Characteristics of a cryogenic supercritical hydrogen pump with dynamic gas bearings at J-PARC

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ABSTRACT

Supercritical hydrogen pump characteristics were measured at the temperatures of 21 to 95 K. The dimensionless expressions exist on the same curve independent of the operation temperature and the revolution. The peak adiabatic efficiency appears at around the discharge coefficient of 0.035. Except for it, the flange temperature excessively decreases down to a few °C and consequently the adiabatic efficiency decreases. The numerical simulation of the fluid phenomenon is carried out using a CFD code. It is clarified that the excess cooling phenomenon would be caused by the existence of flow through a narrow gap around the pump casing

INTRODUCTION

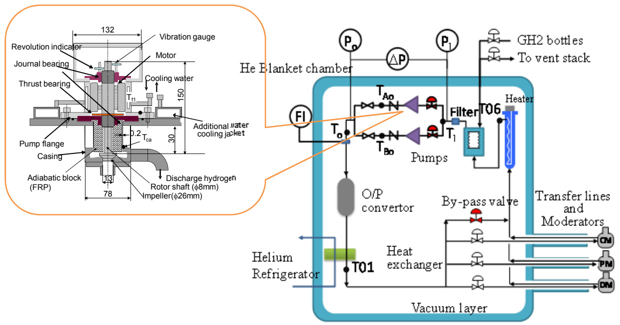
Supercritical cryogenic hydrogen is selected as a moderator material in an intense spallation neutron source (JSNS), which is as one of main experimental facilities in J-PARC.

A cryogenic hydrogen system provides supercritical hydrogen with a temperature of below20 K and a pressure of 1.5 MPa to three moderators and absorbs a nuclear heating of 3.75 kW for a 1-MW proton beam operation.

Design Conditions

- Temperature difference between the inlet and the outlet of the moderator < 3.0 K.
- Para-hydrogen concentration > 99 %.
- Supply hydrogen temperature to moderator < 20 K.
- Supply temperature fluctuation < 0.25 K.

➡ A centrifugal pump with a dynamic gas bearing was developed to circulate the supercritical hydrogen with a large-flow rate of more than 0.16 kg/s based on the supercritical helium (SHe) pump for the International Thermonuclear Experimental Reactor (ITER) project.



- Two hydrogen pumps are simultaneously operated in parallel for redundancy.
- Even if one pump goes wrong, it is possible to continue the proton beam operation just by the other.
- Two journal bearings adopt a foil-type self-acting gas dynamic bearing.
- A closed impeller made of aluminium alloy and has the diameter of 26.0 mm.
- The space around the rotor shaft in the casing is filled up by a G10 block in order to reduce the heat inleak as small as possible.
- Clearance between the G10 block and the pump casing is 0.2 mm.
- Operation revolution is 30,000 rpm to 60,000 rpm and the allowable pump head is 120 kPa.

We had a problem that the flange temperature excessively decreased to 250 K, unlike the SHe pump in 2008. As measures against it, the cooling water for the induction motor is used in order to maintain the flange temperature to be more than 0°C, because an O-ring seal, a journal bearing and a thrust bearing exist on the same level of the flange.

In this study,

- Characteristics of the dynamic gas bearing pump were measured at the pressure of 1.5 MPa and the temperatures of not only 21 K but also 46 K and 95 K during the cool-down process.
- Fluid flow phenomenon was analysed using a CFD code to clarify the excess cooling phenomenon.

EXPERIMENTAL METHOD

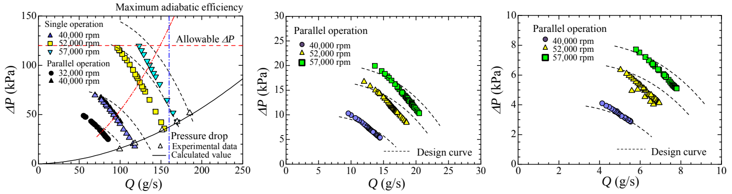
- Pressure difference between before-and-after the parallel arrangement is measured by a differential pressure transmitter and is regarded as a pump head, ΔP.
- Pressure drops through the valve and pipe have negligible effects on ΔP, because they are estimated to be below3.1 %.
- Discharge flow rate, Q, is measured by an orifice flow-meter with b = 0.62 located at the downstream of the pumps.

In this study, the pump head and the discharge flow rate were measured at the pressure of 1.5 MPa and the operation temperatures, T_i, of 95 K, 45 K and 21 K during the cool-down process.

EXPERIMENTAL RESULTS

Pump characteristic

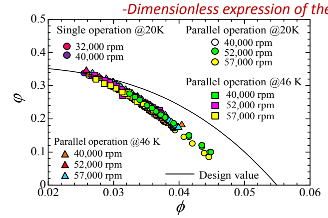
- Flow rate for the parallel operation has been converted to that through one pump.
- Pump performance for the parallel operation agrees well with that for the single operation.
- With increase in Q, the pump head monotonically decreases.
- With increase in the revolution, the characteristic curves shits to the right side.
- The measured pump characteristics similar to the design curve, although they become smaller in high Q.



(a) 21 K (b) 45 K (c) 95 K

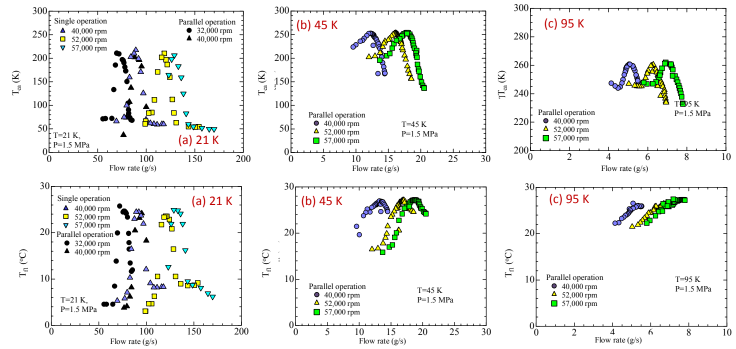
- It is confirmed from this figure that, even if one pump fails, the required discharge flow rate can be achieved by increasing the revolution of the other from 40,000 to 57,000 rpm.

-Dimensionless expression of the measured pump characteristics-



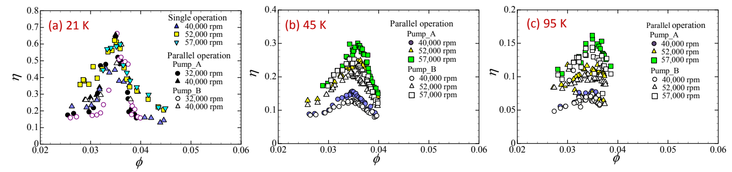
- Discharge coefficient: ϕ (=Q/Au)
- Head coefficient, φ (=$\Delta P/\rho(pnd)^2$)
- It is found that all experimental data exist on the same curve independent of T_i and n, although the tendency is similar.
- For lower φ, the deviation of ϕ from the design value becomes larger and it is 13 % at the same φ of 0.1.

Temperature reduction



- Effect of Q on T_{ca} and T_{f1} for each T_i. The dependence of Q on T_{ca} and T_{f1} is convex upward.
- Peak temperatures of T_{ca} and T_{f1} shift to the right side for higher revolutions and become lower for lower T_i.
- It appears that the temperature distribution is not symmetric and the reduction tendency of T_{ca} is larger for higher flow rate.
- Temperatures at T_{ca} do not go down to T_i and those at T_{f1} are kept above a few °C.

Dependence of ϕ on η.



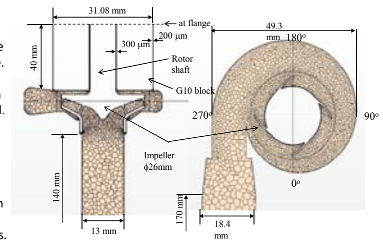
- It is found that the peak adiabatic efficiency, η_{max}, appear at around the same ϕ of 0.035.
- η decreases down to around 0.2 with increase and decrease from 0.035 in ϕ, because the flange temperature excessively decreases.
- For the single operation at η_{max}, it is found that the pump head exceeds the allowable one of 120 kPa to acquire the required discharge flow rate of more than 160 g/s at the operation temperature of 21 K.

➡ The single operation has concern about the excessive flange temperature reduction, although the required flow rate is acquired at the revolution of more than 57,000 rpm.

The excessive cooling problem should be a solved to achieve long-term stable operation for the proton beam power of 1-MW.

NUMERICAL ANALYSIS

As the first step, the numerical simulation of fluid flow was conducted at the operation temperature of 95 K using a CFD code, STAR-CCM+ , in order to clarify the excessive cooling problem.



Analytical Model

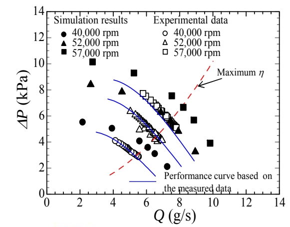
- Conservation equations are implicitly solved by a finite volume method and are discretized by the second-order upwind scheme.
- Standard low Reynolds k-ω model
- A polyhedral mesh is used in the whole analytical region and a prism layer mesh of 10 layers is applied to the vicinity of the wall.
- Thickness of the first layer connected to the wall = 2.9 μm.
- Total number of the grid : 4,524,935 grids.

Boundary Conditions

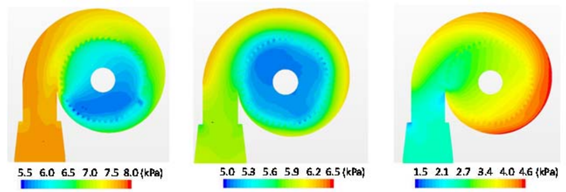
- Analytical region is divided by two regions; a cylindrical portion with a diameter of 29 mm and the rest of it.
- A sliding mesh is created at the boundary between the regions.
- Peripheral velocities corresponding to the revolutions of 42,000, 52,000 and 57,000 rpm are applied to the wall surface of the impeller and the rotor shaft.
- Pressure boundary condition: Suction piping (reference pressure),Discharge piping (a pump head).
- Adiabatic condition is applied to the external wall.
- Properties of equilibrium hydrogen such as density and viscosity are 3.803 kg/m^{3}and 0.4140×10^{-5} Pa-s, respectively, that are given by GASPAK.

NUMERICAL RESULTS

- It appears that the tendency is similar to the experimental data, although the calculated discharge flow rate is 30 % larger than measured one.

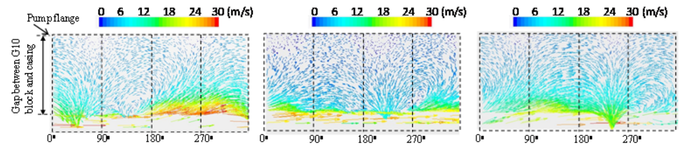


- Pressure distribution



(a) Q = 4.53 g/s (b) Q = 6.29 g/ (c) Q = 8.94 g/s

- Velocity distribution



(a) Q = 4.53 g/s (b) Q = 6.29 g/s (c) Q = 8.94 g/s

- There is a large hydrogen flow through the gap toward the lowest pressure location.
- For Q = 6.29 g/s, the flow is confined almost exclusively to around the the G10 block.
- **It seems that the excessive flange temperature reduction would be affected by the cryogenic supercritical hydrogen passing through the gap caused by the pressure distribution around the impeller.**

CONCLUSIONS

- The flow performance of the developed centrifugal pump with dynamic gas bearings was measured at the pressure 1.5 MPa and the operation temperature of 95 K, 45 K and 21K. All experimental data could be expressed well by using dimensionless parameters of a discharge and a head coefficient and existed on the same curve independent of the operation temperature and the revolution. The tendency was similar to the design curve, although the deviation became larger for higher Q.
- The maximum adiabatic efficiency of 0.66 is achieved at the operation temperature of 21 K for around f = 0.035. However, it drastically decreased to 0.2 except for it because the temperature at the level of flange excessively decreased to a few °C.
- The fluid flow phenomenon was analyzed at the operation temperature of 95 K using a CFD code, STAR-CCM+. It was clarified that a large pressure distribution around the impeller brought about a circulation flow through the gap between G10 block and the pump casing except for the maximum adiabatic efficiency and consequently the flange would be excessively cooled.