Thermal modeling of the ISIS H^- ion source

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The development of H^- ion sources with performances exceeding those achieved today is a key requirement for the next generation of high power proton accelerators. The ISIS Penning surface plasma source, which routinely produces 35 mA of H^- ions during a 200 μs pulse at 50 Hz for uninterrupted periods of up to 50 days, is regarded as one of the leading operational sources in the world, and should provide an excellent starting point for a development program. One goal is to produce pulse widths of 1.2 ms at 50 Hz and 2.5 ms at 50/3 Hz, thereby increasing the duty factor from 1% to as much as 10%. Increasing pulse widths will necessitate an improved cooling system to offset increased heating. The most effective cooling strategy will be determined by thermal finite element analysis of the ISIS source. The modeling will then be extended to find an optimal means of offsetting increased heat loading, and will minimize the amount of engineering required to produce an effective solution. Modeling of the ISIS source has established the temperature profiles of the source components. At the specific locations where temperatures are measured in operation using thermocouples the model values match those seen in practice. Transient modeling has been used to provide temperature variations for the source during the 20 ms period of the 50 Hz cycle. [DOI: 10.1063/1.1695615]

I. INTRODUCTION

A thorough understanding of the thermal characteristics of the ISIS H^- ion source[1] is essential if operation is to be extended to the higher duty factors required for next generation accelerators, while maintaining an optimal regime for H^- ion production and source lifetime. This can be achieved by producing a comprehensive thermal model of the source.

The source (Fig. 1) is of the Penning type, comprising a molybdenum anode and cathode between which a low pressure hydrogen arc is struck. Hydrogen and cesium are fed into the arc via holes in the anode, which can be more clearly seen in Fig. 2. The anode and cathode are housed in the stainless steel source body. The anode is thermally and electrically connected to the body, whereas the cathode is isolated from the body by means of a ceramic spacer. The whole assembly is bolted to the ion source flange, separated by a thin layer of mica to provide electrical isolation for the cathode. The ions are extracted through the slit in the aperture plate.

Source cooling is provided by two systems illustrated in Fig. 1: air cooling via two pipes in the source body nearest the electrodes and water cooling via a channel cut into the ion source flange. Air flows along one pipe and is then returned down the other as shown in Fig. 3. Air is used because of the safety hazards involved with having water close to the cesiated ion source.

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II. INITIAL MODELING

ALGOR[2] finite element analysis (FEA) software has been used for thermal modeling, beginning with a simple model of the ion source to understand its thermal operation.

In typical operation the ISIS ion source operates with a 4 kW, 500 μs, 50 Hz arc. The assumption is made that all the electrical power as measured in the external circuit goes into heating the electrode surfaces via chemical, radiative and kinetic channels, with each channel having roughly equal importance. The arc is bounded on all sides by sections of the cathode, anode, and aperture plate. The total surface area of these sections is found and the power for the chemical and radiative heating channels is divided proportionally between them. However, approximately 90% of the kinetic energy goes into the ions and is therefore deposited on the cathode with only 10% on the anode and aperture plate.

Initial two dimensional (2D) transient modeling has shown that the 19.5 ms off period of the 50 Hz cycle is long enough to allow the surface energy applied during the arc pulse to conduct into the thermal mass of the electrodes before the start of the next pulse. The temperature at the electrode surfaces varies by about 50 °C during the 20 ms cycle, and this temperature increase only penetrates a few millimeters from the electrode surface. This localized effect means that the pulsed power in the arc can be modeled as an average dc equivalent when modeling the entire ion source, thus reducing the complexity of the model and allowing steady state calculations.

In addition to the amount of heating and cooling the thermal resistivity of the ceramic insulator and mica sheet are important factors in determining the source temperatures.

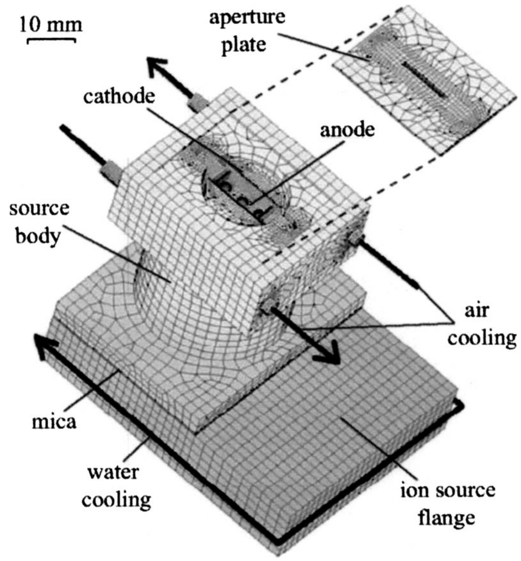

FIG. 1. ALGOR thermal model of the ISIS ion source

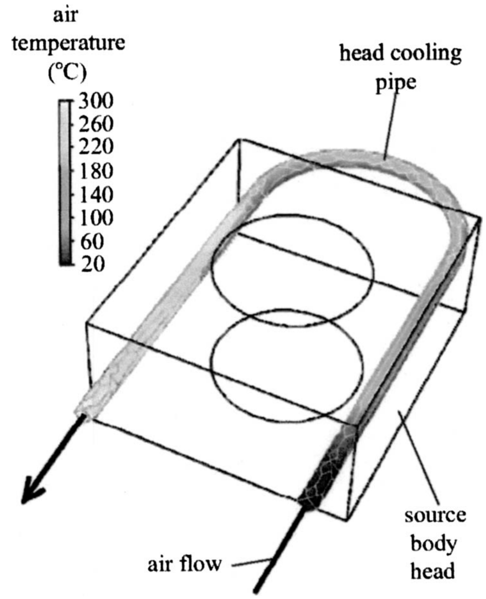

FIG. 3. CFX model of air cooling.

In the real world thermal contact resistance between materials plays an important role. To progress further with the thermal FEA a number of coefficients are required that can only be determined by experiment.

III. THERMAL TEST RIG

A thermal test rig was built to study the convection and radiation from the ion source surfaces and the thermal contact resistances at each interface between materials. The component dimensions were chosen to be the same as those of the ISIS ion source, with blocks of material representing the cathode, copper spacer, mica, and ion source flange. The block of molybdenum representing the cathode was heated and held at a specific temperature while the temperatures of the different materials were monitored using thermocouples.

A series of experiments was run at a range of pressures from 10^{-6} to 10^{1} mbar in atmospheres of N_2 and H_2. The mechanical loading on the components was varied by setting the torque on the four threaded rods which held the components together. The effect of the number of layers into which the mica was cleaved was also studied.

Using a FEA model of the thermal test rig the required parameters were estimated. The thermal contact resistance was modeled as a 0.01 mm thick layer at each material interface. The thermal resistivities of the interface layers were adjusted in the model until the calculated heat-up curves matched those obtained by experiment. This was when the steel/mica and mica/molybdenum interface layers had a thermal resistivity between 30 000 and 40 000 times that of copper (significant contact resistance) and the copper/molybdenum interface had the same resistivity as copper (negligible contact resistance). Different surface radiation functions were tested in the model until the measured low pressure ($<10^{-4}$ mbar) cooldown curves were matched. Convective cooling in a pure H_2 atmosphere begins between 10^{-3} and 10^{-2} mbar, whereas in pure N_2 it does not become significant until pressures of 1 mbar and above. The convective heat transfer coefficients (HTCs) were found by curve fitting the measured cooling curves.

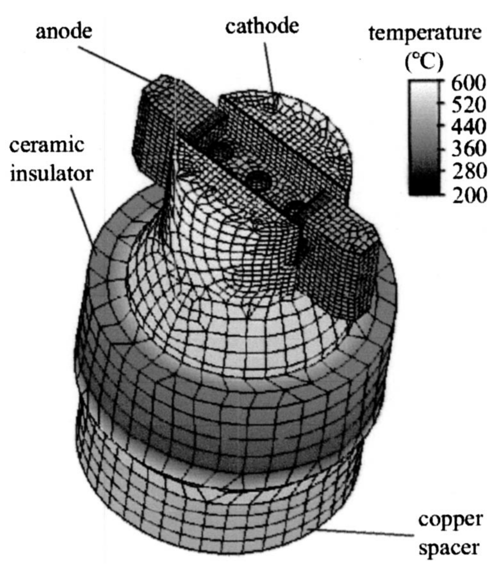

FIG. 2. Component temperatures from the steady state model.

IV. COOLING

The two cooling systems are modeled using HTCs applied to the pipe surfaces. The units of HTC are $\mathrm{W\,m^{-2}\,K^{-1}}$, where K is the temperature difference (ΔK) between the coolant and the surface. Values of HTC can be calculated empirically using the Nusselt number,[2] which depends upon the specific heat capacity, dynamic viscosity, thermal conductivity, mass density, and velocity (v) of the coolant and the diameter of the cooling pipe. For the ISIS source HTCs are

$$\mathrm{HTC_{air}} = 10.65 \times v^{0.8}, \tag{1}$$

$$\mathrm{HTC_{water}} = 6014 \times v^{0.8}. \tag{2}$$

TABLE I. Comparison of results from the FEA model and reality.

Electrode	From model Thermocouple (°C)	Surface (°C)	Maximum (°C)	Typical ISIS thermocouple (°C)
Anode	456	496	535	400–600
Cathode	501	585	631	440–530
Source body	416	441	441	390–460

The range of coolant flow rates used in normal operation on ISIS (30–80 ms^{-1} for air and 0.02–0.04 ms^{-1} for water) provides a range of HTC values to be applied to the model. The thermal model also requires the coolant temperature as an input. Both air and water are fed into the source at 20 °C, however, as the coolant travels along the cooling channels it heats up, thus reducing the amount of heat it can remove from the source (because ΔK decreases).

To find out how much the coolant temperature increases a computational fluid dynamics (CFD) model using ANSYS CFX[3] modeling software has been produced. Figure 3 shows the results from the CFD calculation for air flow in the pipe at 75 $m\,s^{-1}$ with the source body head held at 450 °C. The air temperature increases to ≈300 °C by the time it exits. To allow this increase in coolant temperature to be modeled in the ALGOR FEA, the air cooling pipe in the source head was divided into six sections, with the coolant set to different temperatures as calculated using CFD.

CFD was also used to find the temperature increase of the cooling water in the flange. There is only a few degree difference between inlet and outlet temperature because water has a much higher specific heat capacity and density than air. This allows the water cooling pipe in the ALGOR FEA to be modeled in one section all with the same coolant temperature.

The empirical equations for HTC were tested using CFD and found to be correct for flow rates up to 150 $m\,s^{-1}$ for air and 70 $m\,s^{-1}$ for water, allowing for the onset of turbulence in the cooling pipes.

V. MODEL RESULTS

When all the parameters that correspond to normal operation of the ISIS source are applied in the model the temperatures obtained are very close to those measured in the actual source. This provides validation that the model is realistic.

In normal operation the source temperatures are monitored using thermocouples for the cathode, anode and source body. All three thermocouples are positioned some distance from the electrode surfaces exposed to the arc plasma so they do not give actual surface temperatures. A realistic model of the source allows surface temperatures to be inferred (Table I).

Using the steady state solution as a starting point it is possible to run a transient study. This allows the peak surface temperatures reached during the cycle to be calculated. The initial 2D transient thermal modeling indicated that the surface heating during the arc on period only has time to penetrate a few millimeters into the electrode mass. To ensure accurate results the elements near the electrode surfaces are made very thin (10^{-5} m) in the direction of heat flux.

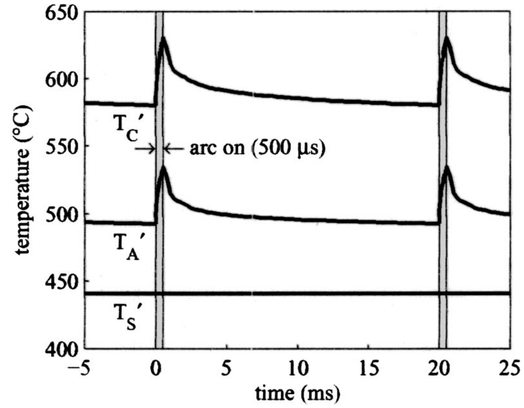

FIG. 4. Peak temperatures of the cathode (T_C'), anode (T_A'), and source body (T_S') from the transient model.

Figure 4 shows how the peak temperatures vary through the cycle. During the on period there is a rapid increase in the surface temperature of the materials directly exposed to the plasma. This temperature then decays away as the arc energy dissipates into the thermal mass of the material. The peak source body temperature does not vary because it is not directly in contact with the plasma. In a similar way there is no detectable change in temperature at the thermocouple measurement points. The maximum temperatures reached are indicated in Table I.

VI. FUTURE WORK

The validated FEA model of the ISIS operational H^- ion source will be invaluable for rapid prototyping of the improved cooling systems which will be required for higher duty cycle ion sources. The model will also be used to investigate the thermal effects of scaling the size of source components, an approach which has been demonstrated to offset increased heating.[4]

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[1] R. Sidlow *et al.*, Proceedings EPAC 96, 1996, THP084L.
[2] ALGOR Inc., 150 Beta Drive, Pittsburgh, PA 15238-2932 ⟨www.algor.com⟩
[3] ANSYS Inc., Southpointe, 275 Technology Dr., Canonsburg, PA 15317 ⟨www.ansys.com/cfx⟩
[4] J. D. Sherman *et al.*, Proceedings EPAC 2002, THALA002.