 4. Velocity vectors at 80% span under the different reduced mass flow conditions.

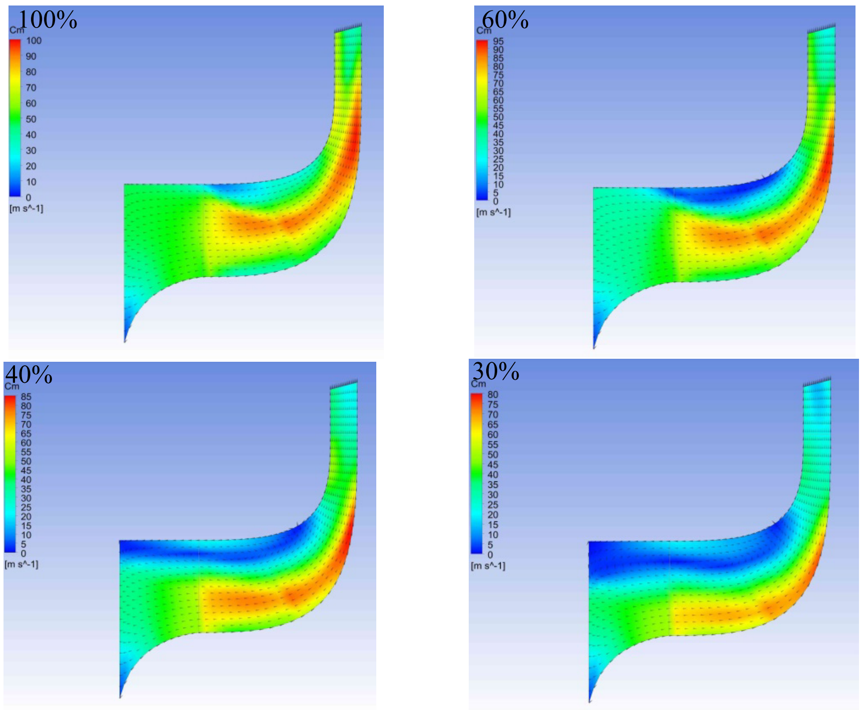

Fig. 5. Vector of area averaged on meridional surface (Cm) under the different reduced mass flow conditions.

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