HVAC OPTIMISATION AT TE PAPA

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ABSTRACT

Te Papa Tongarewa, the national museum of New Zealand, opened in February 1998. It was designed for very constant environmental conditions, necessary for the preservation of priceless artifacts.

Unfortunately, to achieve this, the building normally operates with simultaneous heating, cooling, humidification, and dehumidification.

Several energy-saving projects have been completed, but these have been small, one-off projects, due to budget limitations. The energy consumption of the building has been monitored since opening, and has shown an ongoing reduction.

In March 2005, a systematic optimisation process on the building's HVAC systems was begun, following the Continuous Commissioning procedures documented by Texas A&M's Energy Systems Laboratory (1).

This paper will primarily cover the analysis and recommissioning of the steam humidifier and controls. The humidifier operates almost every day, and appears to be working efficiently (the demand is inversely proportional to the outside air humidity ratio). However, an analysis from basic principles indicates that humidification should almost never be required.

The system is designed so that humidity is only added to the fresh air, so excessive humidification causes excess fresh air to be supplied, which must be heated, cooled, etc. before it is added to the space.

BACKGROUND

Systems description

Te Papa uses constant volume air circulation, with air delivered to different spaces with a combination of air handling units, mixing boxes, and fan coils.

Dual ducts in an unusual configuration supply the mixing boxes and AHUs: not warm air and cold air, but return air and fresh air.

Fresh (outside) air is humidified (or dehumidified) to near the room condition, then supplied whenever needed either for air quality (measured by CO_2 sensors) or low humidity. Target space conditions for most areas are 21°C ±1°C and 52% ±7% r.h.

The building is massive, about 40,000 sq. metres (400,000 sq.ft.) in floor area, and with relatively low internal heat gains (an average load of under 10 W/sq.m. [1 W/sq.ft.] of lights and equipment).

Normal occupancy is about 700 people during the daytime, about 150 in the evening, and a few overnight.

Installed plant

Te Papa uses two 1500 kW (5 MMBtu/h) gas boilers, three water-cooled chillers (one base-loaded 1200 kW [340 T] reciprocating machine and two 1360 kW [390 T] screw units)

Total space airflow is about 145 m3/s (300,000 cfm) through a combination of air handling units, mixing boxes and fan coils. Most of the supply air is handled by the mixing boxes, which mix pre-conditioned outside air with return air, then cool and reheat this air as necessary to maintain space conditions.

Fresh and return air pressures are maintained in the duct trunks via VFDs on the supply fans. These pressures are reset at night only.

Energy use data

As shown in Figure 1, electricity use has been dropping since 1998, due to simple housekeeping measures, and re-scheduling the plant off when unnecessary (reducing the fresh air duct pressure at night).

In October 2001 a new gallery was added, with a consequent increase in HVAC capacity and energy use.

Extreme weather in January 2005, and an apparent sensor failure caused the failure of a chiller, and another increase in electricity use.

Fig. 1 Historical electric energy use

Gas use has shown similar reductions, as shown in Figure 2. (Note that in the southern hemisphere, summer is December through February.)

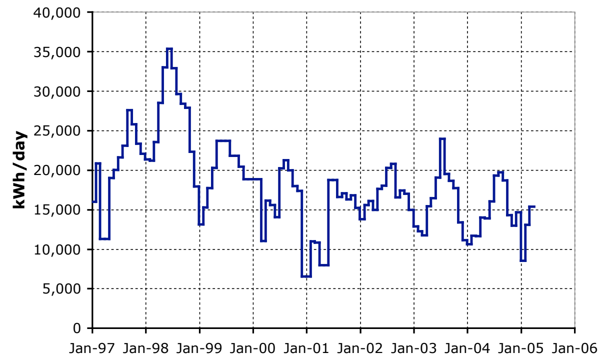

Fig. 2 Historical gas energy use

The summer gas use is 10,000 kWh/day. This supplies service hot water for the building, including about thirty calorifier-type water heaters, and cooking for four different areas, as well as the steam boiler humidifier, and reheating energy for the HVAC system.

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HUMIDITY REQUIREMENTS

Because of its function as a large public space, there is usually a large release of moisture inside the space (about 150 gm/hr per person, corresponding to a 95 W latent load). Outside air is brought in to maintain air quality, and there should be a net humidification load only when the added outside air is so dry that it outweighs the moisture release

The outside air conditions observed at Te Papa in summer are shown on a standard psychrometric chart format in Figure 3. Hourly temperature and moisture content data are shown as the points on the chart, and the target space conditions as the parallelogram.

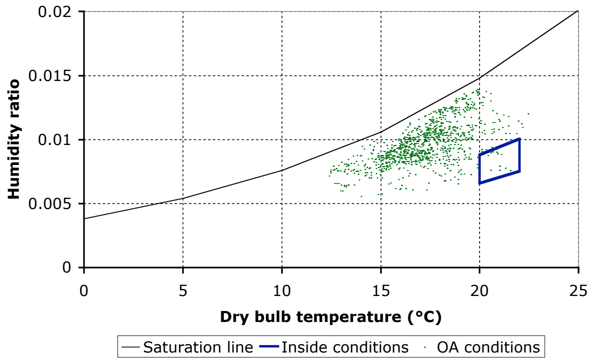

Fig. 3 Summer humidity conditions

As can be seen, summer outside air conditions are never significantly drier than inside the building. Winter, of course, is drier, as shown in Figure 4.

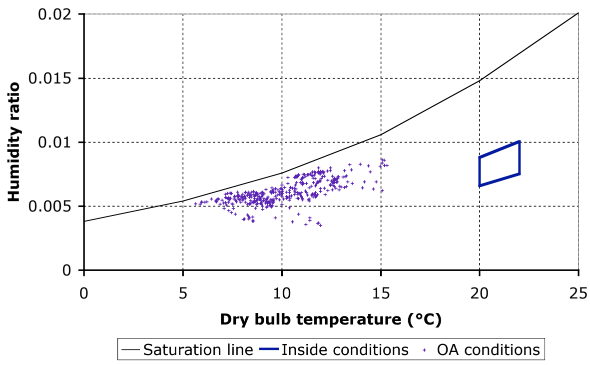

Fig. 4 Winter humidity conditions

Even in winter, Wellington's mild and humid climate means that the outside air is rarely very dry. (Incidentally, Te Papa's position on the harbour means that the air temperatures it faces are several degrees warmer in winter and cooler in summer than at the local weather stations, and the Wellington TMY weather file.)

Actual humidifier operation

The humidifier is a steam boiler that injects saturated steam into the outside airstreams supplied to terminal units (the "fresh air" ducts). On the surface, the humidifier appears to be controlled appropriately, in that more humidity is injected into the space the drier the outside air is, as shown in Figure 5.

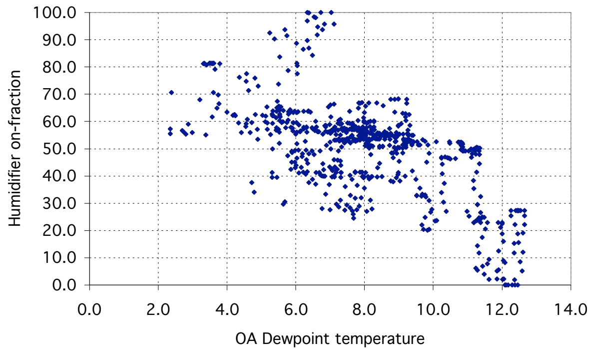

Fig. 5 Humidifier Operation vs. OA Dewpoint

The humidifier follows its expected seasonal pattern of operation, with much more use in winter than summer, as shown in Figure 6. Water usage dropped to very low levels around January 2004, when there was no apparent need for humidification of the space, and moved to higher levels in winter.

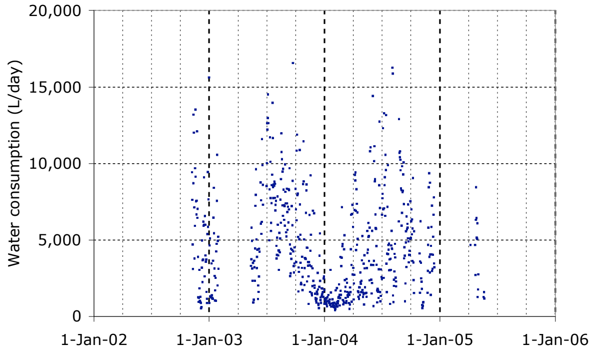

Fig. 6 Daily humidifier water use

However, the pattern that held for the summer of 2003-04 is apparently not repeated in 2004-05. The very high water use incidents were caused by blow-down of the humidifier.

The relatively high humidification loads at other times are believed to be caused by excess fresh air ventilation. This is supported by the histogram of measured CO2 concentrations in the space, as recorded by the 62 sensors on the BMS, as shown in Figure 7.

This shows the number of sensors in each CO2 band, as the average of eighteen readings for each sensor taken during operating hours on different days.

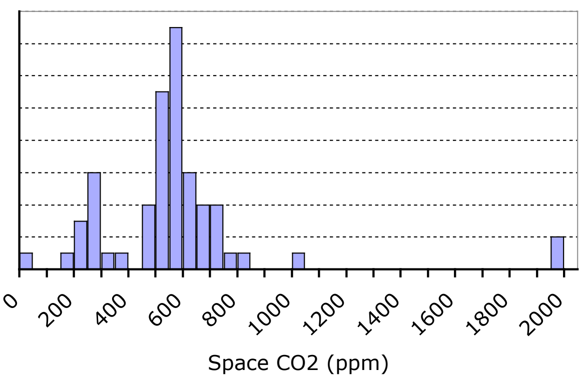

Fig. 7-Measured space CO2 concentrations

It is obvious that many sensors are well out of calibration, as CO2 under 400 ppm is unlikely without absorption, which is not evident in the space, and some sensors seem stuck on 1000-2000 ppm, though air quality in those spaces seems fine.

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However, these remaining data do at least imply that the average CO2 concentration is about 550 ppm, which matches hand-held meter readings. This means that outside air ventilation is more than required to meet air quality requirements.

The space CO2 concentration can be used to infer the amount of excess outside air delivered to the space. Compared to the target CO2 concentration of 1000 ppm, Figure 8 shows the amount of excess outside air, as a ratio of actual to required, as a function of indoor CO2, for two ambient concentrations, 400 and 500 ppm. (Due to Te Papa's location on the harbour, ambient CO2 levels vary with wind direction and time of day.)

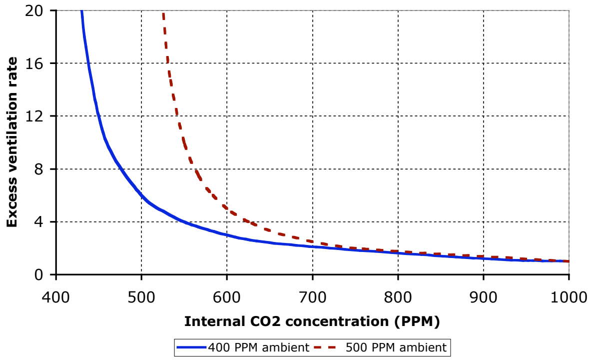

Fig. 8 Excess ventilation rate vs. CO2

With an average daytime CO2 concentration of 550 ppm, and an ambient concentration of 450 ppm, we see that the average amount of outside air ventilation is about six times what would be required to maintain CO2 below 1000 ppm.

To check if this is reasonable, we can plot the hourly measured water consumption of the humidifier, as shown in Figure 9, for Spring 2004 (September – December).

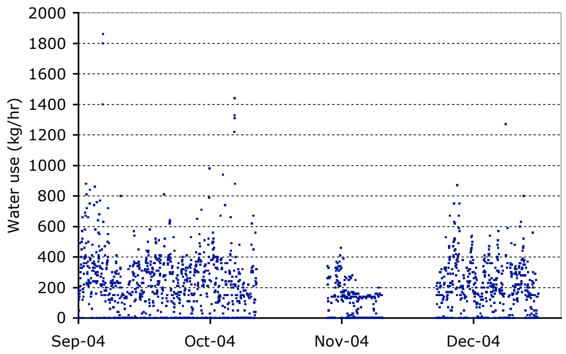

Fig. 9 Measured hourly humidifier water use

As can be seen, typical water use is usually between 200 and 400 kg/hour.

To estimate what the humidification load would be, the building's ventilation loads were simulated using EnergyPlus (2), and the extra humidity load from supplying more outside air than required calculated directly. This is shown in Figures 10 and 11, below, for an outside air quantity of 7.5 L/s-person (15 cfm/person), and 45 L/s-person (90 cfm/person).

Each graph shows a humidification requirement when the line is positive, and a dehumidification requirement when the value is negative.

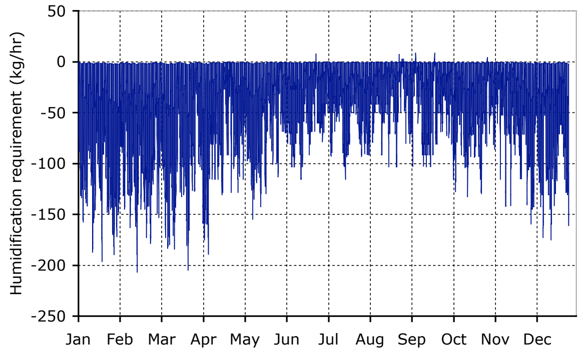

Fig. 10 Humidification need at 7.5 l/s-person

As can be seen, the humidification requirement is inconsequential when 7.5 L/sec-person of outside air is supplied. – under 100 kg for the entire year. Also, the de-humidification requirement peaks at about 200 kg/hr.

However, when outdoor airflow is raised to 45 L/s-person, to match our estimates from CO2 concentrations, as shown in Figure 11, humidification is regularly required all year round, typically in quantity 200-400 kg/hr. This is quite similar to the measured amounts, as shown in Figure 9, above.

With this amount of outside air ventilation, the peak dehumidification requirement is also higher, at over 600 kg/hr., though it is less common in winter.

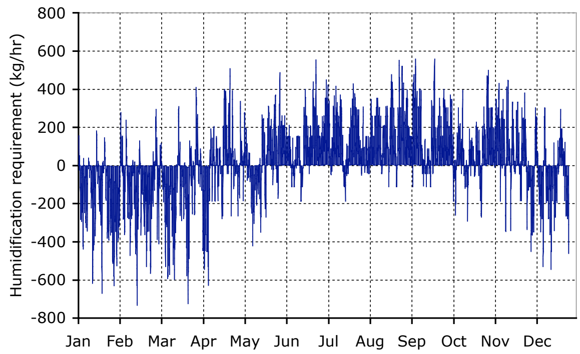

Fig. 11 Humidification need at 45 l/s-person

The above analysis has indicated that the outside air ventilation rates at Te Papa are several times as much as are required to maintain good air quality, and that this is the cause for most of the humidification load.

Mixing box operation

The mixing boxes deliver most of Te Papa's conditioned air to occupied spaces. The following section describes the survey of the mixing boxes and the elements of their control.

The intention of the mixing box controls was to:

- read the temperature, relative humidity and air quality (CO2 concentration) of the spaces they served, to
- control space temperature and reduce high humidity by adjusting the flows through the heating and cooling coils
- control low humidity and high CO2 by resetting the OA velocity pressure setpoint, to control the OA damper position, to adjust the amount of pre-conditioned (heated or cooled to 18°C and humidified to 60% r.h.) outside air supplied.

- control total supply airflow to a constant amount, by adjusting the return air damper to maintain a constant SA velocity pressure setpoint (reset for day and night operation only).

The mixing box controls are very effective at maintaining space temperature and humidity conditions, which are within setpoints virtually all the time.

The problem of chronic excess outside air is believed to be caused by the difficulty of controlling the position of the outside air damper via feedback from a velocity pressure sensor, which is typically trying to control at 1-5 Pa. However, the resolution of the sensors is about ±5 Pa.

Figure 12 shows the position of the outside air (OA) damper as a function of space relative humidity. A damper position of 100% is fully open. The oval shows the expected pattern of operation, whereby (as there were no air quality problems) the fresh air damper would have been open wider when humidity was low, and at minimum position when humidity was higher than 52%. The points show the actual measured conditions – an average of eighteen surveys done in May 2005.

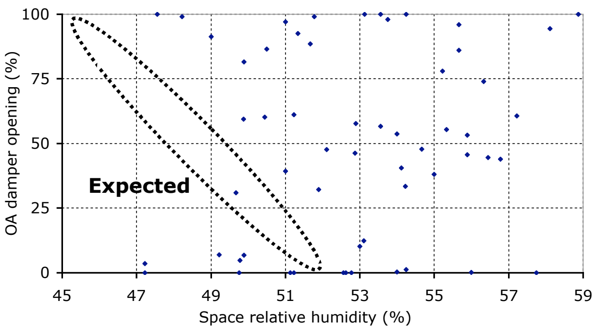

Figure 12 – OA damper vs. space humidity

As can be seen, the measured data from the BMS was very different than expected. The damper positions showed no apparent pattern, with an almost random distribution of damper openings, regardless of space humidity.

Next, the feedback signals that controlled the dampers were analysed. Figure 13 shows the position of the outside air damper as a function of the velocity pressure sensor reading, in the outside air stream.

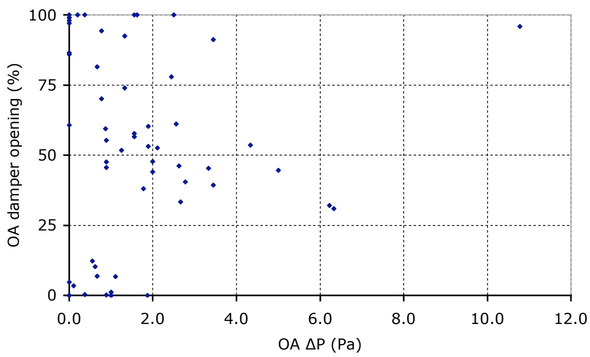

Figure 13 – OA damper vs. OA ΔP

As can be seen, there were several cases where the outside air velocity pressure sensor reading was zero, yet the damper was open fully. All the points in the upper left quadrant of the graph seem unreasonable.

By way of comparison, the supply air damper position was plotted against the velocity pressure control signal from the supply air stream. As shown in Figure 14, it shows a much more reasonable pattern.

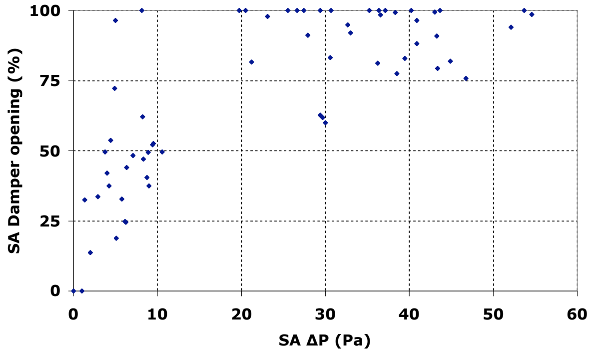

Figure 14 – SA damper vs. OA ΔP

In this case, the damper position is near zero when the differential pressure is near zero, and the damper position is uniformly high when the pressure is high.

Next, the chilled water valve position was plotted versus space temperature and relative humidity, with the expectation that the chilled water valve would be closed when space temperature was cool and relative humidity low (both below the setpoint), and more open the warmer or more humid the space was. This was generally true, as seen in Figures 15 and 16.

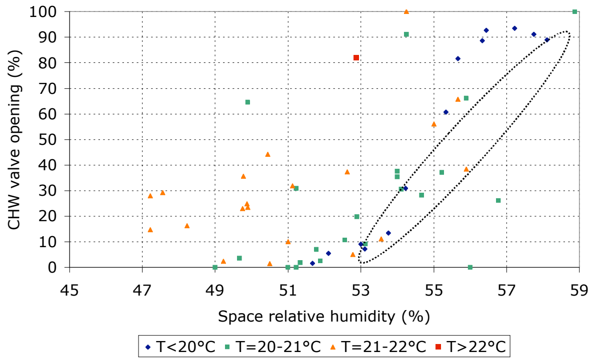

Figure 15 – CHW valve vs. space humidity

The chilled water valve was generally wider open when space relative humidity was higher. The exceptions were usually the spaces with higher temperatures (requiring cooling), shown as orange in Figure 15.

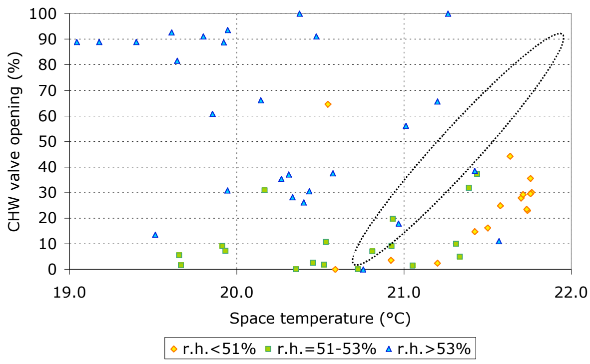

Figure 16 – CHW valve vs. room temperature

The chilled water valve position as a function of space temperature was also generally as expected. Drier spaces are shown as orange, and more humid ones in blue. As can be seen all the cool spaces, with valves wide open had high humidities. There were, however, some inexplicable results where the cooling valve was wide open (in all eighteen tests), and neither space humidity nor temperature were high. These were believed to have local overrides in place that were not visible from the BMS.

Finally, the control of the operation of the heating valve is quite simple, being only controlled by space temperature. As shown in Figure 17, it works well.

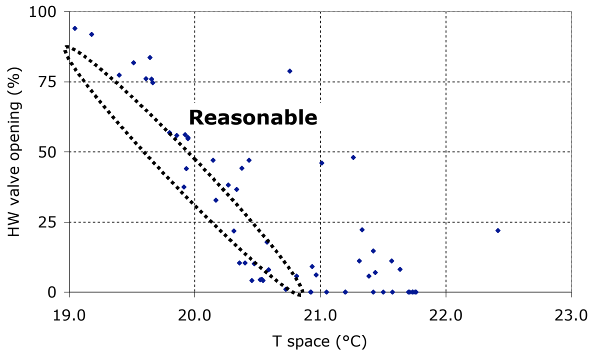

Figure 17 – HW valve vs. space temperature

SUMMARY

The control of outside air supply to mixing boxes at Te Papa, using velocity pressure sensors, appears to be very poor, as the amount of outside air supplied to spaces bears little resemblance to the amount required by air quality or low humidity considerations.

It is not clear why this is, as the design flowrates are 5-10 m/s (1000-2000 ft./min.), well within the range where velocity pressure sensors should register clearly.

Based on this analysis, it is intended to simplify the OA control loops to the mixing boxes, by removing the OA velocity pressure from the system and controlling the damper position directly, depending on the space relative humidity (and air quality).

Given that the historical gas use of the humidifier is about 4,000 kWh/day, as shown in Figure 18, below, the savings could be up to 3,000 kWh/day, or 1 GWh/year, worth about $50,000/year (at 5¢/kWh).

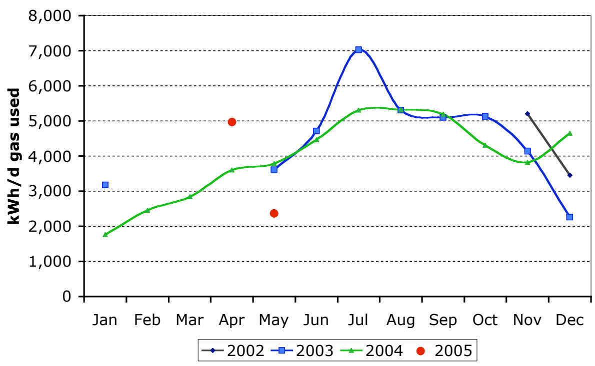

Figure 18 – Average daily gas use, by month

ACKNOWLEGEMENTS

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REFERENCES

(1) Liu, Claridge and Turner, Continuous Commissioning SM Guidebook – Maximising Building Energy Efficiency and Comfort, Federal Energy Management Program, US Department of Energy, October 2002.

(2) http://www.eere.energy.gov/buildings/energyplus/ is the main website documenting and supporting this program.