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Thermal analysis of the CSNS H$^-$ ion source

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Abstract There are two cooling systems to maintain the thermal stability of the CSNS H$^-$ ion source during its operation: Air-cooling in the source body of the discharging chamber and water-cooling in the flange on which the discharging chamber is installed. The optimal cooling parameters to ensure the operation of the H$^-$ ion source are determined through a thermal analysis. In addition, a transient analysis is also performed to know exactly the transient temperature variation during the whole 40 ms period of the pulsed mode operation of the ion source.

Key words H$^-$ ion source, water-cooling, air-cooling

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1 Introduction

The China Spallation Neutron Source (CSNS) is an accelerator-based high power project currently under R&D in China [1]. The accelerator complex consists of a 81 MeV H$^-$ linear accelerator as an injector and a 1.6 GeV rapid cycling proton synchrotron (RCS). The linear accelerator consists of a 50 keV H$^-$ Penning surface plasma ion source, a low energy beam transport line (LEBT), a 3.0 MeV Radio Frequency Quadrupole (RFQ) accelerator, a medium energy beam transport line (MEBT), a 81 MeV Drift Tube Linear Accelerator (DTL) and a high energy beam transport line (HEBT). At present, there are basically two kinds of H$^-$ ion sources being used for spallation neutron source in the world: Multi-cusp volume plasma source (RF multi-cusp volume plasma source (SNS) [2] or thermal filament multi-cusp volume plasma source (J-PARC) [3, 4]) and surface plasma ion source (ISIS) [5–8]. The Penning surface plasma source is adopted as a CSNS H$^-$ ion source due to its technical maturity, reliability, stability and comparatively lower cost. More importantly, it fully satisfies the beam requirements asked for an ion source by CSNS Phase I. Due to the good collaboration between the Rutherford Appleton Laboratory (RAL) and the Institute of High Energy Physics (IHEP), the R&D of the H$^-$ ion source test at IHEP is now proceeding successfully. In Table 1, some relevant parameters of the ion source are listed.

Table 1. CSNS H$^-$ ion source design parameter.

energy/keV	50
current/mA	>20
emittance (πmm·mrad, Norm., rms)	<0.20
repetition rate/Hz	25
beam duty factor (%)	1.3
life time (month)	>1

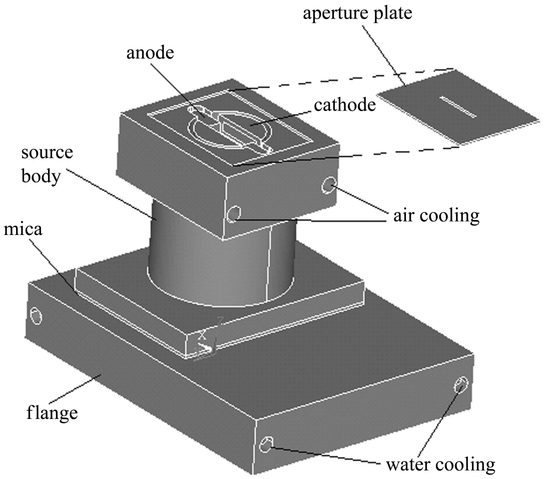

Fig. 1. ANSYS thermal model of CSNS H$^-$ ion source.

The structure of the H$^-$ ion source discharging chamber is shown in Fig. 1. The chamber mainly consists of a molybdenum anode, a molybdenum cathode, a molybdenum aperture plate and a stainless

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steel source body. Both the anode and cathode are housed in the source body. The anode is mechanically squeezed into a slot in the source body and is thus thermally and electrically connected with the source body, whereas the cathode is electrically isolated from the body via a ceramic spacer. The discharging chamber is indirectly installed on a flange, between the chamber and the flange a mica plate with a thickness of 0.6 mm is used to electrically insulate the cathode from the flange.

As shown in Fig. 1, both the air-cooling and water-cooling are applied to maintain the thermal stability of the ion source. The air-cooling channel is drilled in the head of the source body while the water-cooling channel is embedded in the flange.

2 Thermal modeling

The code ANSYS has been used for the thermal modeling. The thermal power of the ion source comes from the applied Arc power supply between the anode and the cathode. The pulsed power of the Arc power supply is about 4 kW. Assuming that all the electrical Arc power is converted into thermal power and the thermal power dissipates on the electrodes proportional to the electrode surface area. Then it is estimated that there are approximately 90% of the power deposited on the cathode and 10% on the anode [5, 8].

The heat transfer coefficient $h(\mathrm{W\cdot m^{-2}\cdot K^{-2}})$ is used to calculate the convection heat between the moving fluids and a solid in thermodynamics. In our case, it is used to calculate the heat transfer between the cooling water and the water-cooling channel surface; between the cooling air and the air-cooling pipe surface [9, 10].

$$\begin{aligned} h_\mathrm{w} &= 0.023k_\mathrm{w}^{0.6}D_\mathrm{w}^{-0.2}c_{p\mathrm{w}}^{0.4}\mu_\mathrm{w}^{-0.4}\rho_\mathrm{w}^{0.8}v_\mathrm{w}^{0.8}\,(\text{for water}), \\ h_\mathrm{a} &= 0.023k_\mathrm{a}^{0.6}D_\mathrm{a}^{-0.2}c_{p\mathrm{a}}^{0.4}\mu_\mathrm{a}^{-0.4}\rho_\mathrm{a}^{0.8}v_\mathrm{a}^{0.8}\,(\text{for air}), \end{aligned} \tag{1}$$

where k_w, $c_{p\mathrm{w}}$, μ_w, ρ_w, v_w are the thermal conductivity, the special heat, absolute viscosity, density and velocity of water, and D_w is the diameter of the water pipes; k_a, $c_{p\mathrm{a}}$, μ_a, ρ_a, v_a are the thermal conductivity, the special heat, the absolute viscosity, the density and the velocity of the air, and D_a is the diameter of the air pipes. In our case, $D_\mathrm{w} = 0.0032$ m, $D_\mathrm{a} = 0.0033$ m.

2.1 Steady state analysis

In order to obtain a steady state solution only the average power densities need to be applied on the electrode surfaces. In the case when the duty factor for the Arc pulse is 1.25%, the velocity of the water and air flow are 0.006 m/s and 40 m/s. The simulation results are shown in Fig. 2.

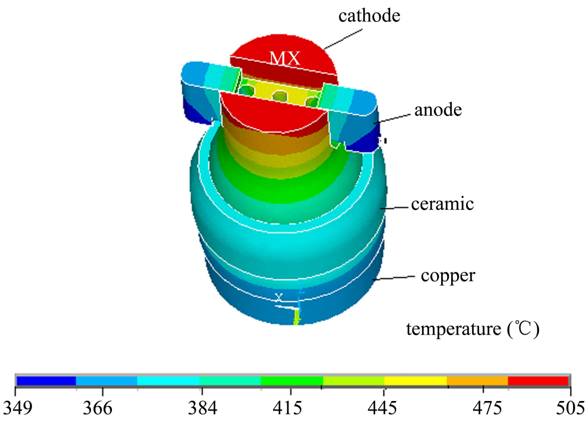

Fig. 2. Temperature distribution of the electrode from steady state analysis.

As shown in Fig. 2, the highest temperature occurs at the top surface of the cathode, which is about 505 ℃. The temperature variation in the cathode ranges from 370 to 505 ℃, while in the anode it ranges from 349 to 460 ℃. The temperature at the measuring point where the thermal coupler is located is 495 ℃ for the cathode, and 435 ℃ for the anode. The temperature of the anode, cathode and the source body at the measuring point obtained here is basically in accordance with those from the experimental results of the ion source at RAL [6, 7].

The electrode temperature is an important factor for the stable operation of the ion source. To find out the operating condition of the ion source, the following simulations are carried out. First, the air flow velocity was kept constant at v_a=40 m/s, while changing the water flow velocity v_w. The simulation result is shown in Fig. 3.

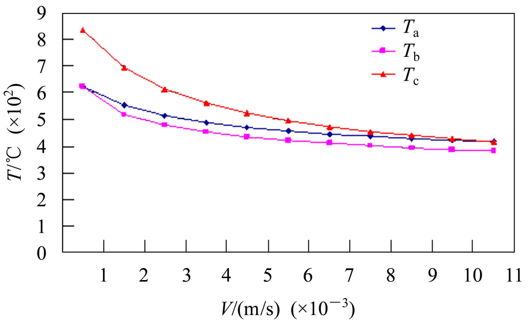

Fig. 3. Variation of the component temperatures with the velocity of the water flow. T_a, T_b and T_c symbolize the temperatures of the anode, the source body and the cathode at the measured points, respectively.

As can be seen from Fig. 3, with the increase of water flow velocity, the temperature of the electrode surfaces decreases sharply, especially for the cathode. To assure the steady operation of the ion source, based on the experimental results [6, 7], the optimum velocity of the water flow range is 0.004–0.006 m/s.

Second, the water flow velocity was kept constant at v_w=0.006 m/s, while changing the air flow velocity v_a. The simulation result is shown in Fig. 4.

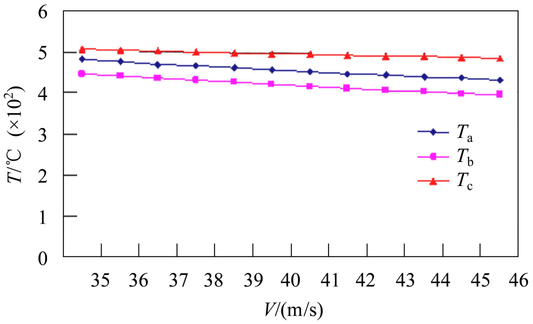

Fig. 4. Variation of the component temperatures with the velocity of the air flow. T_a, T_b and T_c symbolize the temperatures of the anode, the source body and the cathode at the measured points, respectively.

As can be seen from Fig. 4, the electrode surface temperatures decrease smoothly with the increasing of the air flow velocity. To assure the steady operation of the ion source, maintaining the temperature difference between the anode and cathode of about 40 ℃ [6, 7], the optimal velocity should be chosen between 38 m/s and 42 m/s based on the experimental results.

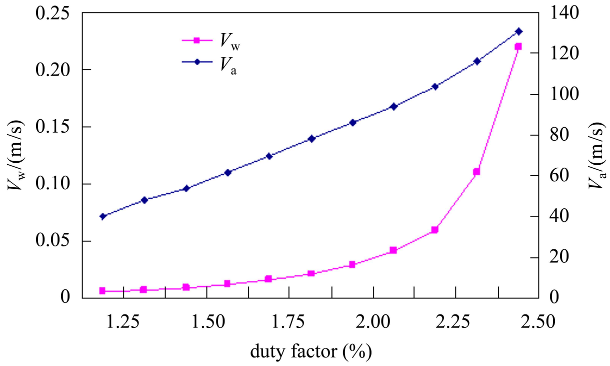

Fig. 5. Water and air flow velocity with the increasing duty factor. V_w and V_a symbolize the velocity of the water and air flow.

In order to satisfy the various requirements on the ion source beam asked for the accelerator complex, the beam duty factor, thus the duty factor of the Arc power supply often needs to be changed. Obviously, the temperature distribution on the ion source components will vary with the duty factor. To maintain a steady electrode surface temperature distribution the velocity of the water and air flow should also be changed corresponding to the duty factor. Simulations are carried out to determine the relation between the duty factor and the velocity of the water and air flow. The result is shown in Fig. 5.

Obviously, when increasing the duty factor of the Arc power supply, the velocity of the water and air flow should also be increased. As shown in the figure, the air flow velocity varies smoothly and almost linearly with the increase of the duty factor, while the water flow velocity varies slowly in the range from 1.25% to 2.25% but increases quickly for a duty factor greater than 2.25%. As a result, in the actual operation, when the duty factor is smaller than 2.25%, a comparatively small water flow velocity is needed, and only little change is needed. When the duty factor is larger than 2.25%, the water flow velocity needs a quick increase. This is because the cooling water cools the discharge chamber indirectly via the mica plate which has a poor thermal conductivity. In addition, it can also be seen from the figure that the discharging chamber is mainly cooled by the cooling air and the cooling water only functions as fine adjusting factor to the thermal stability of the discharging chamber.

2.2 Transient analysis

The steady state analysis only calculates the average electrode surface temperatures and cannot reflect the variation of the temperature during the whole pulsed period. In order to know the maximum transient temperature and examine further the time-variation of the temperature during the whole pulsed

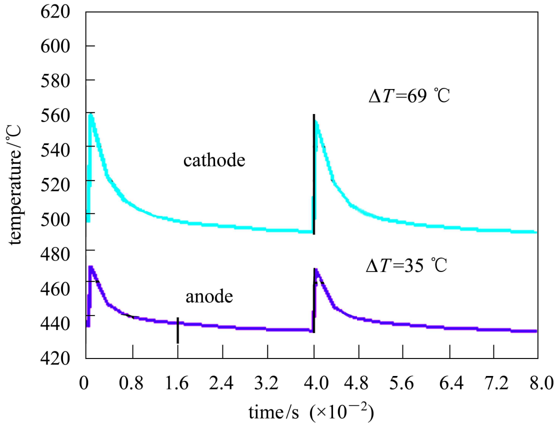

Fig. 6. Cathode and anode surface temperature variation with time for a 500 μs duty cycle from transient analysis.

period, the transient analysis is carried out. The result is shown in Fig. 6.

As shown in Fig. 6, the curve of the transient temperature variation with the time has a sharp peak during the Arc busy time. And the transient electrode surface temperatures are much higher than the average temperature during the Arc busy time. The reason is that these electrode surfaces are directly exposed to the plasma, and the large heat due to the high Arcing power cannot be instantly carried away by the cooling air and water during the Arc busy time. In addition, the heat capacitor of the discharging chamber is small. The temperatures lower to the steady state temperatures as the power dissipates into the electrodes and is carried away by the cooling air and water during the Arc rest time.

3 Conclusions

The two cooling systems play an important role to ensure the steady operation of the ion source. To maintain a stable plasma state and thus a steady Arc discharging current, a stable temperature distribution of the anode and the cathode is highly essential. The simulations show that the optimal velocity ranges of the water and air flow are 0.004-0.25 m/s and 38-140 m/s, respectively. In addition, the thermal analysis also shows that the air-cooling is dominant while the water-cooling only functions as a fine adjusting factor in ensuring a thermal stability and stable temperature distribution of the discharging chamber.

Mica is a good electrical insulator but a poor thermally conductive material. To improve the cooling of the cathode, the width of the mica is often changed accordingly with the Arc duty factor.

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