MMTO Internal Technical Memorandum #08-2

MMT Observatory

Smithsonian Institution &
The University of Arizona®

MMT Primary Mirror Ventilation System Temperatures Versus Carrier Chiller Setpoint Values: A Linear Regression Analysis, January through December, 2007

J. D. Gibson, D. Clark, B. Comisso, T. Pickering, G. Williams, S. Callahan, C. Chute, T. Gerl, C. Knop, R. Ortiz, D. Smith, T. Trebisky, K. Van Horn, B. Stangret, J. T. Williams

March 2008

MMT Primary Mirror Ventilation System Temperatures Versus Carrier Chiller Setpoint Values: A Linear Regression Analysis, January through December, 2007

J. D. Gibson, D. Clark, B. Comisso, T. Pickering, G. Williams, S. Callahan, C. Chute, T. Gerl, C. Knop, R. Ortiz, D. Smith, T. Trebisky, K. Van Horn, B. Stangret, J. T. Williams

Introduction

This paper presents analysis of thermal data at various locations along the MMT primary mirror ventilation system with respect to the main control parameter for this system, the Carrier 30GN-040 chiller setpoint[1] (Figure 1). The analysis examines the first-order, linear relationship, using a "least squares" method, of local ventilation air temperatures to the Carrier setpoint (e.g., Figure 2). The results are a best-fit line, expressed in the form of "y = mx + b" with associated statistical terms.

For the models presented here,

$$T_{vent} = (\text{slope} * T_{Carrier}) + \text{offset}$$

where "T_{vent}" is the ventilation air temperature (in °C) at a specific location and "$T_{Carrier}$" is the Carrier setpoint (in °C).

To solve for the Carrier setpoint, given a ventilation temperature, we would use:

$$T_{Carrier} = (T_{vent} - \text{offset})/\text{slope}.$$

These relationships define what the expected ventilation air temperature would be at a specific location for a given Carrier setpoint. A major goal of this and related studies is to develop a strategy for automating control of the Carrier chiller, based upon desired ventilation air temperatures.

The Carrier 30GN-040 chiller is a reciprocating liquid unit that has a primary objective of maintaining a constant leaving coolant temperature[1]. This coolant temperature averages very closely to the Carrier setpoint, which can be set by the telescope operator to control the thermal ventilation system. Details of the coolant temperature produced by the Carrier unit, referred to as the "Carrier leaving water temperature," will be described elsewhere. In general, there is a very close correlation (~98% correlation of determination, "R^2") between the Carrier setpoint and the Carrier leaving water temperature throughout the operating range of the chiller. This Carrier leaving "water" is the coolant circulated through the shop heat exchanger and the first half of the pit heat exchanger (see Figure 1). The Carrier chiller used by the MMT has been modified to use a water/glycol mixture, so that it is possible to use a setpoint as low as -10°C. Without this modification and the use of glycol, the minimum possible Carrier setpoint would be at freezing (0°C). This lower setpoint is needed since much of the operation of the MMT occurs in sub-freezing conditions[2].

Software related to the various hardware devices and probes here are sampled by a set of "miniservers." Each hardware device typically has one miniserver associated with it. The miniserver is responsible for acquiring new data from the hardware at a regular interval (e.g., every five seconds), logging these data into a MySQL and other databases, and making the data available to other network applications.

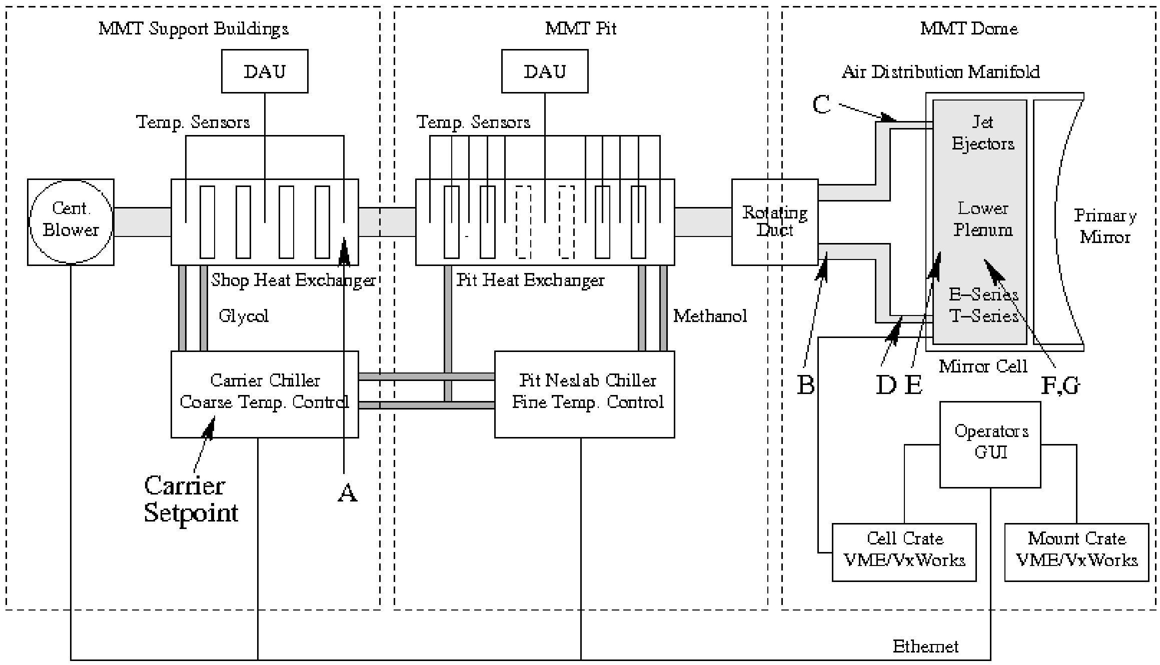

Figure 1. Schematic representation of the MMT ventilation system for the primary mirror. Seven temperature sampling locations within the ventilation system are labeled "A" through "G." These locations and the associated linear regressions at these locations are described in more detail in the text. The location of the Carrier chiller, where the Carrier setpoint is applied to the system, is shown. The pit Neslab chiller, a Neslab HX-540 unit, was off and not affecting the thermal system for the data in this analysis. Figure 1 is modified from Williams et al., 2004.

Data

Data for these linear regressions were obtained from a MySQL database on the main MMT server, "hacksaw." Up to four years of data are available from this database. The emphasis in this analysis is on the most recent year of data, 2007, since those data will most accurately characterize the current status of the ventilation system.

SQL queries were made on the MySQL database with the following constraints:

1) Data are from January 1, 2007 to December 31, 2007.
2) Data are from midnight to 4 a.m. During this time period the ventilation system has typically been running for several hours and should be close to "normal" operating conditions.
3) The temperature drop across the shop heat exchanger is greater than 10°C. This ensures that the ventilation system is running and that the blower has reached its operating temperature.
4) The Carrier chiller setpoint is above -9.5°C. This ensures that the ventilation system is not operating at temperatures that are too cold for the system to handle.
5) There is less than a 1°C difference between the chamber and outside ambient temperatures. In more cases this criterion ensures that the chamber is open.
6) The coolant flow for the pit Neslab chiller is zero, ensuring that the unit is not being used.

These SQL queries resulted in around 27,000 rows of data for each of the temperature sensors. These data sets form the basis for the linear regressions presented here.

Location A: Shop Heat Exchanger Exit Temperature
Miniserver: "Shop HPDAU"; Miniserver Parameter: "shop_hpdau_tc2_C"

The ventilation air temperature is sampled at the entrance, midpoint, and exit of the shop heat exchanger by three T-series (Copper/Constantan) thermocouples, attached to an Agilent (formerly Hewlett-Packard) model 34970A Data Acquisition/Switch Unit (DAU). This data acquisition unit is referred to here as the "Shop HP DAU" unit. The thermocouples are sampled every five seconds by the "Shop HPDAU" miniserver. These thermocouples, including the exit thermocouple (TC2) being evaluated here, are suspended in the airstream and show a significant temperature drop (around 20°C) from the entry to exit of the heat exchanger when the ventilation system is in operation. This heat exchanger removes the vast majority of heat introduced into the ventilation system from the adiabatic heating of air in the blower. Data are collected at location "A" (see Figure 1) by a T-series thermocouple (TC2) that is connected to the Shop HP DAU. These data are logged as parameter "shop_hpdau_tc2_C" in the MySQL database.

Figure 2 shows the least-squares linear regression between the ventilation air temperature at the exit of the shop heat exchanger (Location A, Figure 1) with the Carrier setpoint. This regression has the highest statistical coefficient of determination (R^2 = 0.96) of any regressions presented here (see Table 1). Although data are not presented here over a short-term (e.g., 15- to 20-minute) time interval, the exit temperatures for the shop heat exchanger also most closely follow the cyclical changes in coolant temperature from the Carrier that occur on that time scale.

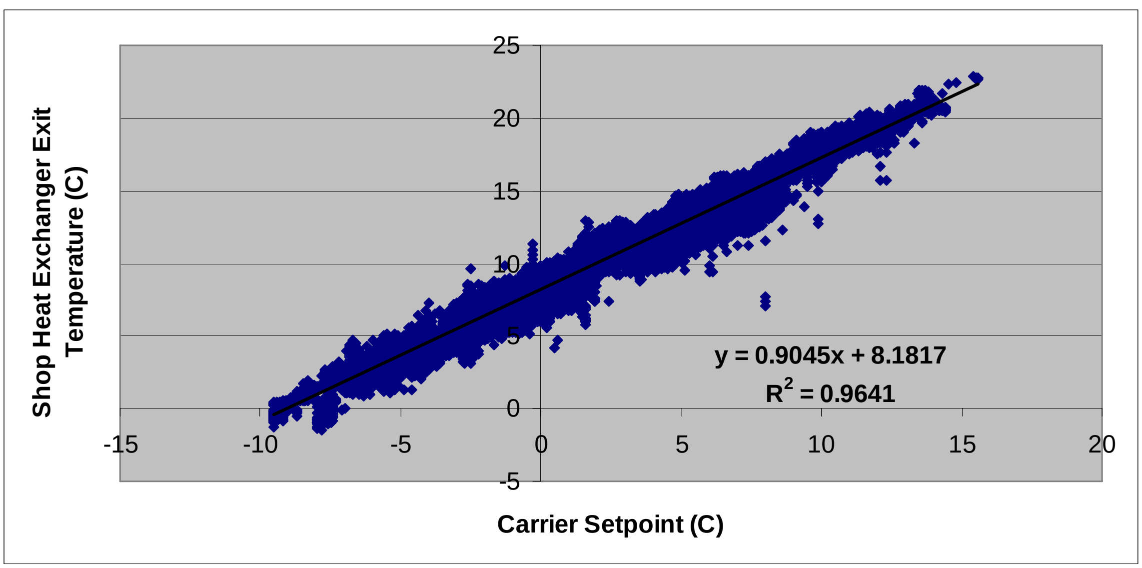

Figure 2. Linear regression at location "A," using the "least squares" method, of the Carrier setpoint vs. shop heat exchanger exit temperature. See text for details.

Analysis of data from the other six locations was performed in a manner similar to that for location "A." Results for linear regressions from these other six locations are also presented in Table 1.

Location	Slope	Y Intercept	Standard Error	R^2	F-Statistic
A	0.9044 ± 0.001068	8.1817 ± 0.006254	0.9073	0.9641	717614.5
B	0.8187 ± 0.001188	7.0994 ± 0.006957	1.0094	0.9467	475107.4
C	0.8562 ± 0.001734	7.1435 ± 0.010159	1.4739	0.9011	243684.6
D	0.8386 ± 0.001152	6.5595 ± 0.006748	0.9790	0.9520	529862.8
E	0.8615 ± 0.001585	7.2363 ± 0.009282	1.3467	0.9171	295578.2
F	0.8605 ± 0.001736	7.5031 ± 0.010150	1.4717	0.9023	245686.8
G	0.8241 ± 0.001764	7.5123 ± 0.010335	1.4995	0.8908	218163.1
Mean	0.8520	7.3194	1.2411	0.9249	389385.3
Maximum	0.9044	8.1817	1.4995	0.9641	717614.5
Minimum	0.8187	6.5595	0.9073	0.8908	218163.1
Std Dev	0.0288	0.4964	0.2643	0.0290	189213.9

Table 1. Regression parameters for the seven locations within the MMT primary mirror ventilation system. The slope and Y intercept, along with the errors for these two parameters, are listed in columns 2 and 3. The standard error, R^2 (the "coefficient of determination"), and the Fisher F-statistic for the seven regressions are given in columns 4 through 6.

Location B: Feed Pipe to West Ventilation Duct

Miniserver: "TempTrax3"; Miniserver Parameter: "temptrax3_probe8"

Location B in the ventilation airflow is near the rotating collar, in the feed pipe to the west ventilation duct (see Figure 1). This location is "down airstream" from the pit heat exchanger in Figure 1. The probe is held in place with RTV sealant. Data are collected at this location by a TempTrax thermistor (TempTrax3, Probe8), miniserver parameter "temptrax3_probe8."

The pit heat exchanger itself is equipped with T-series thermocouples, sampled by an HP DAU. It was discovered recently (February 2008) that these thermocouples were mounted in a manner such that they did not sample the air temperature accurately. Because of this discovery, results from these thermocouples are not presented here. The mountings for the thermocouples are being modified to better measure air temperatures within the pit heat exchanger.

Location C: East Ventilation Duct

Miniserver: "TempTrax1"; Miniserver Parameter: "temptrax_probe1"

TempTrax1 Probe1 (see Figure 1) is located in the ventilation airstream in the east ventilation duct. This duct, along with the west ventilation duct, transports air from the pit heat exchanger and delivers the air to the lower plenum of the primary mirror cell, where this conditioned air is used to modify the temperature of the primary mirror glass.

Location D: West Ventilation Duct

Miniserver: "TempTrax3"; Miniserver Parameter: "temptrax3_probe9", formerly "temptrax2_probe1"

TempTrax3 Probe9 is in a similar location (location "D," Figure 1) within the ventilation system as location "C," but is in the west ventilation duct. This probe was connected to TempTrax2 unit as Probe1 during the early part of 2007. Data for this probe from both of these TempTrax units are combined here. Data from this location correlate particularly well with those from location "B," which is in the same subsection of the ventilation system.

Location E: Manifold

Miniserver: "Cell"; Miniserver Parameter: "cell_manifold_air_temp_C"

The ventilation air passes through a manifold as it enters the lower plenum of the primary mirror cell. A cell E-series (Chromel/Constantan) thermocouple has been installed at one location of this manifold. Values from this thermocouple, parameter "cell_manifold_air_temp_C," are logged by the "cell" miniserver.

Location F: Lower Plenum

Miniserver: "Cell"; Miniserver Parameter: "cell_lower_plenum_C"

As air enters the lower plenum of the primary mirror cell, it mixes with the existing air in the plenum. These air temperatures in the lower plenum are also strongly influenced by the glass temperature of the primary mirror. The cell miniserver averages approximately 15 temperature values from E-series thermocouples within the lower plenum to obtain an average lower plenum air temperature. This value is published by the cell miniserver as the "cell_lower_plenum_C" variable, the variable analyzed at location "F."

Location G: Lower Plenum

Miniserver: "TempTrax3"; Miniserver Parameters: "temptrax3_probe13", formerly "temptrax2_probe5"

TempTrax3 Probe13 is directly attached to the isothermal junction block (IJB) for the cell E-series thermocouples and is located in the lower plenum of the primary mirror cell. The IJB is a large block of copper that is used as a uniform reference source for temperatures within the cell E-series system.

Results

Results from these linear regressions are expressed as several different statistical parameters as seen in Table 1. These results will be discussed in more detail here.

Slope of Regressions

The slopes of the linear regressions of Carrier setpoint values to ventilation air temperatures at the seven locations range from a minimum value of 0.8187 to a maximum value of 0.9044 with a mean slope of 0.8520 (see Table 1). The uncertainty in the slope estimates is low and ranges from 0.1% to 0.2%. When only the locations after the pit heat exchanger (i.e., locations "B" through "G") are considered, less variation is seen, with a minimum slope of 0.8187, a maximum slope of 0.8616, and a mean slope of 0.8433. The regression at location "A" has the steepest slope for this set of regressions.

Overall, the data indicate that a 1°C change in the Carrier setpoint would result in an approximate 0.85°C change in the ventilation air temperature. This slope suggests that the change in observed ventilation air temperature would typically be slightly less than the change in Carrier setpoint value.

The observed change in slope estimates may be related, in part, to heat gain resulting from limited insulation along the ventilation duct. Thermal inertia of the ventilation system will also influence the slope and other regression parameters.

Y Intercepts of Regressions

Table 1 also presents results of the Y intercepts for linear regressions at locations "A" through "G." The mean Y intercept for all seven locations is 7.3194, although these intercepts range from 6.5595 to 8.1817. The uncertainty in the Y intercepts is 0.1%. If the Carrier setpoint were set to 0°C, the observed ventilation air temperatures should range from 6.6°C to 8.2°C along the ventilation path at these locations, with a mean value of 7.3°C. Similarly, if the Carrier setpoint were set to its lower limit of -10°C, the observed ventilation air temperatures would range from -3.4°C to -1.8°C with a mean temperature of -2.7°C. The Y intercept for the exit of the shop heat exchanger, location "A," is significantly (~1°C) higher than at the other locations. This change in the Y intercept may be related, in part, to heat gain into the ventilation system from the surrounding environment and is expected to be a function of the ambient outside air and ground temperatures. The temperatures within the pit, yoke room, and telescope chamber may also influence the temperatures for locations "B" through "G."

Standard Error of Regressions

The "standard error" for the model, also known as the "root mean square (RMS) error of the fit," is the standard deviation of the error[3]. The standard error of a method of measurement or estimation is the estimated standard deviation of the error in that method. It is the standard deviation of the difference between the measured or estimated values and the true values.

Table 1 shows the standard error for the seven locations for the linear regressions. For all seven locations, these values range from 0.9°C to 1.5°C with a mean value of 1.2°C. This is the expected standard error in the ventilation air temperature, for a given Carrier setpoint, when applying these simple, linear regression models to the thermal system. It is important to note that the standard error values are all close to or greater than 1.0°C, which is much larger than other thermal performance parameters for the MMT, such as a 0.1°C primary mirror isothermality[4]. If the thermal data are assumed to be normally distributed, values for the 95% confidence levels for these errors would range from ±1.8°C to ±3.0°C. This represents considerable variability if fine control of ventilation air temperature is required.

Coefficients of Determination (R^2) of Regressions

The "coefficient of determination," R^2, is the proportion of variability in a data set that is accounted for by a statistical model[3]. For the linear regressions presented here, R^2 is simply the square of the correlation coefficient between the original and modeled data values and gives some information about the goodness of fit of a model. In regression, the R^2 coefficient of determination is a statistical measure of how well the regression line approximates the real data points. An R^2 value of 1.0

indicates that the regression line perfectly fits the data, while an R^2 value of 0.0 indicates that the model does not match the observed data.

Table 1 summarizes the R^2 values for the seven ventilation path locations. Although R^2 values of 0.9641 to 0.8908, as seen in the table, indicate a strong correlation between Carrier setpoint and ventilation air temperatures, there is still considerable uncertainty in assuming a simple linear model for this system. As would be expected, we see an overall decrease in R^2 values the further we are along the ventilation path, suggesting more variability in observed ventilation air temperature values and more factors affecting these air temperatures.

Fisher F- Statistics of Regression

Perhaps a better statistical test of the goodness of fit of a model is the Fisher F-statistic[3]. For the study here, the F-statistic is the ratio of the variance in the data explained by the linear model divided by the variance unexplained by the model. The F-statistic is calculated from the regression sum of squares and the residual sum of squares. If the F-statistic is greater than the F-critical value, a null hypothesis fails and the linear model is considered significant.

For the linear regressions presented here, the degrees of freedom for the data are between 26,000 and 27,000. The R-critical value at α=0.05 (the 95% confidence level) with a degree of freedom between 26,000 and 27,000 is 3.84. All of our F-statistics values are several orders of magnitude higher than this F-critical value, indicating that we are at least 95% sure that the data are not random and that a linear regression model is justified.

Location "C" in the east ventilation duct has a lower F-statistic value than similar values at locations "B" and "D." In addition, it has a lower R^2 value and a higher standard error. It is not known why the data at location "C" has greater variability than the other locations. In addition, locations "E," "F," and "G" have a lower F-statistic than locations upstream of the airflow. These locations have the most complex thermal settings. In general, even if other types of models might more accurately describe the observed data, the F-statistic indicates that a linear regression model is well justified at all seven locations.

Discussion

Linear regressions of air temperatures at various locations within the ventilation system for the MMT primary mirror show an overall strong correlation with the Carrier setpoint, as is expected. However, several factors are believed to be involved in the overall increased variability in ventilation air temperature along the ventilation path.

Blower Factors

The centrifugal blower that drives the primary mirror ventilation system is powered by a 50-HP electric motor. A manual level can be used to adjust the amount of air leaving the blower and flowing through the remainder of the ventilation system. This blower, as well as other components of the ventilation system, has considerable thermal inertia and requires an hour or more to reach normal operating conditions. Outside ambient air is entering the blower. Adiabatic heating of this air by the blower results in a variable 20°C to 25°C increase in air temperature, depending on the blower setting and related conditions. The blower is the main heat source within the primary mirror ventilation system.

The air exits the blower and passes through an uninsulated, 24-inch flexible duct. This duct runs above the ground along the west side of the main support building (the shop). Ventilation air temperatures will be affected by outside ambient air temperatures in this portion of the ventilation system, typically resulting in some loss of heat from the ventilation air to the outside environment.

Carrier Chiller Factors

The 60-HP Carrier chiller is controlled by its own internal control system. Many of the parameters of this control system are available through its software network interface. Some of the parameters can be altered through the network interface, which can affect the behavior of the chiller.

To a first approximation, the chiller is either on or off. This behavior results in a "sawtooth" temperature signature of its coolant as the unit switches on and off. The unit also has distinct intermediate levels of operation at specific percentages of total capacity. The percentage of total capacity for the Carrier chiller is one of several parameters available through telemetry. The behavior of the chiller may be different at these different levels of operation. Glycol coolant from the Carrier unit flows to the shop heat exchanger, a portion of the pit heat exchanger, the pit Neslab (when used), and other portions of the MMT facility. The Carrier chiller is the major source of cooling within the primary mirror ventilation system.

Glycol Coolant Factors

The glycol/water mixture from the Carrier chiller is pumped through a variable and adjustable circulation system to the shop heat exchanger and into the MMT building. Once it enters the MMT building, it is used by various components that directly impact the ventilation air system, e.g., the pit Neslab chiller, and indirectly impact this system, e.g., air conditioning within the building. Some of these components, such as the air conditioning system and the loft Neslab chiller, which is used to remove heat from the secondary mirror electronics, are used intermittently. At the moment, the pit Neslab chiller is used primarily to lower the operating temperature range to the ventilation system during winter months. With a more sophisticated ventilation control strategy, it could be used to fine-tune control of the ventilation air temperature throughout the year. The pit Neslab unit is also capable of heating its methanol "coolant." This methanol circulates through the second half of the pit heat exchanger. Glycol from the Carrier chiller is used to remove heat from the pit Neslab.

Shop Heat Exchanger Factors

The shop heat exchanger contains radiators that are larger in volume and surface area than those in the Pit heat exchanger. The majority of the glycol coolant from the Carrier chiller circulates through this heat exchanger. At the moment, telemetry on the amount of coolant circulating through the heat exchanger is not available. The amount of coolant circulating through the Shop heat exchanger may vary based upon other demands for glycol within the system.

Other factors can affect the amount of air passing through the Shop heat exchanger. The most dramatic factor is icing of the radiators under colder, more humid operating conditions. This happens rarely, but, when it does occur, effectively prevents any heat transfer between air and coolant. Less noticeable obstructions to air flow would be debris, moisture, and rust accumulation.

Ventilation Duct from Shop into Building Factors

The ventilation air exits the Shop heat exchanger through a flexible duct and runs underground into the basement, the "Pit", beneath the telescope dome. During this portion of the ventilation system, the ventilation will be influenced by both the ambient outside air temperature and the ambient ground air temperature. Outside air temperature will fluctuate on a diurnal basis while the ground temperature will vary over a longer, roughly seasonal, time scale. Typically, heat will transfer from the surrounding air and ground into the ventilation air, warming the air. The amount and direction of this heat transfer will vary with operating conditions.

Pit Heat Exchanger (Carrier Portion) Factors

The first half of the Pit heat exchanger circulates glycol/water coolant from the Carrier chiller. Recent modifications to the glycol system have increased the amount of coolant flow through this portion of the heat exchanger. At the moment, there is no telemetry on coolant flow rates for glycol in the Pit heat exchanger. The amount of glycol circulating through the Shop heat exchanger is several times that of the Pit heat exchanger. Recently modified temperature sensors in the Pit heat exchanger will provide additional temperature information on the efficiency of this portion of the Pit heat exchanger.

Pit Heat Exchanger (Pit Neslab Portion) Factors

As mentioned previously, the Pit Neslab, which provides coolant to the second half of the Pit heat exchanger, was not included in this study. The unit was off when data analyzed here were sampled. The Pit Neslab is currently used only during the winter month when the additional cooling capabilities that it provides are needed.

When the Pit Neslab is in used, it diverts an unknown amount of glycol coolant from the first half of the Pit heat exchanger. So, although the second half of the Pit heat exchanger is assisting in conditioning air when the Pit Neslab is in use, there may be some decrease in the ability of the first half of this heat exchanger to condition air. Current data suggest that there is additional cooling potential for the system when the Pit Neslab is used. Further study is needed to better quantify this potential.

Ventilation Duct through Pit/Yoke Room/Chamber Factors

After exiting the Pit heat exchanger, the air passes through a rotating duct that encircles the telescope pier. The rotating duct connects to two large ventilation hoses that run into the telescope chamber and connect to PCV pipes mounted to the bottom of the mirror cell. The PVC piping splits into an air distribution manifold inside the primary mirror cell that feeds 150 jet ejectors in the lower plenum.

In this portion of the ventilation system, the ventilation will interact thermally with air in the Pit, the yoke room, and the telescope chamber. The air temperature in the Pit is commonly warmer than the outside and chamber air temperatures. Some air is funneled from the building into the Pit. In addition, there are exhaust fans to direct air from the Pit to the outside. The yoke room contains a large number of computers and related electronics and is relatively warm compared to surrounding rooms. Finally, even though the chamber is open during operation, there are local variations in temperature within the chamber and between the chamber and outside. In general, the Pit, yoke room and chamber will be warmer than the ventilation system air and there will be heat transfer from the air at these locations to the ventilation system air, warming the ventilation air.

Lower Plenum Factors

Pressurized air from the ventilation system is directed through each of the jet ejector nozzles. This flow of air draws air from the upper plenum and mixes that air with conditioned air from the ventilation system. The mixed air then travels through the lower plenum and, eventually, enters the 1020 honeycomb cells of the primary mirror. Any variation in this flow of air, such as the extent of mixing or restrictions on flow, can affect the temperature of air within a certain portion of the system. The ~15 thermocouples used to analyze lower plenum temperature in this study are distributed roughly evenly throughout the lower plenum. Local conditions and effects will, in part, be averaged out because of the distributed sampled.

Air/Glass Factors

The analysis presented here emphasizes the ability to deliver conditioned air with a specific temperature to the primary mirror cell and lower plenum, rather than the use of the conditioned air to chill the primary mirror directly. Many additional factors are involved in the interaction of this conditioned air with the primary mirror glass. These factors can impact control strategies for modifying primary glass temperature. For example, the primary mirror is thicker at its edges than at the center. This can result in more rapid cooling of the center of the mirror and the development of radial thermal gradients across the mirror. Front-to-back thermal gradients can also develop in the primary mirror as cold, conditioned air flows into the lower plenum.

Other Factors

Other factors can add to the transient nature of the ventilation system. Air leaks periodically develop that affect air flow. These leaks are repaired when they become noticeable. As mentioned earlier, some equipment that uses glycol is employed only under certain telescope configurations or operational conditions. For example, the Loft Neslab chiller, which is identical to the Pit Neslab unit, is used only during f/15 secondary mirror runs to cool secondary mirror electronics. While this chiller does not directly influence the air temperatures in the ventilation system, it does remove glycol that might circulate through the Pit heat exchanger. Similarly, air conditioning of the MMT building is seasonal and places an additional load on the Carrier chiller and the glycol distribution system. The combined influence of these factors is probably small, but may have a measurable effect on the conditioned air in the ventilation system.

Finally, each of the temperature sensors has its own limits of accuracy and sensitivity. These sensors are also influenced by the local conditions and setting. The ventilation system itself is a highly turbulence flow regime that can influence the ability to accurately measure air temperatures.

This analysis suggests that these factors commonly contribute to a 1°C to 1.5°C increase in temperature from the exit of the Shop heat exchanger to the manifold system and lower plenum behind the primary mirror. These factors affect the Y intercept values, but also appear to affect the slope of the linear regressions. They also create 95% confidence levels for the standard error in Y estimates for the linear regressions from ±2°C to ±3°C. This decreased ability to deliver chilled air to the primary mirror cell is most critical during the winter months when the current ventilation system is unable to chill the mirror.

Additional analysis of the thermal data will be required to determine the extent of each of these influences on observed temperatures at various locations in the ventilation system. In addition, more sophisticated thermal models are needed to understand all of the complexity of this system. Use of these sophisticated thermal models may be required to develop appropriate control strategies for the MMT primary mirror ventilation system.

References

1. G. G. Williams, J. D. Gibson, S. Callahan, D. Blanco, J. T. Williams, and P. Spencer, 2004, "Performance and Control of the MMT Thermal System," Proceedings, SPIE, 5489, 938.
2. J. D. Gibson, D. Clark, B. Comisso, T. Gerl, C. Knop, R. Ortiz, T. Pickering, D. Porter, D. Smith, P. Spencer, T. Trebisky, K. Van Horn, G. Williams, J. T. Williams, 2008, "Outside Minimum Daily Ambient Air Temperatures for the MMT Observatory, Mt. Hopkins, Arizona, December 2003 through January 2008", Internal Memo MMT Observatory, ITM 08-1.
3. P. R. Bevington and D. K. Robinson, "Data Reduction and Error Analysis for the Physical Sciences," McGraw-Hill, Third Edition, 2003.
4. D. G. Fabricant, B. A. McLeod, and S. C. West, "Optical Specifications for the MMT Conversion," MMT Technical Report #35, MMTO, 1999.