An Experimental Investigation of an Air Cooling Scheme for the

Multichip Modules of the Multiplicity and Vertex Detector

by

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Abstract

This report presents a summary of an experimental investigation of an electronics air cooling system for the multiplicity and vertex detector (MVD), a device used to determine and characterize the collision location of two accelerated heavy ions. Measurements of the flow rates of the cooling air and the temperatures of the air and electronic components were used to assess and optimize the performance of the proposed air cooling system, identify potential assembly problems and system limitations, and provide the necessary information for designing and sizing the final MVD cooling system components.

NOMENCLATURE

Symbol	Description
c_p	Specific heat (J/Kg K)
n	Number of instrumented multichip modules (MCMs)
Q	Volumetric flow rate (m^3/s)
q_{MCM}	Power dissipation of an individual MCM (W)
T	Temperature (°C)
	T' Air temperature corresponding to a condition of zero power input to the MCMs
ρ	density

Subscript	Description
f	Property corresponding to the air
i	inlet
MCM	Property corresponding to an MCM
o	outlet

INTRODUCTION

The PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is being developed to detect and investigate a phase of matter called the quark-gluon plasma. This will be achieved by accelerating heavy ions to 100 GeV/nucleon and allowing them to collide. To determine the collision point and characterize the event, PHENIX will employ the multiplicity and vertex detector (MVD). Highly detailed information concerning all aspects of the MVD is available (http://p2hp2.lanl.gov/phenix/mvd), but only relevant and brief introductory information is provided here.

The MVD, shown in Figure 1, resides in an enclosure that opens in a "clam-shell" fashion to allow for installation around the beam pipe in which the ion collisions will occur. Each clam-shell-like half of the MVD houses twelve "C-shaped" cages, each of which contains silicon strip detectors, used to detect charged particles emitted during heavy ion collisions. Each silicon detector is connected by means of a Kapton cable to its own front-end electronics circuit board, also referred to as a multichip module or MCM. The

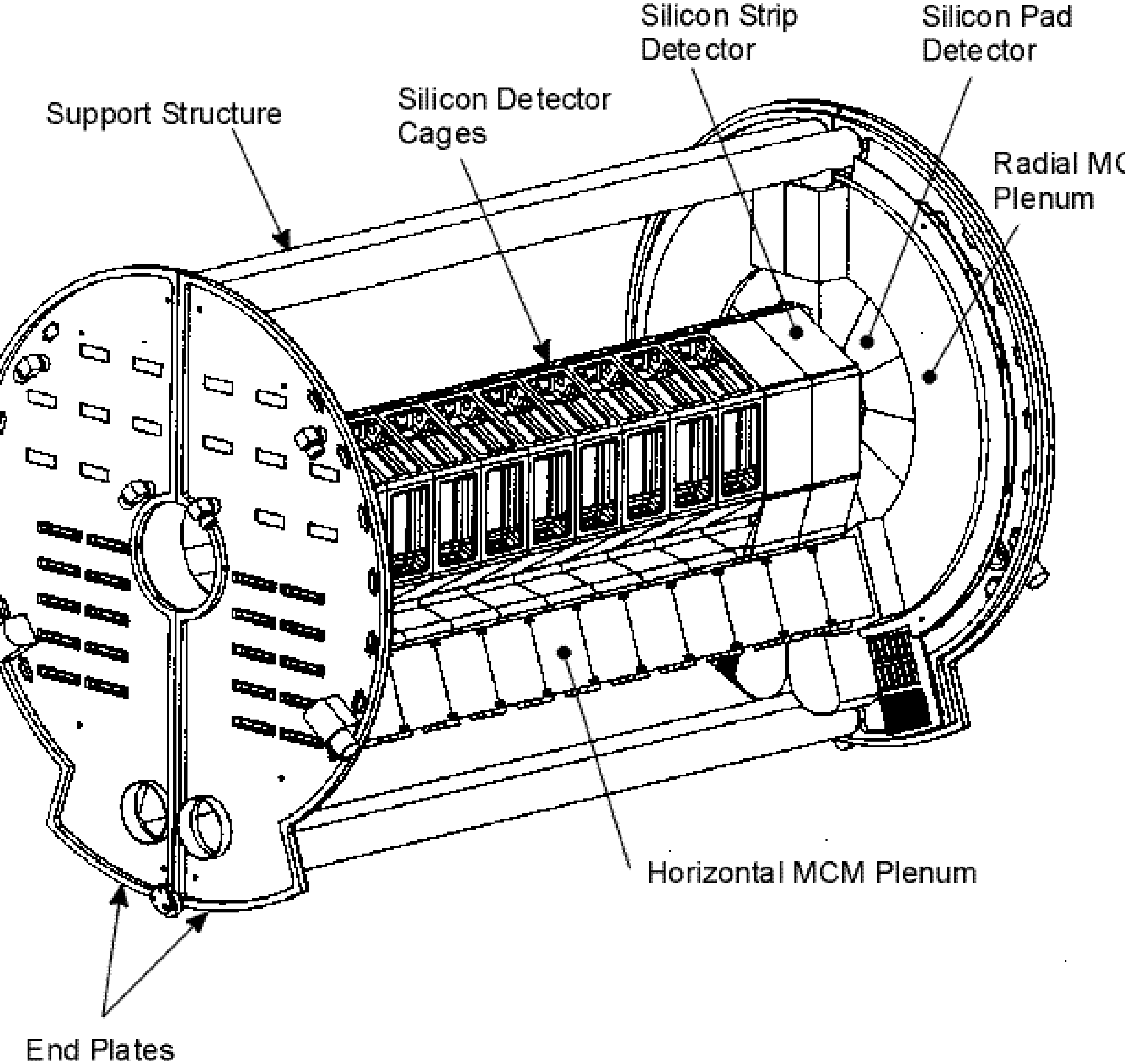


Figure 1. Schematic diagram of the MVD showing the full set of silicon detector cage assemblies, horizontal MCM plenum, support structure, and end plates including motherboards, pad detectors, and radial MCM plenums.

disk-shaped endplates located on either end of the MVD each contain a total of twelve silicon pad detectors and twelve corresponding MCMs. The MCMs corresponding to one set of twelve C-cages (or one half of the MVD) are contained in a horizontal Rohacell foam plenum located beneath the C-cages. This plenum houses the MCMs and provides a channel for the cooling air. The C-cages in the center of the detector are partially populated with silicon detectors in order to minimize the amount of material in the electron-sensitive acceptance of PHENIX. Thus, a complete MVD will contain two sets of twelve C-cages with two horizontal MCM plenums and two radial endplates, each with twelve silicon pad detectors and corresponding electronics.

The electronics in the MCMs generate a relatively high amount of waste heat that must be effectively dissipated to ensure reliable operating temperatures. Past investigations [1,2,3] have studied the feasibility of using a forced convection air cooling system to maintain these temperatures. An air cooling system is more desirable than a liquid system as the former represents less mass in the PHENIX electron acceptance. The following design criteria were specified for the MCM electronics and associated air cooling system:

- Maximum allowable MCM operating temperature ---------------------------- 50°C
- Cooling system design goal for maximum MCM operating temperature---- 40°C
- Approximate power dissipation of single MCM------------------------------ 3.8 W
- Cooling air supply temperature--- 10 to 20°C
- Dimensions of MCM ------------------- 50 mm (H) by 48 mm (L) by 1.7 mm (T)
- Equal and uniform heat dissipation from each side of all MCMs

The purpose of this study was to determine the performance of the proposed air cooling system in a realistic geometry, identify potential problems and limitations, define assembly and system integration issues, and provide the necessary information for designing and optimizing the final MVD cooling system.

EXPERIMENTAL METHODS

For the present study, a full-scale mock-up of a portion of the PHENIX apparatus to which the MVD mounts and one half of the MVD were used. In addition, a complete plumbing system that closely emulated the anticipated final system was employed to fully investigate assembly and performance issues. Only one half of the MVD was used because the two halves are mirror images and rely on separate but identical cooling systems. A photograph of the entire mock-up, including the experimental MVD air cooling system, is shown in Figure 2. Further details of the major air cooling system's components are provided in the schematic of Figure 3.

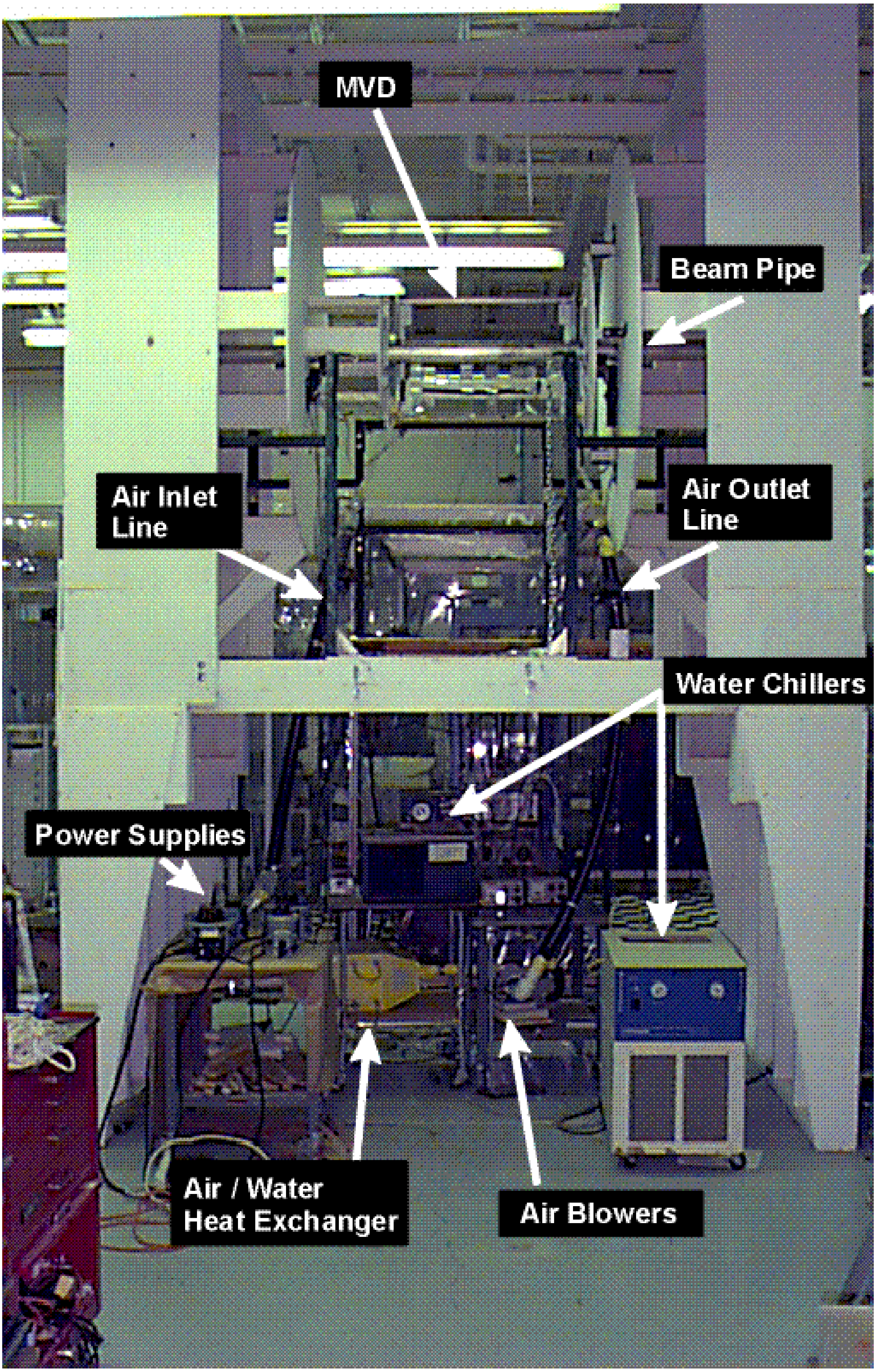


Figure 2. Photograph of the experimental MVD air cooling system set-up.

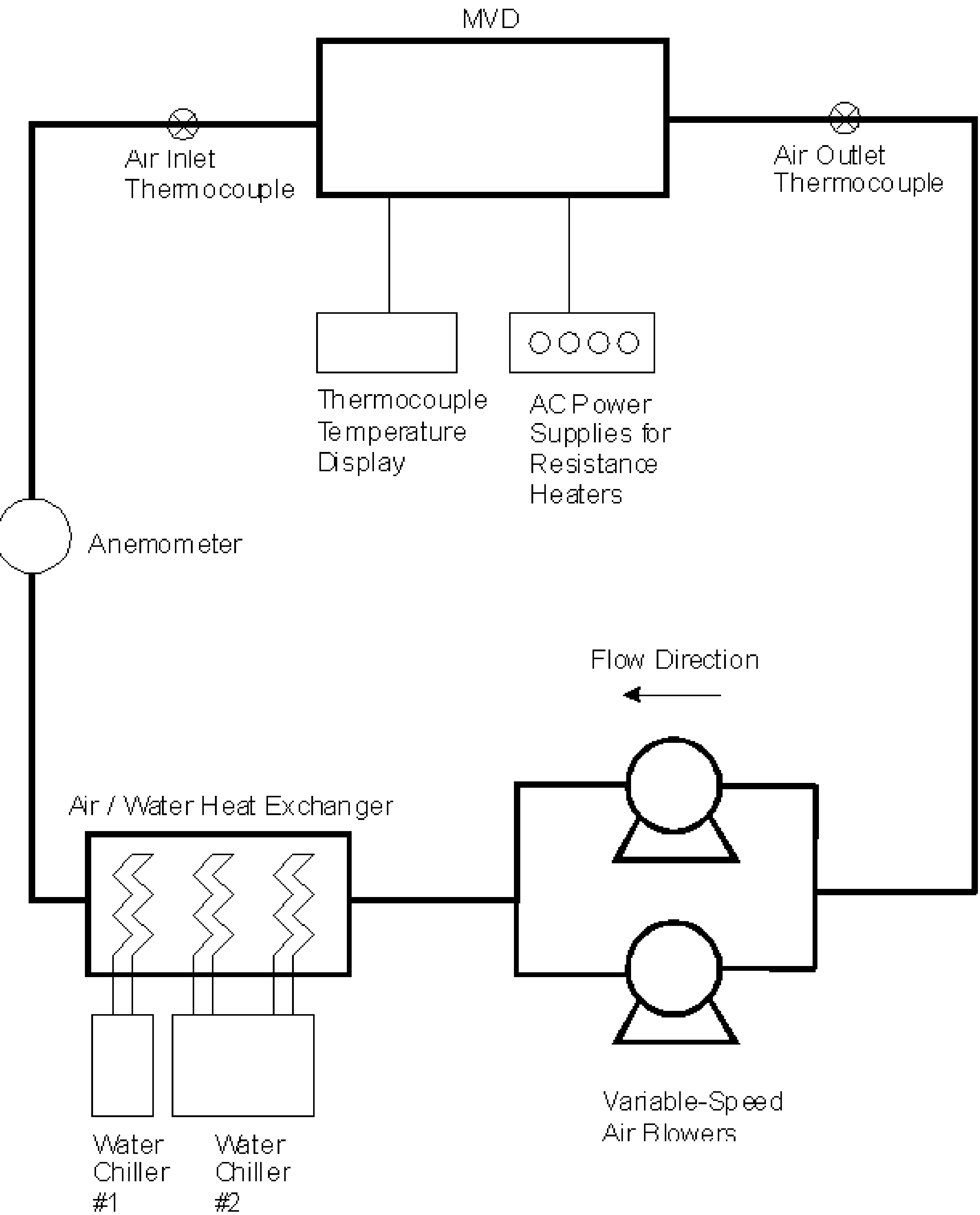


Figure 3. Schematic diagram of the experimental air cooling system for the MVD electronics

Air cooling was provided in a closed-loop circulation system by two Ameteck Windjamer blowers connected in parallel. An air/water heat exchanger comprised of three Car Quest Transmission Oil Coolers connected to two water chillers (VWR Scientific 1174 and a Neslab Endocal) was used to precool the air supply and remove the MCM waste heat from the system. Two inch diameter PVC lines and flexible hoses were used to connect the cooling system components to the MVD. A Sper Scientific 840003 anemometer (0 to 44.8 m/s, 0.1 m/s resolution with ±3% accuracy) was used to monitor the MVD inlet air volumetric flow rate. A TSI 8340 hot-wire air velocity meter (0 to 10.2 m/s, ±5%) was used to monitor air velocities within the horizontal MCM plenum.

Upon entering the MVD, the supply air was immediately divided into two streams by a flow diverter. The majority of the airflow was directed into the horizontal MCM plenum. A secondary air flow stream was directed into the first of two radial MCM plenums. This secondary air flow stream exited the first radial plenum, passed through the upper aluminum support member, and then entered a second radial MCM plenum on the opposite end of the MVD. After passing through the second radial plenum, the secondary air flow stream rejoined the air exiting the horizontal MCM plenum and the combined airflow exited the MVD. The major components of the air cooling passages in the MVD are shown in the photograph in Figure 4.

Each MCM was fabricated from aluminum sheet with the dimensions specified above. Each radial plenum on the MVD endplates contained 6 MCMs in the radial pattern depicted in Figure 5(a). Passages on both sides of the MCMs allowed for the necessary flow of cooling air. The horizontal MCM plenum was made up of 12

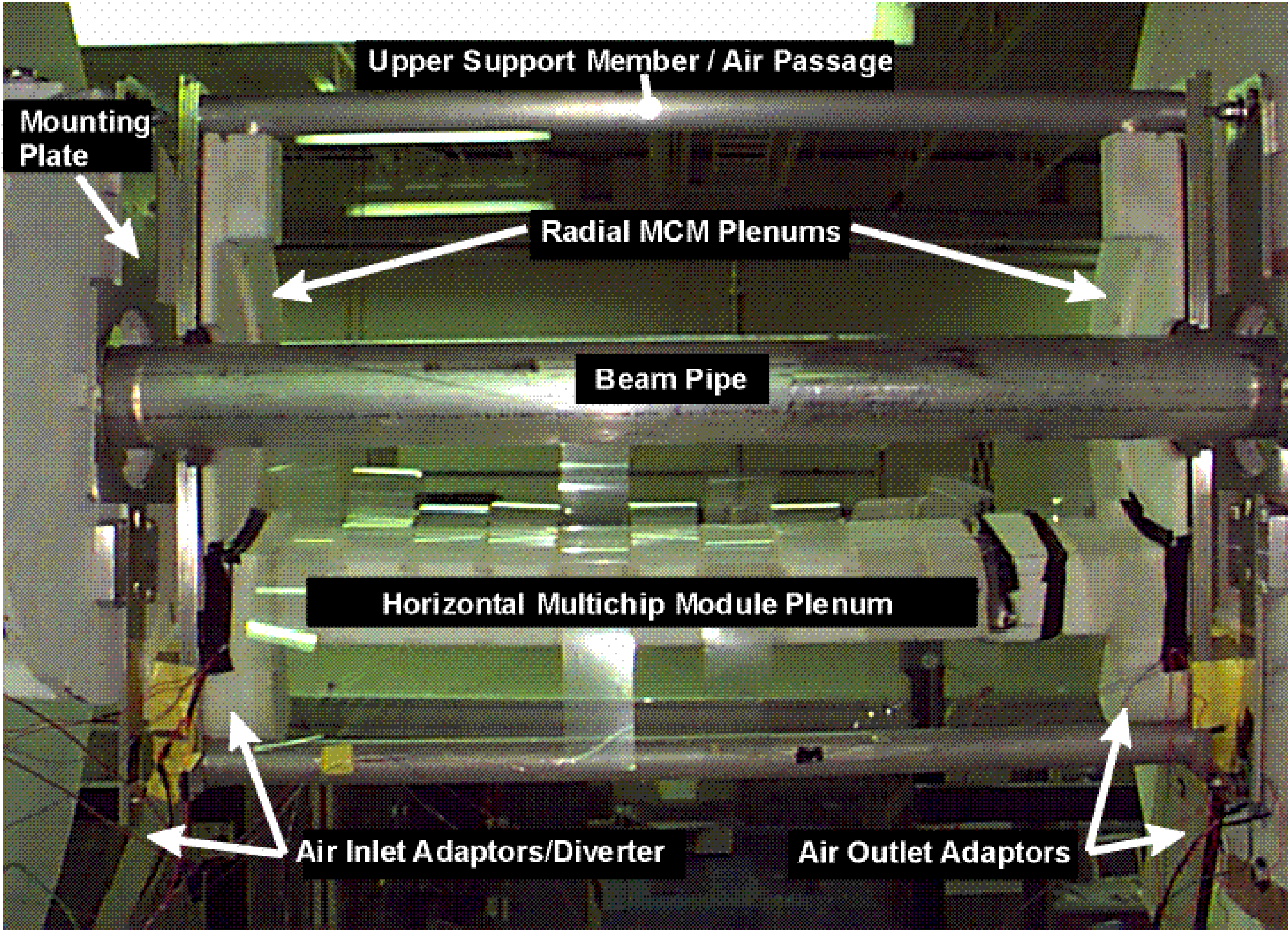
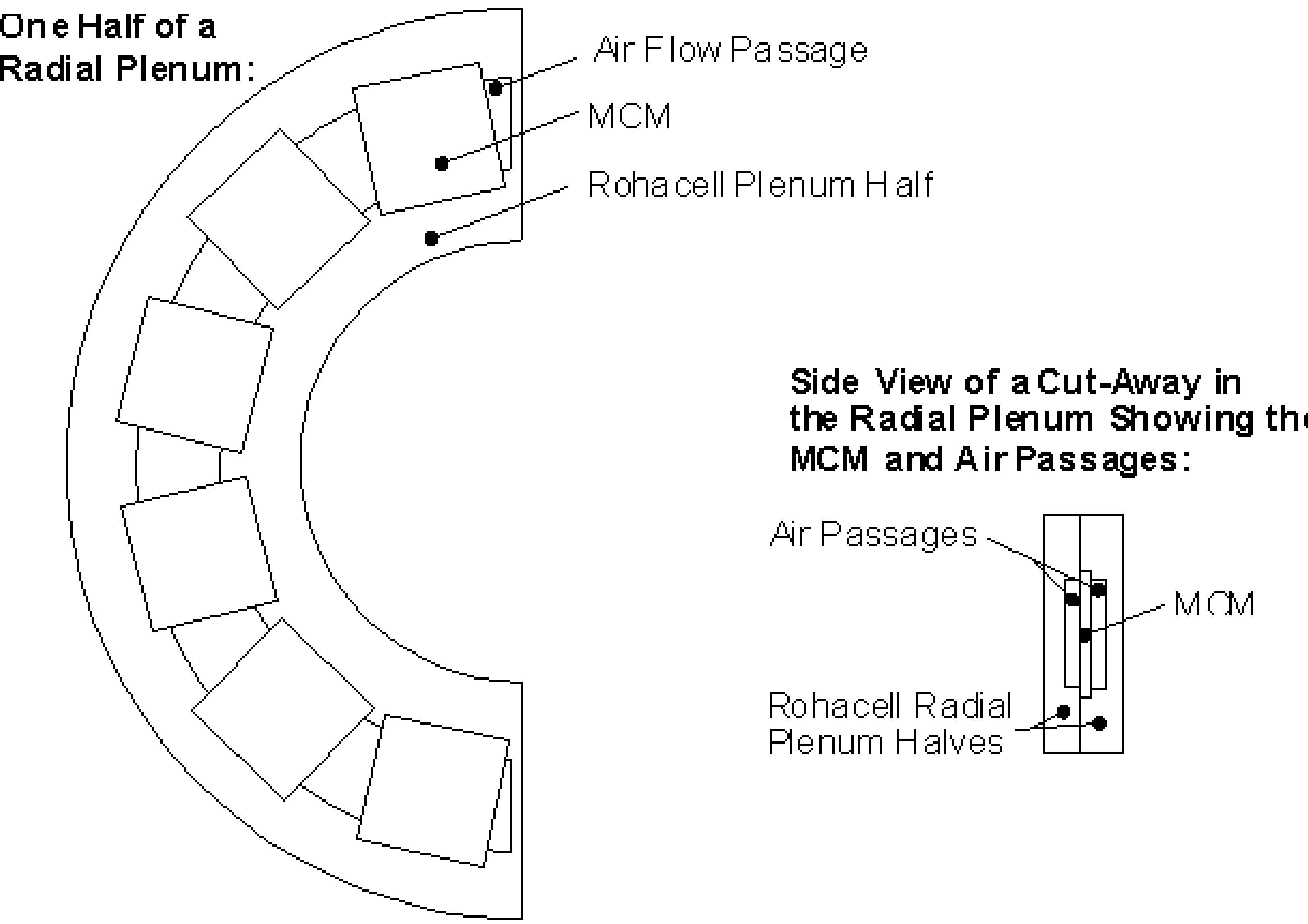
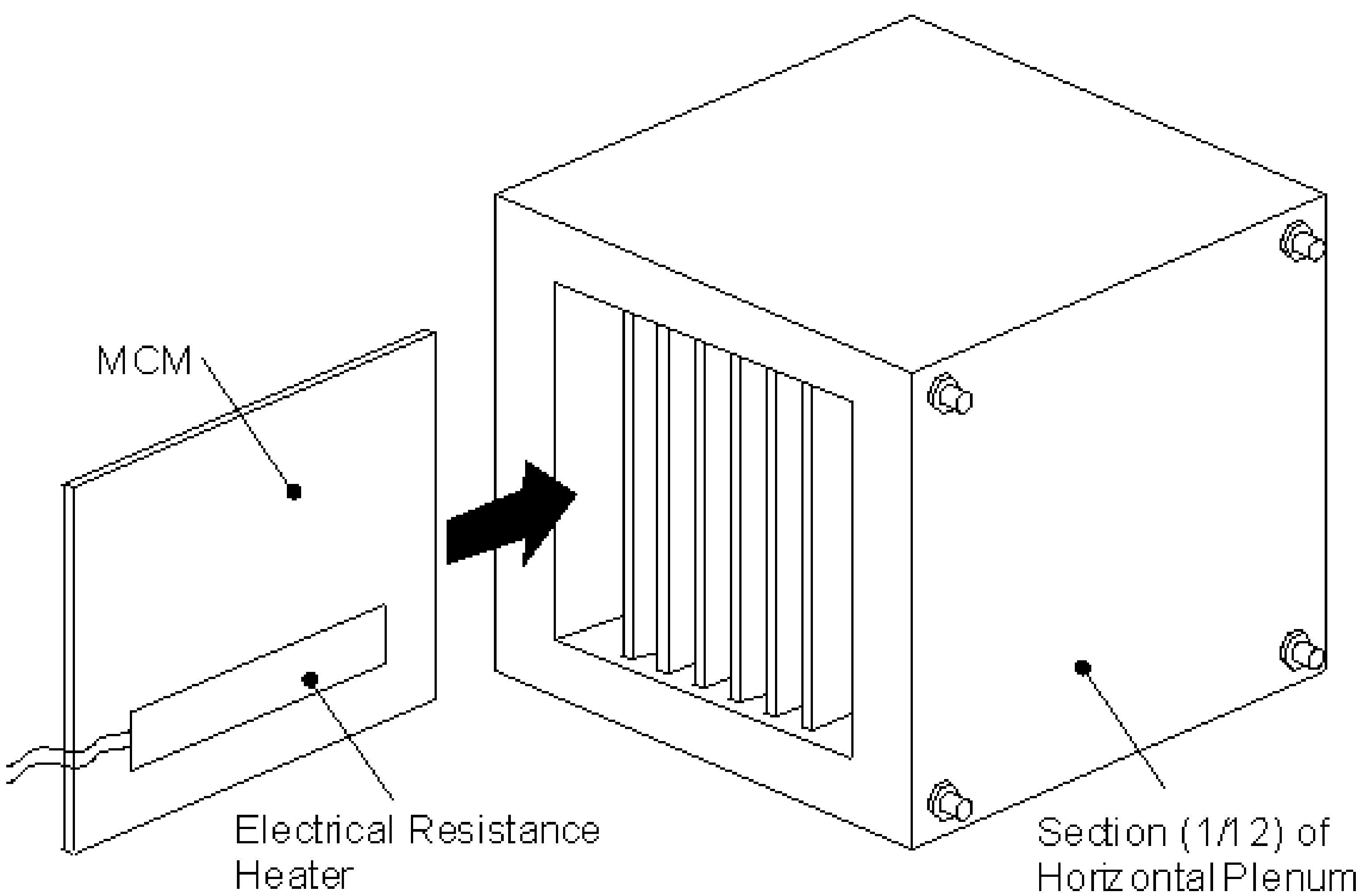


Figure 4. Photograph of the experimental MVD used in the air cooling tests.



(a)



(b)

Figure 5. MCM placement in the (a) radial and (b) horizontal plenums.

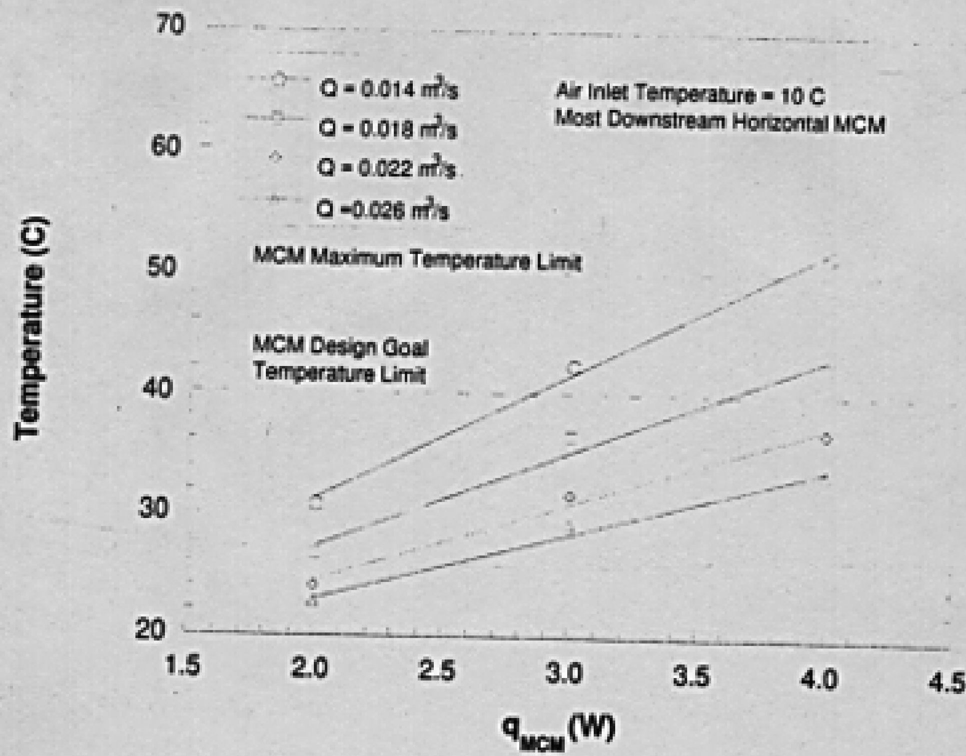
sectors,one of which is shown in Figure 5(b). Six MCMs were spaced approximately 6 mm apart to allow for the flow of cooling air. The first two and last two sectors contained six instrumented (supplied with an electrical resistance heater) MCMs each, while the center eight sectors each contained four instrumented MCMs and two dummy (no resistance heater) MCMs for flow uniformity. This distribution of instrumented MCMs was the result of the non uniform distribution of the associated silicon strip detectors along the length of the MVD. A Minco electrical resistance heater capable of dissipating 5 W was attached with a conductive adhesive to each instrumented MCM as shown in Figure 5b. Four 120 V AC power supplies were used to control the heat dissipation of the radial and horizontal plenum MCMs with an accuracy of ±5%. Type T thermocouples were used to record the temperatures of the MVD inlet and outlet air at the respective MVD air line connectors, an MCM in the horizontal plenum sector closest to the air outlet, and the first, seventh, and twelfth MCMs in the radial plenums (counting from the air inlet side). The thermocouples possessed an accuracy of ±0.5°C and were found to agree to within 0.5°C of a mercury thermometer at 23°C.

The experiments were initiated by precooling the circulating air with the water chillers and heat exchanger to the desired MVD inlet temperature for a specified inlet air volumetric flow rate. The air volumetric flow rate was monitored immediately before the MVD air inlet adapter with an anemometer and was adjusted by using the variable-speed air blowers. Next, the AC power supplies were set to provide the desired power dissipation of the MCMs. During the MCM heat-up phase, the water chillers had to be fine-tuned to account for the extra heat load of the MCMs in order to maintain the proper air inlet temperature. The temperatures of the air and the MCMs were continuously monitored by an Omega DP462 six channel thermocouple display. Once equilibrium was established, the power setting, air volumetric flow rate, and air and MCM temperatures were recorded. This procedure was conducted for MCM power rates of 0, 2, 3, and 4 W, for air inlet temperatures of 10 and 20°C, and for air volumetric flow rates of 0.014, 0.018, 0.022, and 0.026 m^3/s. Several runs were repeated for a single set of operating conditions to ensure reproducibility. Tests corresponding to an MCM power setting of 0 W were performed to determine the heat gain to the cooling air by the environment. This environmental heat gain data was later used in energy balances to determine temperature and air flow rate measurement accuracies. Finally, a hot-wire anemometer was used to take air velocity measurements in the horizontal plenum for a variety of MVD inlet air volumetric flow rates. This was done to determine the approximate division of airflow between the radial and horizontal plenums as well as to provide the horizontal plenum air velocity information required for comparing the experimental temperature results to previous numerical model data [3].

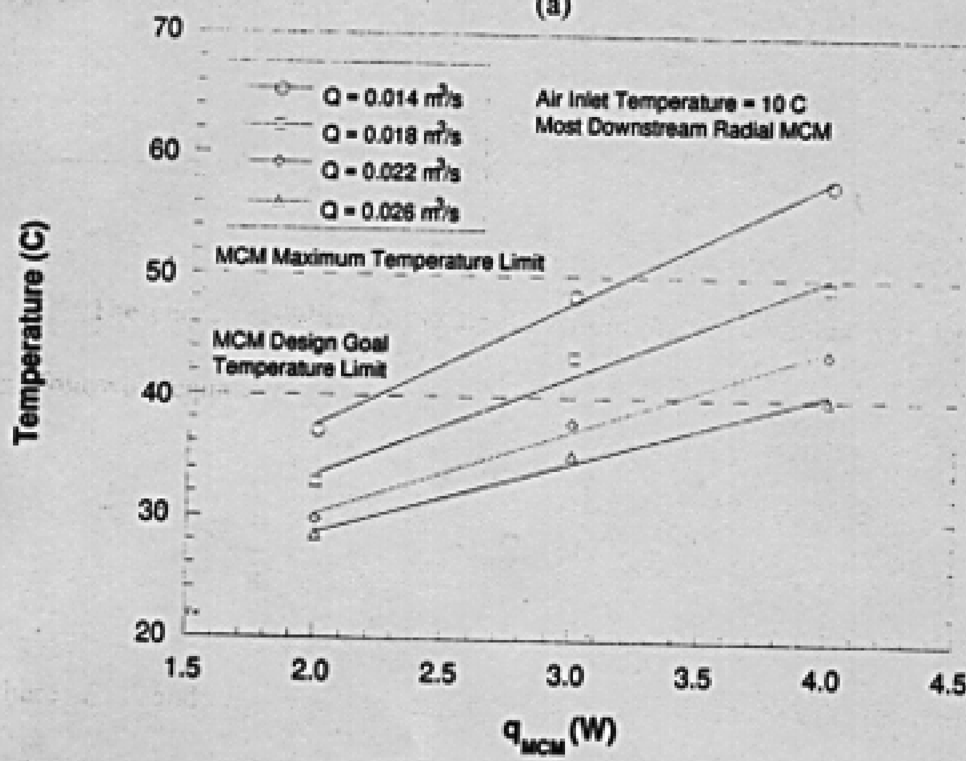
RESULTS

Experimental Data

The results presented in this paper show the effects of individual MCM operating power, air inlet temperature, and air inlet volumetric flow rate on the steady-state temperature of the most downstream MCMs in the radial and horizontal plenums.



(a)



(b)

Figure 6. Plots of temperature versus individual MCM operating power for various air volumetric flow rates and an air inlet temperature of 10 C for the most downstream (a) horizontal plenum MCM and (b) radial plenum MCM.

Figures 6(a) and 6(b) display the MCMs' temperature versus operating power for four different air volumetric flow rates with a 10°C inlet air temperature for the most downstream MCMs in the horizontal and radial plenums, respectively. In each plot, the upper MCM operating temperature limit of 50°C and the design goal of 40°C are also noted. As expected, both plots show the trend of increasing MCM temperature with increasing MCM operating power, $q_{MCM,}$ and/or decreasing air volumetric flow rate, Q. For the current system design, Figures 6a and 6b indicate which operating conditions result in a satisfactory MCM temperature of ≤ 40°C. At the higher power settings and lower flow rates, however, the design goal temperature limit is exceeded. For a single set of operating conditions, the data in Figure 6 indicates that the most downstream radial plenum MCM consistently operates at a higher temperature than the most downstream horizontal plenum MCM. This suggests that the air flow rate in the radial plenums should be increased slightly at the expense of the horizontal plenum, a task which can be accomplished by changing the air inlet and outlet flow adapter/diverter geometries.

The reproducibility of the experimental data is displayed in Figure 7, which shows agreement to within 1°C for repeated tests. In addition, an energy balance was checked for each data point to ensure measurement accuracies. In the following energy balance equation, the left-hand side represents the energy supplied to the air by the n instrumented MCMs, $n\ q_{MCM}$, and by the environment, q_{gain}, and the right-hand side represents the total enthalpy gained by the air as it passes through the MVD with a volumetric flow rate Q:

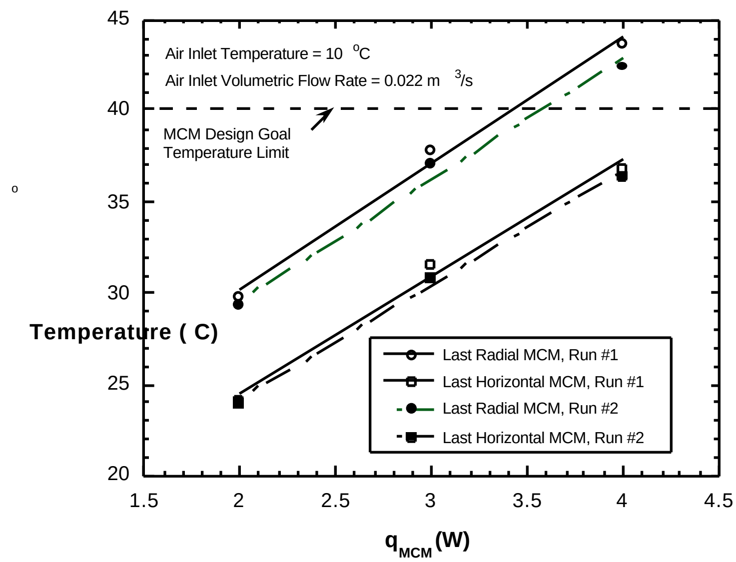


Figure 7. Reproducibility plots of temperature versus individual MCM operating power for an air volumetric flow rate of 0.022 m^3/s and an air inlet temperature of 10 ^oC for the most-downstream horizontal and radial plenum MCMs.

$$nq_{MCM} + q_{gain} = \rho_f \, Qc_{p,f} \, (T_{f,o} - T_{f,i}) \, . \qquad (1)$$

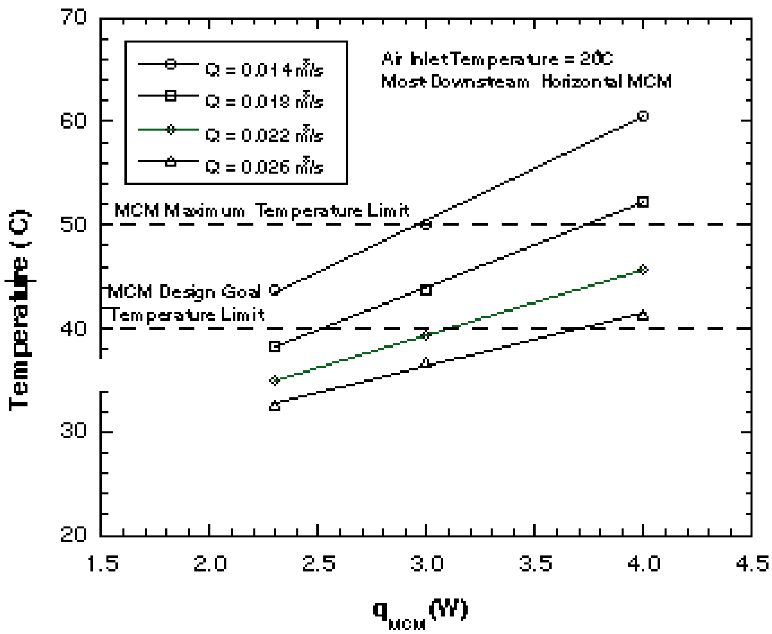
The energy supplied to the airflow from the environment was determined from the following equation:

$$q_{gain} = \rho_f \, Qc_{p,f} \, (T'_{f,o} - T'_{f,i}) \, , \qquad (2)$$

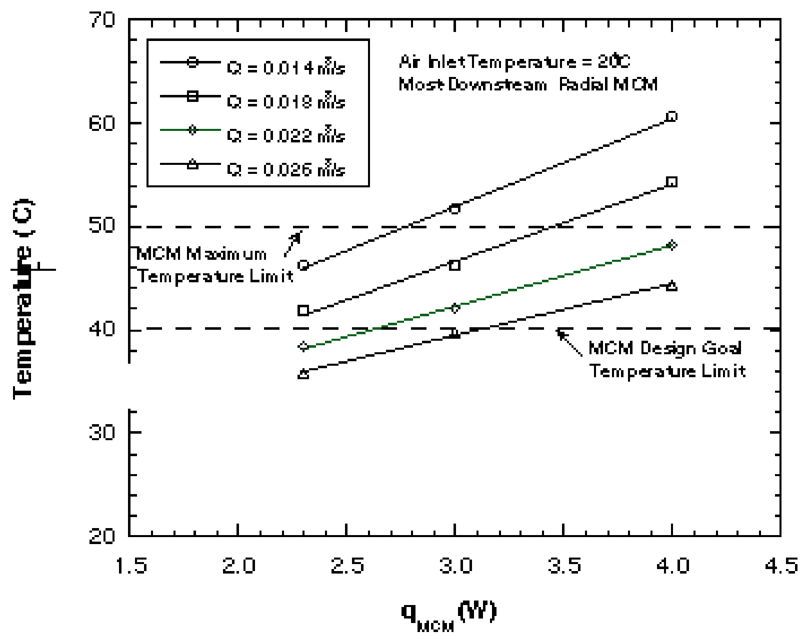
where $T'_{f,o}$ and $T'_{f,i}$ are the experimentally measured MVD air outlet and inlet temperatures, respectively, that correspond to an air volumetric flow rate Q, when no power is being supplied to the MCMs (q_{MCM} = 0 W).

The left and right-hand sides of Equation (1) were found to agree to within 14% for all of the experimental data, indicating that the measurement techniques were supplying acceptable results. The environmental heat gain measurements of the airflow, the energy balance results, and the full set of experimental data are tabulated in the appendix.

The MCM operating temperature performance for an air inlet temperature of 20°C is shown in Figure 8. All trends shown and discussed previously in terms of Figure 6 are again evident in Figure 8. The major difference is that for a given volumetric air flow rate and MCM operating power, the MCM operating temperature has increased several degrees above that obtained with the 10°C inlet air temperature. For the majority of data points given in Figure 8, the temperature limit is exceeded. Consequently, it can be

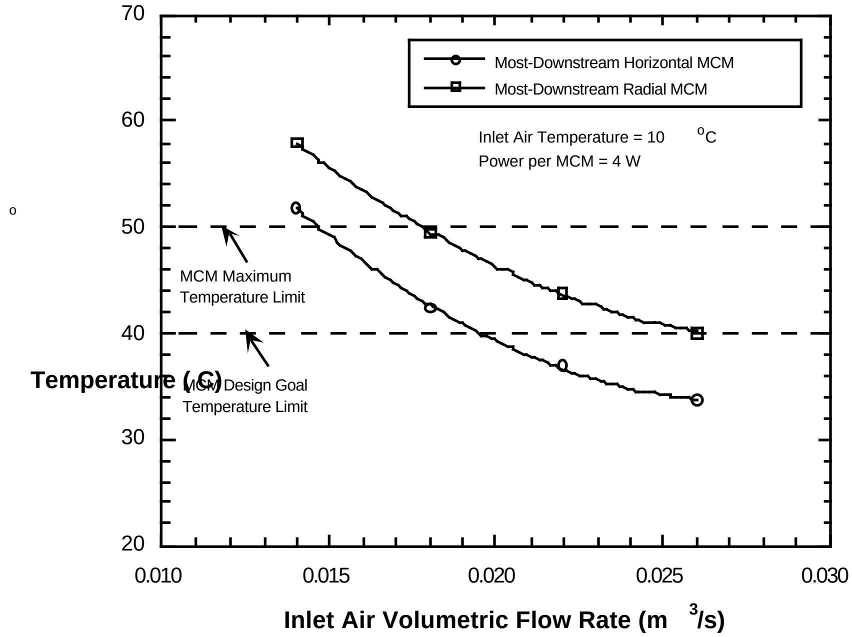


(a)

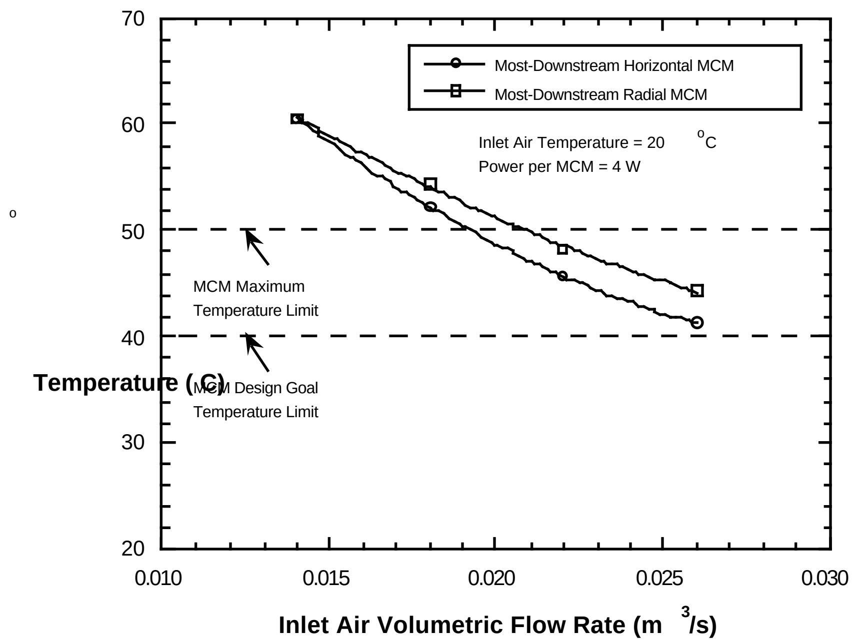


(b)

Figure 8. Plots of temperature versus individual MCM operating power for various air volumetric flow rates and an air inlet temperature of 20 C for the most-downstream (a) horizontal plenum MCM and (b) radial plenum MCM.


Most-Downstream Horizontal MCM
Most-Downstream Radial MCM
Inlet Air Temperature = 10 °C
Power per MCM = 4 W
MCM Maximum
Temperature Limit
MCM Design Goal
Temperature Limit
Temperature (°C)
Inlet Air Volumetric Flow Rate (m³/s)
70
60
50
40
30
20
0.010
0.015
0.020
0.025
0.030

(a)


Most-Downstream Horizontal MCM
Most-Downstream Radial MCM
Inlet Air Temperature = 20 °C
Power per MCM = 4 W
MCM Maximum
Temperature Limit
MCM Design Goal
Temperature Limit
Temperature (°C)
Inlet Air Volumetric Flow Rate (m³/s)
70
60
50
40
30
20
0.010
0.015
0.020
0.025
0.030

(b)

interpreted from Figure 8 that the use of 20°C cooling air during operation of the MVD would require relatively high volumetric air flow rates to maintain allowable MCM operating temperatures.

Figures 9(a) and 9(b) display the temperatures of the most downstream horizontal and radial plenum MCMs versus inlet air volumetric flow rate for an individual MCM operating power of 4 W and inlet air temperatures of 10 and 20°C, respectively. The MCM operating temperature limit of 50°C and the design goal temperature of 40°C are also indicated on each plot. The maximum individual MCM operating power of 4 W was selected to generate the plots in Figure 9 so that the minimum air volumetric flow rate required by the air blowers to keep the MCM temperatures below the operating limit under worst-case conditions could be identified. By extrapolating the curve fits of Figures 9(a) and 9(b), it can be seen that for air inlet temperatures of 10 and 20°C, air volumetric flow rates of at least 0.026 and 0.035 m^3/s, respectively, are needed to satisfy MCM operating temperature requirements. Because the worst-case operating condition corresponds to roughly a power input of 4W per MCM and 20°C inlet air, the final designed cooling system must be able to supply an inlet air volumetric flow rate of 0.035 m^3/s.

Using the data of Figures 6 though 9, the minimum required inlet air volumetric flow rates for a variety of operating conditions were determined for the current airflow adapter design. These are summarized in Table 1.

Table 1. Summary of minimum MVD inlet air volumetric flow rates required to maintain the last radial MCM (worst-cooled MCM) at an operating temperature of 40°C for various MCM heat dissipation rates and inlet air temperatures, assuming no changes in the current air flow adapter design.

Individual MCM Heat Dissipation Rate (W)	MVD Inlet Air Temperature (°C)	Minimum Required MVD Inlet Air Volumetric Flow Rate (m^3/s)
2	10	0.013
2	20	0.020
3	10	0.021
3	20	0.026
4	10	0.026
4	20	0.035

Model Validation

A finite element model of the horizontal plenum was developed by Zukun and Gregory [3] to study the operating performance of the forced convection air cooling system and to determine the required air flow velocities for an individual MCM operating power of 2.3 W and an inlet air temperature of 20°C. The present experimental study used a horizontal plenum geometry and a set of operating conditions that match those used in the numerical study. Consequently, the empirical data was used directly to estimate the accuracy of the finite element model.

To provide a comparison between the experimental operating temperature of the most downstream horizontal MCM and that predicted by the numerical model, the mean air velocity in the experimental horizontal plenum had to be determined because this was the independent variable used in the numerical study. A hot-wire anemometer provided this information, which is summarized in Table 2 along with the corresponding MVD inlet air volumetric flow rates as measured with the Sper Scientific anemometer.

Table 2. Correlation of the inlet air volumetric flow rate to the mean air velocity in the horizontal plenum of the MVD as determined experimentally.

Inlet Air Volumetric Flow Rate (m^3/s)	Mean Air Velocity in Horizontal Plenum (m/s)
0.014	5.5
0.018	7.1
0.022	8.9
0.026	11.0

Table 3 summarizes the comparisons between the predicted and measured temperatures of the most-downstream horizontal plenum's MCMs for three different mean horizontal plenum air velocities. In all three cases, the model over predicts the MCM temperature by a few degrees Celsius. This temperature difference can be attributed to experimental heat losses from the MCM to the plenum Rohacell, which were not accounted for in the model, as well as accuracy limitations of the experimental measurements and of the empirical heat transfer correlation used in the model. However, the model appears to provide satisfactory results and may be used to provide future analyses should the design of the MVD change significantly.

Table 3. Comparison of the most-downstream horizontal plenum's MCM operating temperatures from model predictions [3] and present experimental data for an MCM operating power of 2.3 W and an air inlet temperature of 20°C.

Mean Air Velocity	Numerical Model	Empirical	Absolute Difference

in Horizontal Plenum (m/s)	MCM Temperature (°C)	MCM Temperature (°C)	(°C)
7	44.5	38.3	6.2
9	39.5	34.9	4.6
11	36.3	32.6	3.7

CONCLUSIONS AND DESIGN RECOMMENDATIONS

This study investigated the performance of a proposed forced convection air cooling system for the MVD's silicon detector front-end electronics. From the experimental results of this study, the following key conclusions can be drawn:

1. The operating temperatures of the MCMs were found to increase with increasing MCM operating power, increasing air inlet temperature, and decreasing air volumetric flow rate.
2. The most-downstream MCMs in the radial and horizontal plenums represented the worst-case or highest operating temperatures of the MCMs in their respective plenums. For the current configuration, the most-downstream radial MCM consistently operated at a higher temperature than the most-downstream horizontal MCM.
3. The success of the air cooling system in meeting performance requirements was found to be limited. The design goal MCM temperature limit of 40°C could not be met for all test conditions used in this study. Table 1 summarizes the required minimum cooling air temperature and volumetric flow rate requirements to maintain safe MCM

operating temperatures for various individual MCM heat dissipation rates for the current air flow adapter/diverter design.

4. Comparisons between experimental and numerically predicted temperatures [3] of the most-downstream horizontal plenum MCM are quite good. Consequently, the numerical model by Zukun [3] may be used with a good level of confidence if design changes in the MVD electronics or cooling system require additional analyses.

The results of this study add further support to finalizing the design of the MVD air cooling system with some modifications. In particular, the following issues should be considered in the final design:

1. The air blowers should be able to supply an air volumetric flow rate of at least 0.035 m^3/s to the MVD. An oversized blower system with an emergency backup or failure warning system is advised. Oversizing the system is necessary so that adequate cooling can be supplied should the water chillers (which cool the air) fail on the hottest possible day.
2. Enlarging the inlet and outlet air ports on the radial MCM plenums is recommended to allow additional airflow at the expense of the horizontal MCM plenum airflow. Increasing the area of these ports by 20% should supply additional cooling such that the most-downstream radial and horizontal plenum MCMs approach the same operating temperature. Currently, the radial plenum MCM operates several degrees

Celcius above the horizontal plenum MCM. Additional performance measurements following this design change are recommended.

3. Water chillers and the air/water heat exchanger should be sized to supply MVD inlet cooling air down to 5°C. An extra 5°C of cooling (below 10°C) will be required should the temperature in the PHENIX Facility rise above normal (22 to 28°C) operating levels.
4. Having temperature sensors on the actual MCMs are recommended to observe operating temperature levels under all operating conditions.
5. The airflow adapters and diverters used in this study were found to leak and had to be supported with various sealants to perform adequately. Consequently, the design of these devices and their fabrication tolerances must be revisited. In addition, the mounting fixtures used to attach the MVD to the PHENIX magnet nosecones were inadequate and difficult to use and should be redesigned.

One other factor concerning the MVD air cooling system needs to be commented upon. The land elevation at Los Alamos National Laboratory (LANL) is approximately 7000 feet higher than that at Brookhaven National Laboratory (BNL). Thus the air density, and hence the forced convection heat transfer coefficient at LANL, where the experimental testing of the air cooling system was performed, are approximately 80% of those expected at BNL, where the actual MVD will be installed (assuming all other conditions are the same). Consequently, MCM operating temperatures at BNL will be several degrees Celsius less than those at LANL for identical operating conditions.

References

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[2] Parietti, L., Potter, C., Thompson, T., and Martin, R., 1996, "ESA-DE PHENIX MVD Design Review," Internal design report, Engineering Sciences and Applications Division, Design Engineering, Los Alamos National Laboratory, Los Alamos, NM 87545.

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Appendix

Table A.1. Summary of experimental heat transfer data and energy balance checks using Equation (1).

Power per MCM (W)	MVD Inlet Air Vol. Flow Rate (m^3/s)	Inlet Air Temp. (°C)	Outlet Air Temp. (°C)	1st Radial MCM Temp. (°C)	7th Radial MCM Temp. (°C)	12th Radial MCM Temp. (°C)	Last Horiz. MCM Temp. (°C)	% Diff. In Energy Balance of Eqn. (1) (%)
2.0	0.014	10.3	24.3	16.3	30.2	37.2	30.9	14
2.0	0.018	10.0	22.1	14.9	27.3	32.8	26.6	12
2.0	0.022	10.1	20.6	14.2	25.3	29.8	24.1	16
2.0	0.026	9.8	19.9	13.6	24.4	28.4	22.7	11
3.0	0.014	9.9	29.7	18.5	37.4	48.5	42.3	8
3.0	0.018	9.8	26.9	17.1	34.2	43.2	36.5	3
3.0	0.022	9.9	24.6	16.0	30.9	37.9	31.6	7
3.0	0.026	9.9	23.3	15.2	29.3	35.2	29.2	6
4.0	0.014	9.9	34.4	21.9	44.3	57.9	51.8	8
4.0	0.018	9.8	30.0	19.5	38.9	49.4	42.3	7
4.0	0.022	10.1	27.5	18.1	35.4	43.7	36.9	9
4.0	0.026	10.0	25.7	17.1	33.1	40.1	33.6	8
2.3	0.014	19.9	32.4	26.6	37.8	46.2	43.6	NA
2.3	0.018	20.1	30.1	25.4	35.2	41.8	38.3	NA
2.3	0.022	20.1	28.8	24.8	33.5	38.3	34.9	NA
2.3	0.026	20.2	27.7	24.3	31.9	35.7	32.6	NA
3.0	0.014	20.1	35.9	28.7	41.9	51.6	50.1	NA
3.0	0.018	20.2	33.1	27.2	38.7	46.2	43.7	NA
3.0	0.022	19.9	31.0	26.0	36.4	42.1	39.3	NA
3.0	0.026	20.2	29.9	25.5	34.7	39.7	36.7	NA
4.0	0.014	20.4	41.0	32.0	48.0	60.6	60.6	NA
4.0	0.018	20.1	37.3	29.7	44.4	54.4	52.3	NA
4.0	0.022	20.2	34.3	28.2	40.8	48.3	45.6	NA
4.0	0.026	20.1	32.1	26.9	38.5	44.3	41.3	NA
2.0	0.022	10.1	20.8	14.4	25.5	29.3	24.0	15
3.0	0.022	9.9	24.3	16.6	31.2	37.1	30.9	7
4.0	0.022	10.2	27.3	18.6	35.4	42.5	36.4	9

Table A.2. Summary of environmental heat gain to MVD airflow.

MVD Inlet Air Vol. Flow Rate (m^3/s)	Inlet Air Temp. (°C)	Outlet Air Temp. (°C)	Total Heat Gain by Air (W)
0.014	10.2	16.1	77.3
0.018	10.1	15.7	94.3
0.022	9.9	15.8	121.4
0.026	9.8	15.6	141.1