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# Flow performance of cryomodules in C-ADS Injector Ⅱ

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**Abstract**

Two β=0.10 cryomodules are required for the China Accelerator Driven Subcritical System (C-ADS) injector II accelerator. Flow design is of great importance in the performance of cryomodules, including thermal design, flow distribution, pressure drop and so on. This paper will study convection heat transfer of helium and relation among the pipe diameter, mass flow rate and Reynolds number. Furthermore, the influence of flow geometries on pressure drop and flow distribution will also be done. It was found that the theoretical flow distribution were in good agreement with the experimental data.

*Keywords*: cryomodule, Heat transfer, Flow distribution, Pressure drop

## 1. INTRODUCTION

The China Accelerator Driven Subcritical System (C-ADS) project has being developed by Chinese Academy of Sciences (CAS). The linac of C-ADS injector II in Lanzhou was designed and constructed by Institute of Modern Physics (IMP, CAS), which can provide a 10 MeV high-intensity proton beam in original design, as shown in Fig1 [1-3]. The superconducting part of the linac is composed of two cryomodules with 6 superconducting 162.5 MHz, β=0.10 half-wave resonators interleaved with 6 superconducting solenoids（HCM6）in the final design.

## 2. FLOW SCHEME OF THE CRYOMODULE

HCM6 consist of a string of cold mass, flow sub-system, current leads, thermal shield, and vacuum vessel. The cryomodules are connected to the flow plant by transfer lines that run alongside the linac. The cryogenic system necessary to support the cryomodules operation in a range of steady state and transient operating modes including RF on/off, cool- down, warm-up, and fault scenarios.

Helium supply comes from transfer lines flows into the bottom of the cavities at the flow process, then across the cavity vessel in parallel, finally confluence at two-phase vessel, as shown in Fig2. Both cavities and solenoids operate at a temperature of 4K and a pressure of 1.05 bar.

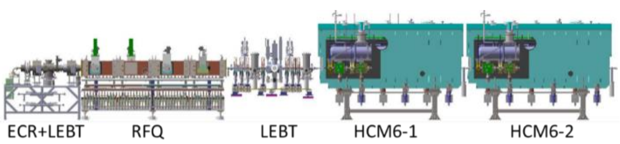


Fig. 1. ADS injector Ⅱ layout.

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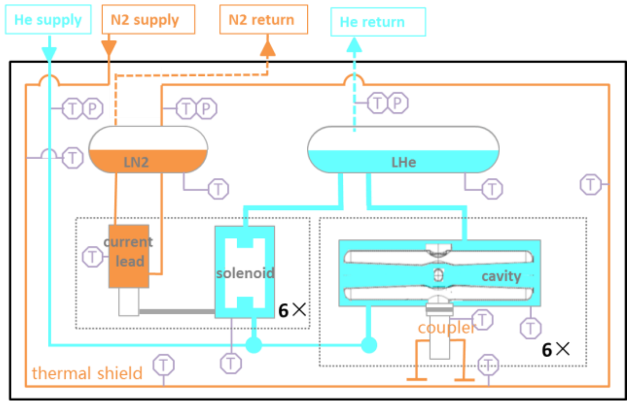


Fig. 2. HCM6 flow scheme.

## 3. FLOW THERMAL DESIGN

Superconducting radio frequency (SRF) cavities in cryomodules are cooled by liquid helium from the temperature of 290K to 4K. The stream flows and turns the liquid into the vapor in the warm transfer lines. The liquid flow boiling heat transfer happens when the fluid temperature decreases to the saturation temperature at a certain pressure and the fluid temperature in the cavity decreases from the room temperature to the cryogenic temperature during the cool-down process. Therefore, the inlet fluid of cryomodule can be regarded as gas helium until the cold mass reached the temperature of 4K. The shape of cold mass which contains the cavities and solenoids are complex. One of the biggest concern is that there are no universal heat transfer correlations for simulating the process. Theoretical calculation is used the simplified smooth tube, which is conservative compared with the real HCM6. Besides, the calculational heat transfer area is smaller than the actual area, causing the result is more conservative.

TABLE 1
KCM6 FLOW PARAMETERS.

| Parameters | Value |
|---|---|
| initial temperature of the system (K) | 290 |
| the inlet pressure of gas helium (MPa) | 0.12 |
| velocity of gas helium (m/s) | 5 |
| the diameter of flow tube (mm) | 8 |
| cold mass (kg) | 480 |

Therefore, the boundary conditions of heat transfer can be assumed to be single-phase convection in cryomodule flow process. The main parameters for HCM6 are given in Table1.

According to the energy conservation and Newton's Law of Flow [4-5], heat transfer rate may be written as follows:

$$C_P m\left(T_{s\_\tau} - T_{s\_\tau+d\tau}\right) = q_m d\tau \Delta H = h_c \mathrm{A}\left(T_{s\_\tau} - T_{ave}\right) \quad (1)$$

Where $C_P$ is the specific heat at constant pressure of solid, m is the mass of solid, τ is the time, $T_{s\_\tau}$ and $T_{s\_\tau+d\tau}$ is the solid temperature at τ and after dτ, $q_m$ is mass flow rate, ΔH is the enthalpy difference of fluid, $h_c$ is the convective heat transfer coefficient, A is heat transfer area, $T_{ave}$ is the average temperature of inlet and outlet ($T_{out}$) fluid in cryomodule.

Reynolds number, Re, is an important parameter in forced convection heat transfer which can influence the convective heat transfer coefficient. For turbulent flow inside a smooth tube of circle cross-section:

$$N_u = 0.023{R_e}^{0.8}{P_r}^{0.4} \quad (2)$$

The Nusselt number is defined as follows:

$$N_u = h_c D / k_f \quad (3)$$

Where Pr is Prandtl number, D is the diameter of pipe, k_f is thermal conductivity of fluid.

Fig3 shows the density, Prandtl, viscosity and thermal conductivity for helium in different temperature while the pressure is 1 bar [6]. These properties are just a function of the temperature of helium.

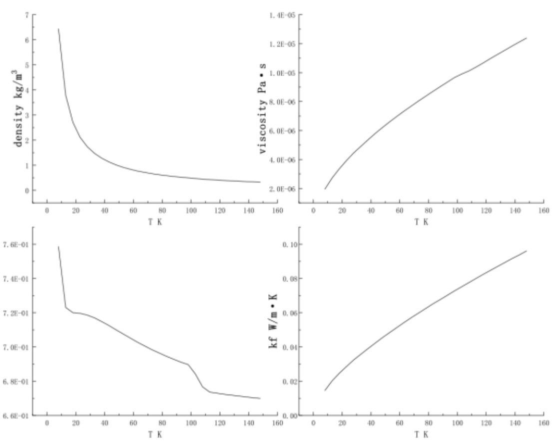

Fig. 3. Thermophysical properties for helium in different temperature.

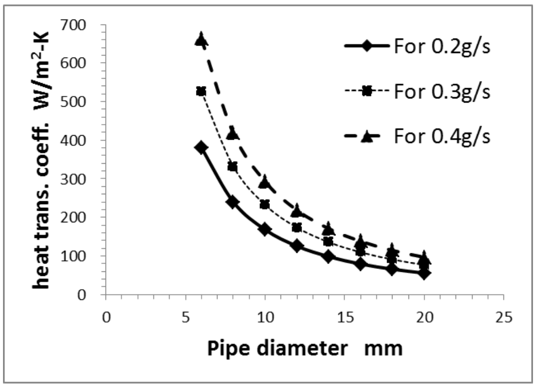


Fig. 4. Variation of heat transfer coefficient with diameter for required mass flow rate.

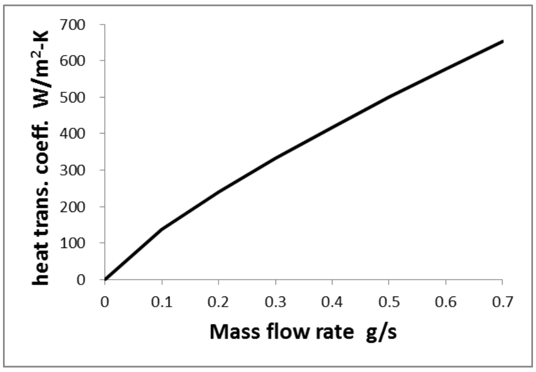


Fig. 5. Variation of heat transfer coefficient with mass flow rate for 8mm pipe.

Fig4 shows variation of heat transfer coefficient with diameter of pipe and the assumed fluid temperature is 18K. There have three curves for mass flow rate of 0.2g/s、0.3g/s and 0.4g/s. It can be found that there is a significant influence of the diameter on the heat transfer coefficient. This means that the influence becomes more significant when the diameter decreased and mass flow rate increased. A proper selection of diameter of pipe does improve the efficiency of heat transfer. For a certain diameter of pipe, heat transfer coefficient is basically proportion to mass flow rate, as shown in Fig5 (D=8mm, T=18K).

Furthermore, the heat transfer coefficient also has the relationship with the average temperature $T_{ave}$ of the fluid in flow pipes. Fig. 6 gives the relationship when the mass flow rate is 0.3g/s. It can be seen that the curve of heat transfer coefficient is discontinuity. This is because the Reynolds number reaches the critical point and the flow regime has changed at that moment. When $T_{ave}$ <120K, it is the turbulent flow and the heat transfer coefficient changes quickly with the decrease of the temperature. When $T_{ave}$ >120K, it is the laminar flow and the heat transfer coefficient exhibits a linear increase with the temperature to the contrary.

## 4. FLOW DISTRIBUTION AND PRESSURE DROP

Helium stream entrances a manifold and branches continuously along the manifold in flow process. There

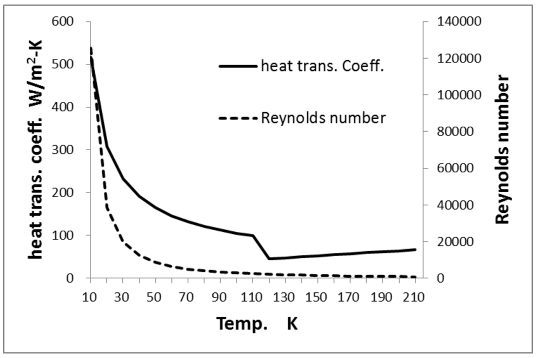


Fig. 6. Heat transfer coefficient and Reynolds number with temperature.

have 6 ports for cavities and 6 ports for solenoids alternately in HCM6 flow system. The advantages of this structure are less manufacturing cost and cycle. However, the main problem which arises in the design is a possibility of the severe flow maldistribution problems. Some ports may be starved of helium gas, while others may have them in excess, which reduces cryomodule performance and efficiency [7]. Therefore, rational helium gas distribution can reduce the temperature difference of cold mass and thermal stress and then improve the cavity performance in cryomodules.

It is assumed that the helium gas with fully developed velocity profile is one dimensional steady flow and the property parameters are based on the average temperature T_ave of inlet and outlet. According to the first principle of mass and momentum conservation, the equation of the distributor can be written as follows [8-9]:

$$\frac{1}{\rho}\frac{dP}{dx}+\frac{f}{2D}w^2+2kw\frac{dw}{dx}=0 \qquad (4)$$

Where ρ is the density of helium gas, P is pressure in manifold, x is the distance of the ports, f is the friction factors, D is the diameter of the manifold, w is axial velocity in manifold, k is the pressure recovery factors. Discrete solutions of (4) are given in Reference [8]. Then the velocity w and pressure drop of each port in manifold can be calculated. Pressure drop of ports can be calculated as follows:

$$\Delta\mathrm{P}=\frac{1}{2}\rho\xi\left(\frac{FL}{F_c n}\right)^2\left(\frac{dW}{dX}\right)^2 \qquad (5)$$

Where $\xi$ is the coefficient of non-smooth ducts, F and $F_c$ are the cross-sectional areas of the manifold and the port, W is the axial velocity in manifold, X is axial coordinate in the manifold, and n is the number of ports and L length of the manifold. Pressure drop in manifold can be calculated by the sum of the pressure drop of ports and the linear loss of manifold.

Besides, flow distribution can be defined as follows:

$$\eta=\frac{q_{mi}}{q_{m0}/n}=n\frac{{d_c}^2}{D^2}\cdot\frac{u}{w} \qquad (6)$$

Where $q_{mi}$ and $q_{mo}$ are mass flow rate of ports and manifold, n is numbers of ports, $d_c$ is the diameter of the ports, u is the velocity of the ports.

In the design of the cryomodule, some parameters have been confirmed on the basis of cold mass heat load and project experience [10]. In the following calculation of this paper, the diameter of ports is 8mm, the inlet velocity $w_0$ in manifold is 5m/s.

Fig. 7 shows influence of the manifold diameter on axial velocity, flow distribution and pressure drop of ports. With increase of diameter, the curves of axial velocity became non-linear in the manifold as shown in Fig. 7a. It is clear that a proper selection of D does improve uniformity after other parameters are fixed. Therefore, it is possible to have a design with linear axial velocity when a set of proper structure parameters are selected. Fig. 7b shows that manifold diameter has a significant effect on the flow distribution, and a bigger diameter has a better flow distribution. When D is 40mm, the flow distribution could be considered as uniform. However, pressure drop of ports

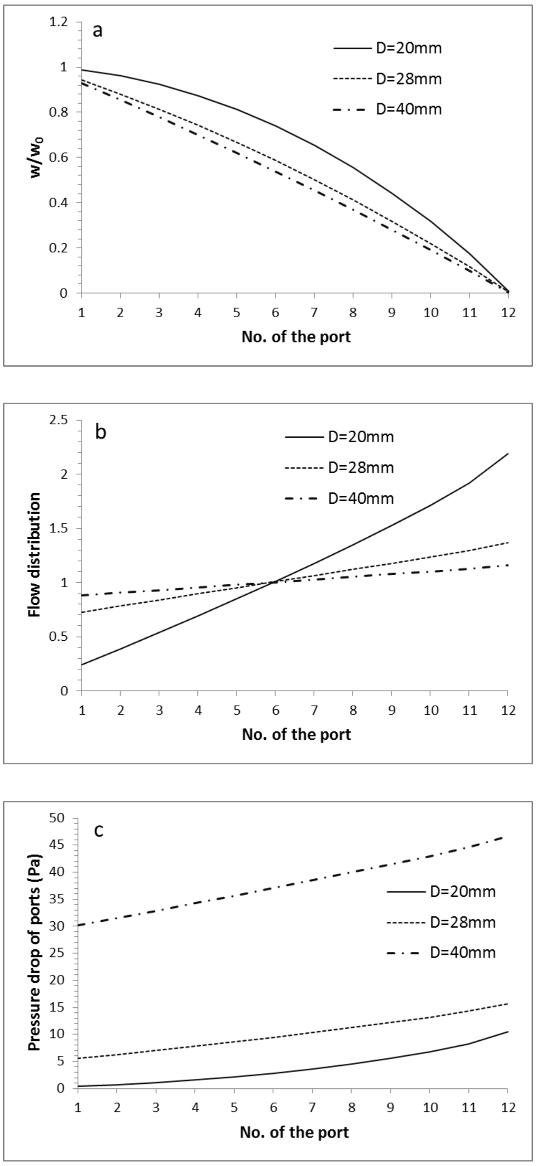


Fig. 7. Effects of the manifold diameter D to velocity (a)、flow distribution (b) and pressure drop of ports (c).

is proportionate to the cross-sectional areas of manifold according to the Eq. (5) and then a bigger diameter has a large pressure drop as shown in Fig. 7c. Hence, it is important to optimize a proper manifold diameter in the design of cryomodule.

Fig. 8 shows influence of the manifold length on axial velocity, flow distribution and pressure drop along the manifold, in which the same manifold diameter of 40mm has been used. It can be seen that there is a little influence of the manifold length on the flow distribution and pressure drop. So the parameter of manifold length has a wide range of options in the design of cryomodule.

## 5. CRYOMODULE PERFORMANCE AND DISCUSSION

Cryomodules for HWR cavities of C-ADS injector II project, HCM6, have finished the work of design,

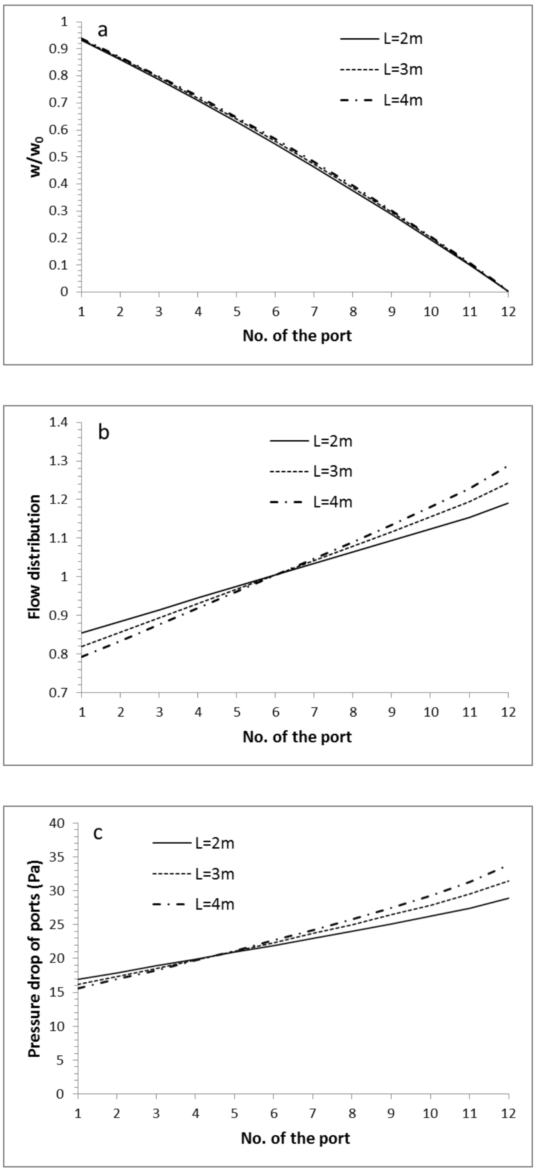


Fig. 8. Effects of the manifold length L to velocity (a)、flow distribution (b) and pressure drop of manifold (c).

Fig. 9. HCM6 and transfer lines in tunnel

manufacture and test online, and then succeeded in accelerating a proton beam to an energy of 10.06MeV with a peak beam current of 1.16mA in continuous wave [11]. Before that, HCM6 had achieved several cycles of cool down and warm-up successfully, as shown in Fig. 9.

Fig.10a shows the temperature of cavities during the flow process of HCM6 and the manifold diameter is 20mm. It can be seen that the larger temperature difference exists between the branches. In other words, there is a non-uniform flow distribution. So the research of the flow distribution had been done and the new design was applied to the taper cavity cryomodule[12]. Taper cryomodule consists of five β=0.15 half-wave resonators taper cavities and is different from HCM6 (β=0.10). Fig.10b shows the temperature of taper cavities during the flow process and the optimized manifold diameter is 40mm. Compared with Fig.10a, Fig. 10b has a more uniform distribution. This is in agreement with Fig. 7b. The location of manifold also has an impact on fluid distribution according to the change

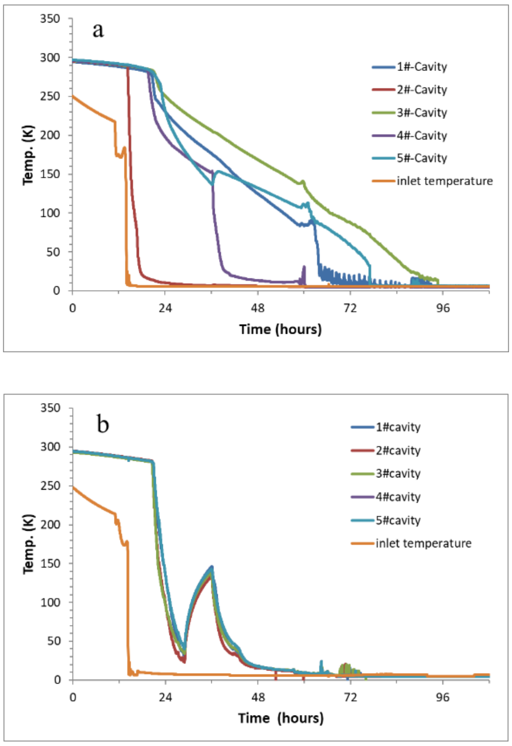


Fig. 10. Temp. of cavities in flow process of cryomodule: (a) HCM6, (b) Taper.

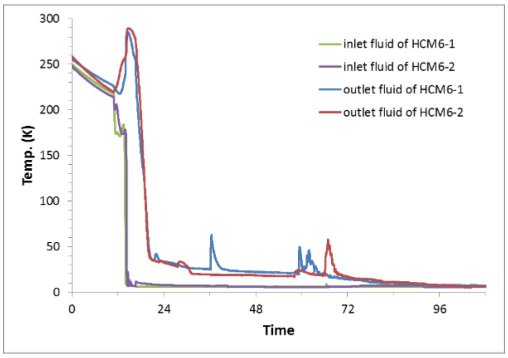


Fig. 11. Helium temperatures in flow process of HCM6.

of HCM6 and taper cryomodule. Therefore, it is possible to have a uniform distribution in the design of cryomodule when a set of proper structure parameters is selected. Inlet temperature information also shows in Fig.10a and Fig. 10b which can be compared with cavities temperature. The cool down of taper cryomodule is controlled by the valve box through automatic control program in order to meet the cavity cool down requirements, and the mass flow rate is always changed. Then the calculation results by the average heat transfer coefficient have a quite deviation with the real situation.

Fig. 11 shows the helium temperature in flow process of HCM6. It can be seen that experimental dates have almost no difference between the two cryomodules. Without considering the radiation flow, the inlet fluids accomplish cool-down quickly from room temperature to about 6K and then maintain the temperature in a long time. After heat exchange with cold mass, the outlet fluids warm up to about 30K. Hence, the average temperature in (1) can be corrected, more accurate Reynolds number can be got, and it is helpful for optimizing the cryomodule of next project.

## 6. CONCLUSIONS

Thermal performance and flow distribution based on the cryomodules of C-ADS injector II have been studied in this paper. The convective heat transfer coefficient plays an important role in heat transfer process, which can improve the efficiency of helium heat transfer. The cryomodules have undergone the great temperature difference in the flow process, which will result in the problem of stress, strain, even the cavities performance. So it is important for us to investigate the influence factors of flow distribution in preliminary design. Finally, the research of the flow system has been developed far from comprehensively and thoroughly, and the further study should be done next.

## ACKNOWLEDGMENT

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