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An Experimental and Analytical Study of a Buoyancy Driven Cooling System for a Particle Accelerator*

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Abstract

A buoyancy driven closed-loop cooling system that transports the heat generated in a particle accelerator to the ambient has been evaluated both through experiments performed earlier [1] and analysis techniques developed elsewhere [2, 3]. Excellent comparisons between measurements and calculations have been obtained. The model illustrates the feasibility (from a heat transfer viewpoint) of such a cooling system for a particle accelerator.

I. INTRODUCTION

The primary purpose of this study was to establish the feasibility of cooling a typical particle accelerator by a *purely* natural convection, closed-loop, cooling system without the need for pumps, blowers etc. However, the use of fins and blowers were also evaluated as a secondary objective.

Consideration was given to a low energy booster (LEB), radio-frequency (RF) cavity, tuner concept at the Superconducting Super Collider (SSC) (Figure 1). During operation the heat generated in the tuner has to be removed in order to maintain the ferrites at a safe temperature. While studies of forced flow [4] and solid conduction [5] cooled tuners are available, a study of a natural convection cooled tuner has not been reported.

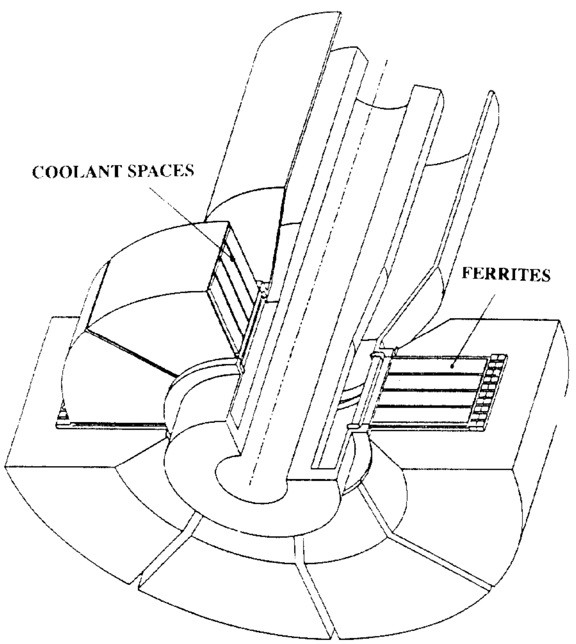

Figure 1. SSC, LEB, RF-cavity concept.

The cooling system involved the use of a coolant storage tank. The bottom of the tank and the tuner as well as their tops were assumed to be connected by tubes. Due to heat generation, the coolant in the tuner will rise and exit through the tubes at the top and flow to the tank. To conserve mass, coolant from the bottom of the tank will flow to the tuner, creating a closed-loop flow of the coolant. Since the flow will occur automatically in response to the magnitude of the heat input rate, the system is self-controlling. The general features of such a cooling system should be the same for any particle accelerator. Only the parameter values may be different.

II. EXPERIMENTS

The experiments consisted of submerging heated plates (that simulate the ferrites) vertically in a tank of water, and measuring the transient water and plate temperatures (Figures 2 and 3) [1]. Heat was generated in the plates by embedded resistive heaters (to simulate tuner operation). The plate temperature vs time at different locations are given in Figure 4.

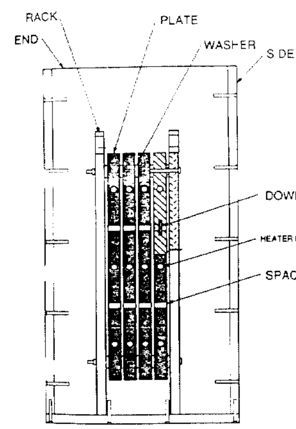

Figure 2. Experimental apparatus (front view).

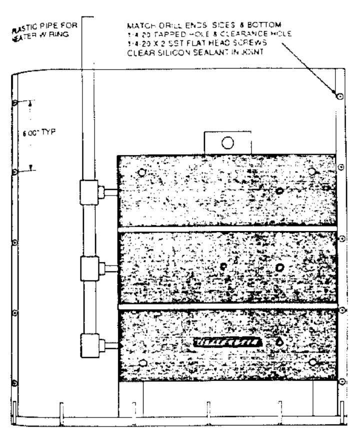

Figure 3. Experimental apparatus (side view).

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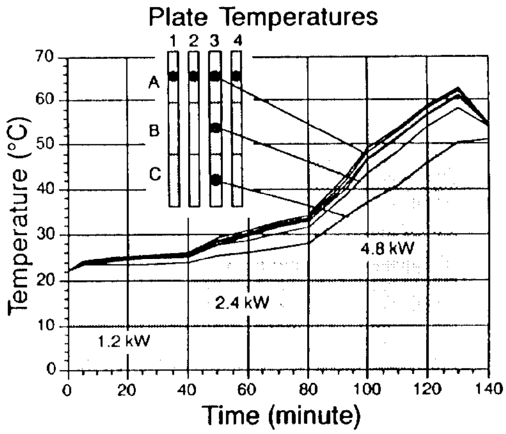

Figure 4. Plate temperatures.

III. ANALYSIS

The heat transfer and flow were assumed to be transient and one dimensional with temperature dependent properties. The Boussinesq approximation was invoked. Conduction in the water was neglected [2, 3]. The momentum balance giving the coolant velocity between the ferrites was derived as:

$$f_e = Gr / Re^2$$

where f_e is an equivalent coefficient of friction; the length scale is the ferrite spacing; Gr is the time-dependent Grashoff number based on the tuner and tank temperatures; and Re is the time-dependent Reynolds number. The above expression is coupled to the governing conservation equations of mass and energy and the set of partial differential equations was integrated in a lagrangian fashion using the predictor-corrector technique [2].

IV. VALIDATION

Figure 5 shows the comparison between measurements and analysis of the water temperature with time. The corresponding water flow rate (between the plates) indicates a spike each time the heat load is increased (according to the schedule shown in Figure 4). The model is "non-empirical," in the sense that there are no constants in the input to "adjust" the results. In this context, the close comparisons obtained are noteworthy. Note also that the present model has given good comparisons with measurements in an earlier application [2].

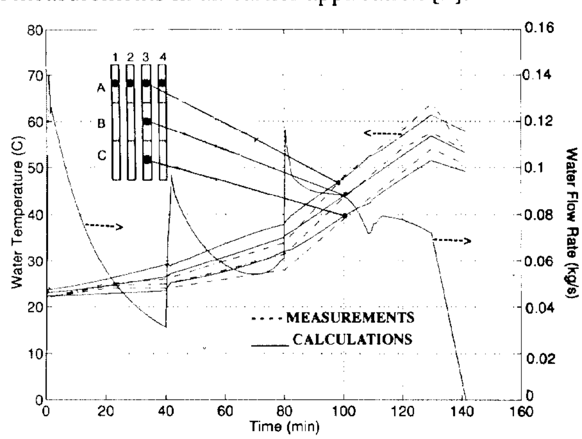

Figure 5. Comparison of measurements and calculations.

V. RESULTS

A. *Baseline Designs*

Two baseline configurations were considered, one for a copper plated tuner housing and the other without copper plating. Though different coolants were considered, only results for water are given here. The parameters for a tuner with a copper plated housing were: datum = tuner bottom, tank volume = 0.5 m^3, tank height = 0.5 m, elevation of tank bottom = 0 m, heat transfer coefficient on the tank surface = 1 $W/m^2 °C$, tube inside diameter = 50 mm, number of tubes at the bottom (top) = 3 (3), initial temperature = 20°C, maximum tuner operation time = 3 hours, housing heat load = 2.5 kW.

For a tuner housing without copper plating, the baseline parameters were the same (as the above baseline) with the following exceptions: tank volume = 2.5 m^3, tank height = 1 m, the number of tubes at the bottom (top) = 12 (12) and housing heat load = 25 kW. For this case a coolant jacket was assumed to be used due to the high heat load on the housing.

Figure 6 shows the temperature distribution in the tank, tuner water and ferrites at hourly intervals, for the baseline case with no copper plating. After three hours of operation of the tuner, the peak ferrite temperature of 77°C is less than the boiling point of water and the curie temperature of ferrite (200°C). The thermal stratification in the tank is due to the poor (zero) conductivity of water and this has been observed in other experiments [2, 3].

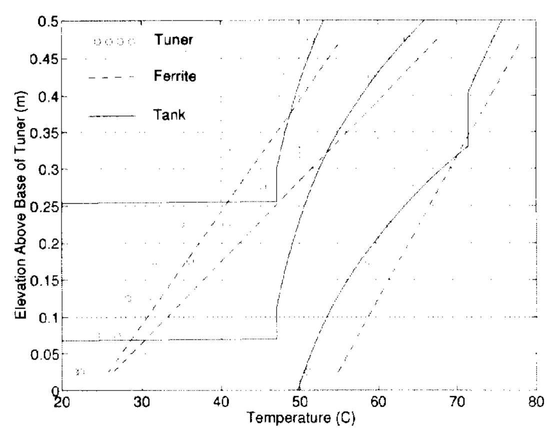

Figure 6. Water cooled tuner: housing = 25 kW.

B. *Senstivity Studies*

The sensitivity of the baseline designs to the height, the elevation and the volume of the tank, the heat transfer rate from the tank, the number and diameter of the tubes are shown in Figures 7 through 9 (after 3 hrs of operation). The baseline cases are denoted by the letters B. The spikes in the curves are caused by the thermal stratification in the tank, which results in a sudden elevation of the tuner temperatures at intervals. Heat transfer coefficients (in $W/m^2 °C$) on the tank varying from 1–10 (free convection of air), 100 (blowing of air), 1000 (finned tank with free convection), and 10000 (finned tank with blowing air) were considered. An optimum cooling system can be chosen based on these results.

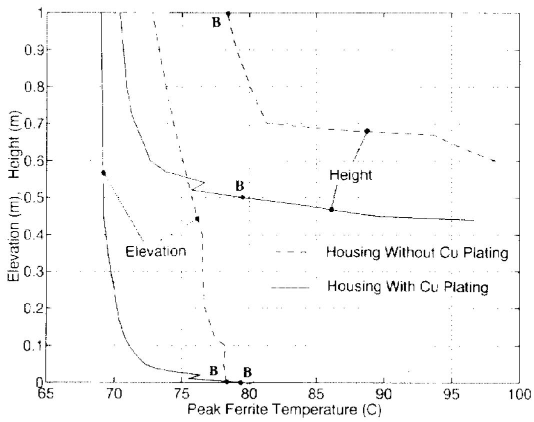

Figure 7. Effect of the height of the water within the tank and the elevation of the tank bottom above the datum.

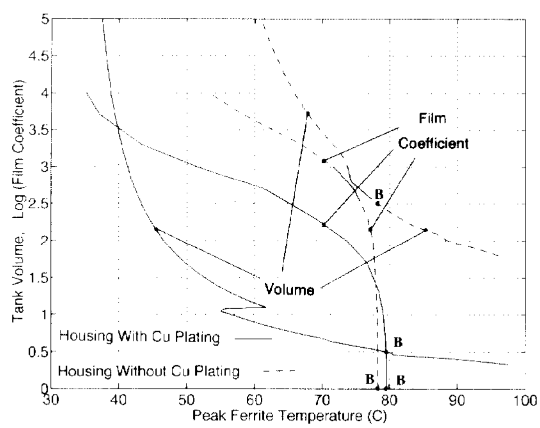

Figure 8. Effect of the tank volume (m^3) and the $\log^{10}$ of the film coefficient ($W/cm^2 {}^\circ C$) on the tank outside surface.

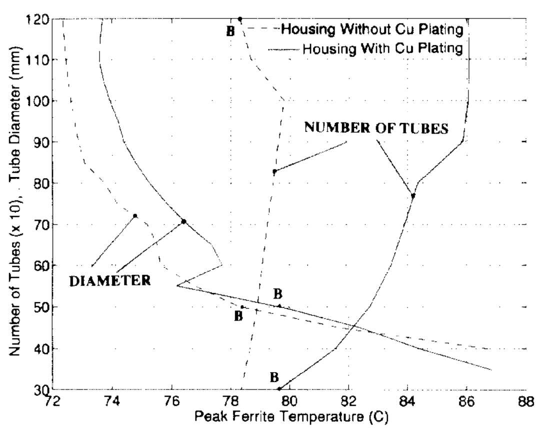

Figure 9. Effect of the number of tubes and the tube diameter.

VI. SUMMARY

A closed-loop, buoyancy driven, cooling system for a particle accelerator has been experimentally and analytically evaluated. Sensitivity studies indicate the feasibility of such a cooling system for an SSC, LEB, RF cavity tuner concept from a heat transfer viewpoint. The present model can be used to thermally optimize such cooling systems for particle accelerators.

VII. REFERENCES

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