A THERMAL ANALYSIS AND OPTIMIZATION OF THE APT 210 kW POWER COUPLER*

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Abstract

This paper presents the thermal analysis and heat load optimization of the continuous power 210 kW, 700 MHz RF power coupler (PC) for the Accelerator Production of Tritium (APT). The PC is a co-axial design with RF power transmitted in the annular region between two concentric cylinders. Thermally, the PC represents a link from room temperature to the superconducting niobium cavities operating at 2 K. The analysis includes all the major heat transfer mechanisms: conduction, RF joule heating in normal and superconducting materials, infra-red radiation, and, forced and natural convection cooling of the inner and outer conductors. A performance comparison is given for one and two single point thermal intercepts, versus a counter-flow heat exchanger on the outer conductor. The benefits of reducing the operating temperature of the center conductor are discussed. The variation in thermal performance of the inner and outer conductors for several operating modes is also presented.

1 INTRODUCTION

The APT utilizes a linear accelerator to produce energetic protons, which strike a metal target of tungsten and lead, producing neutrons through spallation. The neutrons are captured in ^{3}He, producing tritium. The low energy portion of the accelerator uses conventional normal-conducting components, after which, the protons enter the superconducting accelerator section. The superconducting portion of the APT has cryomodules containing superconducting RF accelerating cavities separated by resistive focusing quadrupole magnets. The RF cavities are cooled by saturated superfluid helium at 2.15 K. Although there are two and possibly three variations of cryomodule, depending on the location of the module within the linac relative to the proton energy, this paper will focus on only the β=0.82 cryomodule.

Within a cryomodule, the PCs represent the second largest thermal load on the 2 K system, only the cavities generate a larger heat load. There are several objectives of the PC thermal analysis:

- Develop a model which accounts for the major heat loads and can be used to explore a wide range of geometries, material properties, and operating conditions;
- Ensure viable thermal operation of the PC; and
- Optimize total system refrigeration input power.

This paper will discuss each of the objectives in detail. Section 2 provides a description of the PC and the thermal model that has been developed. Section 3 presents the results for the inner and outer conductors and considers the implications of various cooling schemes on the cryomodule system total refrigeration input power. Section 4 gives a summary and discussion of the work.

2 DESCRIPTION OF THERMAL MODEL

Figure 1 shows a cut-away view of the PC as modeled, with a simple illustration of a counterflow heat exchanger for cooling of the outer conductor. The total length of the PC is about 1006 mm. Not shown are the two RF windows which couple the microwave power from the wave guide to the PC, mating at a 90° angle to the coupler at the 300 K end.

The outer conductor is 152.4 mm ID at the 300 K end and tapers to 100 mm ID at the 2.15 K end where it attaches to the beam tube. The co-axial inner conductor has a similar taper, going from 66.7 mm OD to 43.5 mm OD at the beam tube end. The outer conductor is 2.4 mm thick stainless steel plated with a 15 μm copper film on the inside. About 120 mm from the beam tube end, the outer conductor mates with a niobium nipple with RRR=40 and a wall thickness of 3.2 mm. The inner conductor is solid copper with RRR=50 and wall thickness of 1.5 mm. There is a concentric stainless steel tube within the copper tube (see Fig. 1) which provides coolant for the inner conductor. Helium gas enters the ID of the stainless tube from the left of Fig. 1, passes to the right end of the PC, and returns through a 3.2 mm radial gap between the stainless and copper tubes.

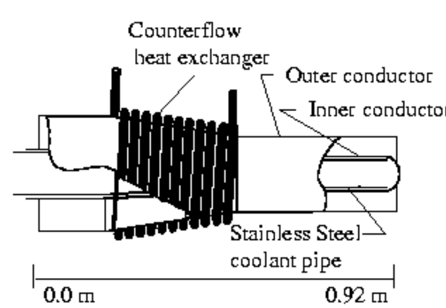

Figure 1: Schematic of the PC with a simple illustration of a counterflow heat exchanger on the outer conductor.

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The thermal model is axisymmetric, one-dimensional, and uses a finite difference approximation. There are over 200 nodes. Temperature dependent properties are used for the thermal conductivity, RF resistivity (RRR = 2, for 750 MHz), and specific heat and enthalpy of the helium gas coolant. Infra-red radiation heating is calculated assuming gray body, diffuse scattering through a CAD based program called RadCAD [1]. SINDA [2] is used for the thermal analyzer.

The heat transfer mechanisms considered for the inner conductor are:

- Conduction through copper (RRR=50)
- Radiation (gray body, diffuse, emissivity=0.3);
- RF heating (distributed or constant current); and
- Internal forced convection (supercritical helium in annular region).

The outer conductor heat transfer mechanisms considered are:

- Conduction through stainless steel (304L) and copper plating (thermal conductivity ratio=50);
- Radiation (gray body, diffuse, emissivity=0.3);
- RF heating (distributed or constant current); and
- Cooling - through localized single point thermal intercepts or distributed through forced convection counterflow cooling.

The emissivity value for copper has been chosen as 0.3. Typical values range from about 0.05 to 0.9 depending on the condition of the surface. We believe our selection of 0.3 represents a conservative choice for copper. How the emissivity will change over the 40 year life of the accelerator is unknown. The emissivity for niobium was also chosen as 0.3.

The inner and outer conductors are joined by a 1.27 mm thick copper plate at the furthest most position to the left of Fig. 1. This plate is the electrical shorting plate of the RF quarter-wave stub.

3 RESULTS

The analysis naturally divides into separate consideration of the inner and outer conductors. The temperature distribution on the inner conductor is only marginally coupled, via radiation, to the temperature distribution on the outer conductor, and hence, may be considered independent of the cooling scheme for the outer conductor.

3.1 Inner Conductor Results

The temperature distribution on the inner conductor was calculated for 210 kW traveling and standing wave (TW, and SW respectively) conditions, and for the special test condition of 500 kW TW. Figure 2 shows the RF-induced power distributions on the inner conductor for the 210 kW, 750 MHz TW and SW as calculated from MAFIA [3]. In Fig. 2, 0.0 represents the leftmost end of the PC shown in Fig. 1, and the beam tube interface is roughly at 0.92 m. Although the RF analysis shows an azimuthal power variation in addition to the axial dependence, the maximum circumferencial value of power dissipation at each axial position was chosen as a conservative and simplifying assumption. The data points show the power values as used at the individual nodal coordinates.

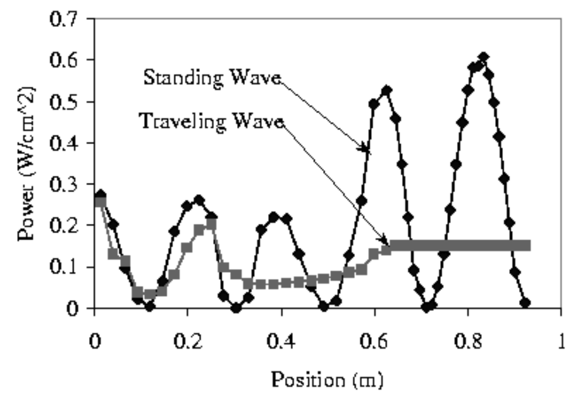

Figure 2. RF-induced heating distribution on the inner conductor for both the 210 kW standing wave and traveling wave.

Figures 3 and 4 show the resulting temperature distributions on the inner conductor and the coolant fluid, assumed to be 3 g/s, 300 K helium at 3 atmospheres at the inlet, in all cases. The temperature distributions from using a constant current with the same total power dissipation in the inner conductor are also shown.

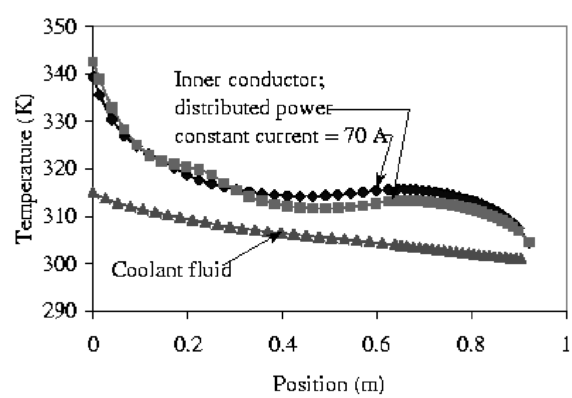

Figure 3. Temperature distribution in inner conductor (upper two curves) and cooling fluid (lower curve) for 210 kW TW. (235 W dissipated on inner conductor).

As seen in Fig. 3, the difference in temperature distribution between distributed power and constant current, is less than 5 K. The difference in the fluid temperatures for constant current vs distributed power is even less, so only one is shown in Fig. 3. The same small difference in temperature between distributed power and constant current is seen in the 210 kW SW results, Fig.4.

The results for the 500 kW TW are not plotted due to space limitations in this article. The highest temperature in the inner conductor is 365 K (at the leftmost end of Fig. 1) and the coolant fluid outlet temperature is 330 K. The results of the analysis of the inner conductor demonstrate that, for the operating conditions considered, the inner conductor is adequately cooled.

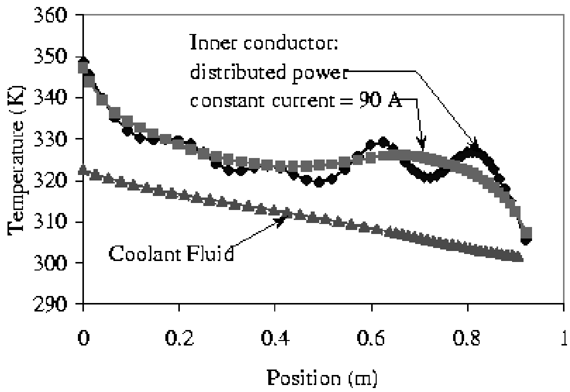

Figure 4. Temperature distribution in the inner conductor (upper two curves) and cooling fluid (lower curve) for 210 kW SW. (310 kW dissipated on inner conductor).

3.2 Outer Conductor Results

The outer conductor analysis focuses on the total room temperature refrigeration input power as a function of two different cooling approaches:

- The distributed cooling of the counterflow vs
- The localized cooling of single point intercepts.

Regardless of which cooling approach is chosen, the heat load to 2.15 K is largely determined in the niobium nipple. This may be understood by reference to the solution of the one-dimensional heat diffusion equation with constant thermal conductivity, k, and uniformly generated heat load, Q_{gen}. Equation 1 shows the solution for a Nb nipple of length, L and heat conduction cross-sectional area, A. The hot end is assumed to be at T_h, while the cold end is at T_c = 2.15 K. If the Nb is kept below its superconducting transition temperature of 9.2 K, the heat load generated in the Nb is mainly due to IR radiation = Q_{gen}. Q_c is the heat load at 2.15 K.

$$Q_c = \frac{kA}{L}(T_h - T_c) + \frac{Q_{gen}}{2} \tag{1}$$

There is an optimum length, L, since Q_{gen} will vary linearly with L, but, generally, L is chosen for mechanical or manufacturing reasons. To minimize Q_c, A should be made as small as practical, and k should also be small, i.e. RRR should be low. Q_{gen} can be reduced by lowering the emissivity of the materials (this has been discussed in an earlier section), or the inner conductor temperature can be reduced (this will be discussed later). In a typical situation, with geometry, emissivities and inner conductor temperature fixed, T_h, and hence, Q_c, are determined by the temperature developed by the cooling configuration at the stainless steel, Nb interface. Table 1 presents the heat loads at 2 K and at the various intercept temperatures, plus the resulting room temperature refrigeration input power. For example, the third configuration, with two single point intercepts, one at 7.8 K at the stainless steel niobium interface, and the other at 56 K at the location for minimum refrigeration input power, has respective heat loads of 7 W and 23 W, and a total 310 K refrigeration input power of 3550 W. Refrigeration input power is based on real refrigerator efficiencies of 0.13 and 0.18 (0.25 and 0.27) for 2.1 K (4.6 K) liquefaction and refrigeration loads respectively. When the lowest temperature intercept is above 9.2 K, a copper strap was used to connect the stainless steel/Nb boundary to the 2.15K helium vessel, which increases the 2 K heat loads.

Table 1. Calculated heat loads at 2 K, intercept 1 at T1, and intercept 2 at T2 for point intercepts, with T2 at optimal location. Calculated 2 K load for counterflow heat exchanger for coolant inlet temperatures of 2.6 K or 4.6 K. Wtot = total refrigeration input power.

Thermal intercept configuration	**Q at 2K (W)**	**Q at T1 (W:K)**	**Q at T2 (W:K)**	**W total (W)**
1 single point	1.8	15:4.6	-	5525
1 single point	4.3	53:15	-	7570
2 single points	2.4	7:7.8	23:56	3550
2 single points	4.1	6.2:15	24:56	4400
Counterflow 2.6 K, 0.07 g/s	1.9	-	-	3070
Counterflow 4.6 K, 0.07 g/s	2.0	-	-	3371

Lowering the inner conductor temperature can reduce the 2 K radiation load, Q_{gen}, but the work required to remove the inner conductor heat load at the reduced temperature increases. Using the double point intercept at 7.8 K and 56 K as an example, the total refrigeration input power can be reduced by as much as 26% by lowering the inner conductor coolant temperature to 200 K.

4 SUMMARY

A thermal model has been built which accounts for the major heat loads in the 210 kW PC. Inner conductor results indicate adequate cooling under TW and SW conditions. There is a 14% reduction in refrigeration input power by using 2.6 K counterflow cooling on the outer conductor over the best double point cooling approach. Further trade-off studies on the outer conductor cooling scheme are required. Lowering the inner conductor temperature adds complexity to the system, but offers a 26% reduction in PC refrigeration input power.

5 REFERENCES

[1] CAD based thermal radiation analyzer, Cullimore and Ring Technologies, Inc, Littleton, CO, crtech@netcom.com.

[2] Systems Improved Numerical Differencing Analyser, Cullimore and Ring Technologies, Inc, Littleton, CO, crtech@netcom.com.

[3] Electromagnetic Simulator, CST, D-64289 Darmstadt, Germany, info@sct.de