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POST OCCUPANCY CALIBRATION AND REASSESSMENT OF DESIGN PHASE ENERGY MODELING

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ABSTRACT

Extensive energy modeling was used during the design process of the Aldo Leopold Foundation Legacy Center in Baraboo, Wisconsin (USA) both to minimize the building's overall projected energy use and in a number of instances to determine whether proposed subsystems were viable for maintaining comfort. This paper focuses on three such simulations: a comparison of the thermal performance of earth ducts versus energy recovery ventilators as outdoor-air pre-treatment devices, the design of a heat pump / radiator system to provide minimal heating in an infrequently used wing of the building, and the use of a heat pipe between the photovoltaic array inverter room and the air handler to provide ventilation air stream reheat in the cooling season. The paper presents a critique of the three design decisions based on experiential performance in the case of the heat pipe and heat pump/radiator systems, and based on data monitoring and model calibration in the case of the earth ducts.

INTRODUCTION

Aldo Leopold (1887-1948) was a forester, ecologist and later a professor at the University of Wisconsin – Madison. He spent much of his life restoring natural habitat on a farm in central Wisconsin and was somewhat central in the development of the concept of land ethics. At the time of his work he and others were learning as they went. That same mentality was given as something of a challenge to the Legacy Centre design team. It was made clear that the Centre building was to leave as small an ecological footprint as possible, achieve net-zero energy, use simulation extensively to inform design, and that it was permissible for the design team to try out innovative ideas and have them fail (within reason) so long as the final decisions were strongly justified within the context of the basis of design. From an energy modeling perspective, this meant that the design team needed a simulation tool that was as close as possible to a library of first-principals components without any managerial structure to them and it meant that whatever simulations were carried out in support of the design work were going to need to be verified once the building was occupied. In this case, a "first principals" model is one that relies only on fundamental energy transfer algorithms and not on empirical relations, curve fits, or artificial simplifications. For example, instead of using a building model that predefines a zone temperature, then calculates a load, then imposes that load on a system, the required "first principals" building model in this case would perform an energy balance on the zone given the current environmental conditions and the current state of the mechanical systems and would simply calculate the resulting temperature and humidity of the zone. Control decisions would be made by models watching the zone conditions and a time step appropriate for making control decisions would be used.

SIMULATION TOOL

The simulations described in this paper were carried out using the TRNSYS v16.0 energy modeling environment (Klein, et. al., 2005) with TESS Libraries v2.0 (Thornton, et. al., 2005), an earth duct/hypocaust model that was developed at the Centre Universitaire d'Études des Problèmes de l'Énergie (Hollmuller, et.al.,1998) and with a number of additional components that developed during the course of the building's design process.

To some extent, energy simulation software can be placed on a sliding scale where on the one end are tools that are fast and efficient to use in part because they have more built-in assumptions and by consequence, less flexibility in what they can model. On the other end of the scale are tools that require a greater investment in time both to learn and to use but which allow the simulation of much more diverse systems through their modularity and flexibility. They also tend to force the simulator to develop a significant understanding of the building's dynamics and energy transfer. In the case of the Legacy Centre and its design objectives, a tool from the second category (ie one the forces the simulator to understand the physics of the building and its systems) is wholly appropriate.

By no means does TRNSYS stand alone in this second category of software tools al be it with the late addition of a buffer tank to the heat pump system. However there is always a push for simpler "easier to use" tools. It is worth noting that these more complex tools are appropriate and necessary in high performance (especially "net-zero energy") building design projects that span the range from design to post occupancy measurement and verification.

One feature of TRNSYS that proved critical in this project is that it can be made to abandon the load-system-plant concept in which a zone set point temperature is predefined, an instantaneous heating or cooling load is determined, and then is imposed on an HVAC system without feeding back to the load (in other words, without accounting for what happens when the HVAC equipment is not sufficient to meet the load). Instead, TRNSYS treats the building as another component of the system; the temperature and humidity of its zones are the result of environmental conditions, the conditioned air and water streams that are entering delivery devices in the zones, and the history of what has happened in the zones. There is complete coupling between the building and the HVAC equipment. Such coupling is critical when one of the energy efficiency measures is to reduce the size of HVAC equipment to as great an extent as possible.

SIMULATED SUBSYSTEMS

Heat Pump / Radiator Subsystem

One wing of the building (approximately 150 m^2) is devoted to three meeting rooms that are expected to see infrequent use (approximately one day per week). The entire wing is served by an HVAC system designed to provide code required outdoor air and to maintain 13C in heating season. The low set temperature is a direct result of the rooms' infrequent use. In heating, fresh air is tempered by an energy recovery ventilator while the thermal load is met by a series of finned baseboard radiators set around the perimeter of the space. Although it was not considered in the simulation, a wood stove is used during occupied periods to maintain heating comfort in the space. The wood stove was omitted from the simulation for two reasons. First, an admittedly inexhaustive search for research on the energy use of woodstoves failed to produce algorithms that would adequately predict their performance on a transient basis. Second, it was assumed that most any adequately sized wood stove would be capable of providing the required heating energy to the space. This assumption turned out to be a poor one as discussed later but it would be inappropriate to claim with certainty that including the wood stove in the simulation would have led to a design change. The design phase simulations and construction documents called for a water-to-water heat pump with its source side connected to a ground field and its load side connected directly to the hydronic loop of radiators. Figure 1 shows a schematic of the modelled meeting wing heating loop.

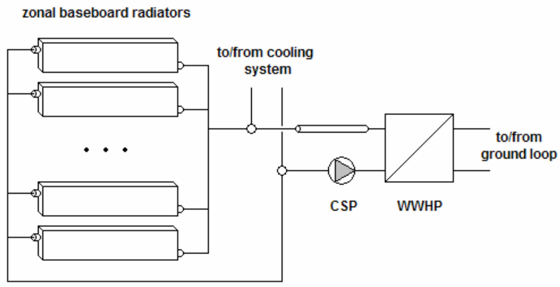

Figure 1: Meeting Wing Heat Pump / Radiator Subsystem Schematic

The Simulated Heat Pump / Radiator Subsystem

The simulation of the meeting room wing heating system consists of a thermostat model that watches the temperature of the largest of the three rooms in the wing and activates a water-to-water heat pump and a constant speed pump when necessary. Hot water flows from the heat pump model through pipe components to a series of radiator models that were developed specifically for this project. The radiators are modeled using the form: m Cp dT/dt = Qin – Qout on the liquid side. Free convection from the radiator is calculated using a correlation for a finned horizontal tube from an introductory heat transfer text (Incorpera, 1990). The water-to-water heat pump component is not a first principals model but makes use of external files that specify capacity and power draw as a function of inlet load and source water flow rate and temperature. Such data can usually be obtained from manufacturers' equipment catalogs. Such catalogs provide performance data over a range of inlet water temperatures that the device is expected to see during operation. The model is able to interpolate power consumption and capacity within the data range of inlet conditions but is not able to extrapolate beyond the range available from the catalog. A first principals model of a heat pump would based solely on fundamental heat transfer algorithms for the compressor, expansion valve refrigerant and heat exchangers and would presumably be able to give accurate performance data for any inlet condition, not just for those inlet conditions provided by the manufactuere. The result of using a curve-fit model instead of a first principals model during design phase simulations was that we had to monitor the predicted temperature of liquid returning to the heat pumps to be sure that it did not often exceed the manufacturer's data range. Simulations were carried out to corroborate load calculations and to show whether radiators directly connected to a heat pump were a viable heating systerm option given that heat pumps operate at somewhat lower water temperatures than are typically used for radiator applications. Simulations showed that the desired heating set point temperature could be maintained by such a system.

The Heat Pump / Radiator Subsystem in Practice

Construction and deployment of the of the meeting room wing HVAC system took place in early spring 2007. It was evident that the heat pump / radiator system operated as intended on cold days but that on warmer days, it would turn on for a time, then switch itself off with alarms for elevated return temperatures. Over the course of an afternoon trouble shooting the system, our interpretation was that as the space warmed to near its setpoint, the temperature difference between the radiators and the surroundings decreased and the radiators were no longer able to transfer as much heat as they were under design conditions. The return temperature to the heat pump consequently rose and eventually tripped the heat pump's alarms. Rerunning the simulations showed the same energy transfer behavior between the heat pump and the radiators. However, the heat pump component used in simulation does not make a check on inlet water temperature and therefore continued providing heating capacity to the return liquid, which in turn raised the supply temperature high enough that the radiators were then able to continue transfering energy to the zone. This is direct evidence of the problem inherent to a curve-fit model of the heat pump; the device capacity remained constant as the return water temperature rose. In the real device, a safety switch shuts off the heat pump (causes its capacity to go to zero) if a particular return temperature is exceeded.

The solution to the problem in the installed system was to decouple the heat pump (which cannot modulate its capacity to load-follow) from the load by placing a 300 L buffer tank between the heat pump loop and the radiator loop and adding another constant speed pump to the system.

This was a situation in which simulation was asked to provide a proof of concept and showed that the system would work effectively. It did so, however, only because the heat pump component in the simulation lacked a safety feature that is included on real-world (as opposed to simulated) heat pumps. In this case, a simplifying assumption in the model meant that the design team missed a dynamic of the system that was under consideration and had to correct the problem at a much later date.

Later in the heating season, the heat pump system was still causing problems. It turned out that the woodstove installed to bring the space up from 13C to 20C during occupied periods was not able to put out enough heat. As a consequence, the owner had reprogrammed the heat pump system to maintain 20C on occupied days and it was not able to do so. With owner approval, the heat pumps had been sized to meet a space load based on a set point temperature of 13C. The sizing was done not using the conventional design method of performing steady state calculations with absolute worst-case assumptions that are almost guaranteed not to happen but by using an annual simulation designed to predict performance during a worst-case scenario that is quite likely to ocurr. As a result the system was not oversized and thus was not able to mask an operator "error" by simply cycling on more often. Had the system been oversized, it would have used more energy than intended but would have maintained temperature. The actual problem (the woodstove was not performing as intended) might have gone undiagnosed. Instead the system failed (did not maintain temperature) and in so doing, led the design and commissioning teams to discover the source of the problem.

Air Handler Heat Pipe Reheat Subsystem

One of the design challenges of the building was in providing reheat to the central air handler. Baraboo's climate is hot and humid enough in summer that it is necessary to undercool the ventilation air for dehumidification. The thermal cooling loads of the building are met by cooled radiant floors run off a water storage tank that is kept cold in summer by staged water-to-water heat pumps and a ground field. As a result of the system design, there is ample cold water for the cooling/dehumidification coil but no hot water for reheat. Gas is not available at the site and the client had provided the design team with a "no electric resistance heat" directive early in the project. The design team worked first on trying to reduce the need for reheat but was not able to eliminate it completely: summertime humidity in Baraboo is too high to avoid undercooling fresh air for dehumidification. Attention turned at some point to the small room adjacent to the air handler that was to house the 9 inverters for the photovoltaic array. The design team decided to proceed with the use of a heat pipe that would remove waste energy from the inverter room and add it to the cooled air stream.

The Simulated Air Handler Heat Pipe Reheat Subsystem

The TESS Libraries heat pipe model takes the conditions of two air streams and an effectiveness for the energy transfer between them. The heat pipe model was inserted into the simulation with the post-coil air flow of the central air handler on one side and the inverter room conditions on the other. A mass flow rate of air past the heat pipe was necessary on the inverter room side in order to calculate the energy transferred. A free convection correlation for air flow around a horizontal pipe from Incorpera and DeWitt was used. What the model showed was not encouraging. Although the heat pipe did drive energy from the inverter room into the air handler when the inverter room was hot enough, it also drove energy out of the air stream and into an otherwise unoccupied room if the air handler air stream was hotter than the inverter room. The inverter room is entirely below grade and remains quite cool, resulting in a significant amount of time when the airstream is warm, does not want to be cooled, but would be cooled by the heat pipe (all throughout the heating season, for example). A number of factors about the simulation caused the modelers to doubt their results. First, it was not felt that they had a good prediction of the temperature in the inverter room. At that time, the size of the photovoltaic array was not fully known and consequently it was difficult to get an estimate of how much heat was going to be generated by the inverters. Second, the methods used for coupling the sub-grade inverter room to surrounding ground temperatures (ASHRAE f-factor method (ASHRAE, 1997)) were simplistic and third they felt that the effectiveness approach to modeling a heat pipe was oversimplified and that sufficient data was not available from the manufacturer to get a credible estimate of the effectiveness value.

The Air Handler Heat Pipe Reheat Subsystem in Practice

In retrospect, it would have been wise to put more faith in the simulation model in this particular case. The heat pipe, when installed, did indeed transfer energy in both directions (from the inverter room to the air stream as intended but from the air stream to the inverter room). It should be mentioned that the heat pipe was installed horizontally (whether incorrectly or by manufacturer's design is not clear) while typically heat pipes are installed on a slope so that the vaporized working fluid rises from the heat source, is condensed at the heat sink and runs back down, effectively preventing bi-directional energy transfer.

After it was installed, it was decided that the heat pipe was not going to work properly and so was removed from the system. Reheat was eventually provided to the air stream from the small solar-heated domestic hot water tank.

Earth Duct Air Pre-treatment Subsystem

Appreciable time was spent in analyzing whether or not pre-treatment of outdoor air should be accomplished using an earth duct / hypocaust system or by more conventional energy recovery ventilators. The advantage of the earth duct was primarily that it is a low maintenance, passive device with a low pressure drop (because UV filtration was possible) and consequently a smaller parasitic energy use. Its main disadvantages were that it was expensive to install and its performance was going to be hard to predict for lack of standardized design methods. The advantage of the ERV was that it is a known technology whose performance is quantifiable using well-established techniques. Its disadvantage was a higher operating energy (because it uses mechanical filtration). In the end, both devices were installed; all of the building's outside air is drawn through a set of five parallel 0.609 m diameter concrete earth ducts (approximately 30 m long) and into the central air handler by a variable speed fan. When the exhibit hall in the building sees high occupancy, earth duct pre-treated air is passed through an ERV that exhausts air from the same space. Figure 2 shows a schematic of the earth duct / ERV subsystem.

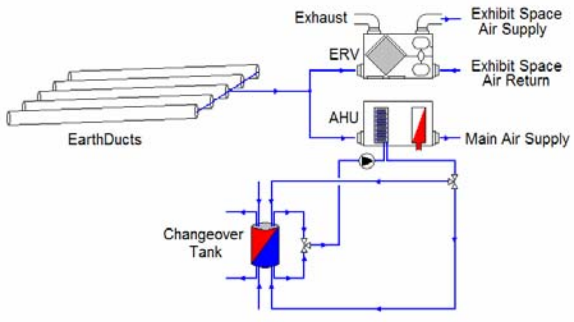

Figure 2: Outdoor Air Pre-treatment System

Design Phase Simulation of the Earth Duct Air Pre-treatment Subsystem

The design team spent significant time simulating the performance of various configurations of earth ducts and energy recovery ventilators. Both earth duct and energy recovery models are performance predictors; they take inlet air conditions, flow rates, and physical parameters and output outlet air conditions. In the case of the ERV model, the component takes temperature, flow rate, and relative humidity of both the fresh and exhaust air streams, a sensible and a latent effectiveness. Values of these physical characteristics were available from the manufacturer. In the case of the earth duct, the model takes inlet air temperature, humidity, and flow rate as well as a fairly extensive parameter file that describes the earth duct layout, soil characteristics, and tube thermal properties. During the design phase, simulations of identical air flow patterns were run through various sized ERVs and through various earth duct configurations. Variations in the earth duct system were made in the number of tubes, tube diameter, tube spacing, tube length, and tube material. One of the most effective metrics that the design team found for comparing results was to overlay psychrometric plots of ambient and pre-treated air conditions. Figure 3 shows such a plot for ERV pretreated air and Figure 4 shows such a plot for earth duct pre-treated air.

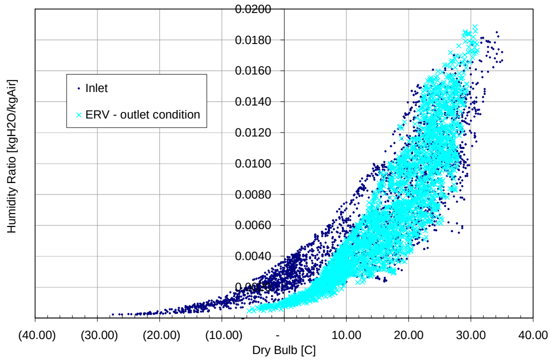

Figure 3: Inlet/Outlet Air Conditions (ERV pre-treatment)

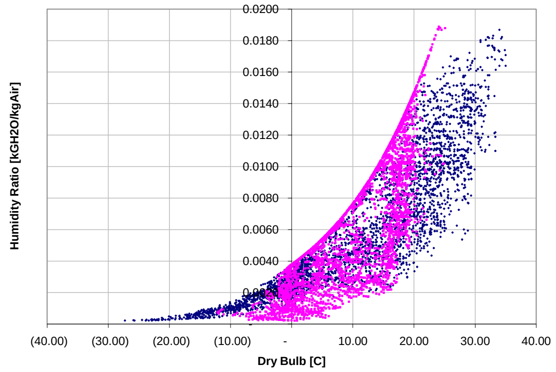

Figure 4: Inlet/Outlet Air Conditions (Earth Duct pre-treatment)

Based on these comparative simulations, the team's conclusion was that the ERV showed a significant benefit in heating but did little to cool and dry the air in summer while the earth ducts showed good cooling potential but less benefit on the heating side. The majority of the building's thermal loads were to be met by radiant floors (both heated and cooled) and the design team had a fairly high degree of confidence in the radiantly heated floors. They had less confidence that the radiantly cooled concrete floors would perform adequately (ie provide enough cooling) without causing condensation. The decision was made to do as much passive outdoor air precooling as possible (in other words to install the earth ducts) and to use the higher operating cost ERV only to assist under peak occupancy periods.

The Earth Duct Air Pre-treatment Subsystem in Practice

The central air handling system is outfitted with data logging equipment that measures and records outdoor air temperature and relative humidity, earth duct outlet temperature and relative humidity, and fractional fan speed. To reduce the required storage space, a data point is logged whenever its value changes by more than a certain (settable) amount. The first step in verifying the post-occupancy earth duct performance was to extract the necessary data from the logging system and export it to a columnar text file. A Fortran program was written to read pairs of points from the text file, linearly interpolate between them and write a new text file containing the same information but at equal time increments. Figure 5 shows ambient temperature, earth duct outlet temperature, and fractional fan speed for a four-day period in September 2008. Note that the fractional speed is plotted on a scale of 0 (fan off) to 10 (fan on at its rated flow rate of 564 L/s).

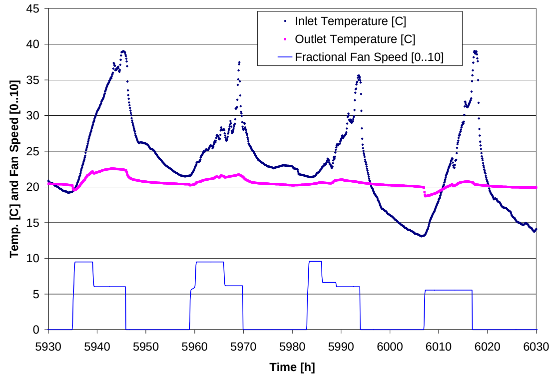

Figure 5: Measured Earth Duct Inlet and Outlet Conditions

It can be seen from the plot in Figure 5 that the air coming out of the earth ducts is at a relatively stable 20 to 22C, beneficially cooler than the average ambient temperature for the time of year but also providing some pre-heating benefit on the one cool morning during the period in question. This would indicate that the tubes are sufficiently long and that the tube surface area to air velocity ratios are such that the air stream has effective energy transfer with the ground. Given the Wisconsin climate, it is hard to believe that the actual ambient air temperature was as high as indicated by the measured data (nearly 40C) and in fact, the sensor array that is logging ambient conditions is located on the roof of the building and not at the inlet to the earth duct system.

With post-occupancy measured inlet and outlet data available on a even time increment basis, a simulation of a data file reader, fan, and earth duct was developed and run repeatedly, tuning physical parameters until the measured and simulated outlet temperatures matched as well as possible. The result is shown in Figure 6; the red lines indicate the simulated earth duct outlet temperature during flow periods. The earth duct temperature during non-flow periods is removed for clarity as the earth duct model simply sets the earth duct air temperature equal to the ambient temperature when there is no flow.

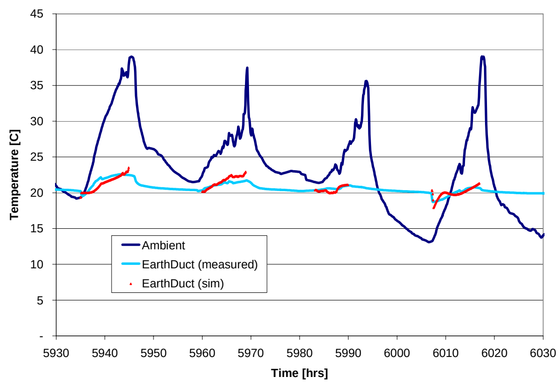

Figure 6: Measured and Simulated Earth Duct Outlet Temperatures

At the end of almost each period, the simulated temperature of the air exiting the earth ducts begins to over shoot the measured data. It is assumed that this behavior is due to the difference between the ambient temperature at the measurement location, and the ambient temperature at the actual earth duct inlet.

The earth duct model requires a rather extensive file of parameters that describe the noding of the ground field, the location of the earth ducts within the ground field, thermal properties of soil and tube material, tube interior heat transfer coefficients, water infiltration, etc. Water infitration was assumed to be negligeable both during the design phase (because the design team didn't feel that it would be possible to estimate) and during the post-occupancy data calibration because a team member was sent down into the earth ducts after a particularly rainy period and reported that not only were they dry but that there didn't seem to be any sign of water that had dried (silt buildup, staining, etc.)

In order to tune the model, six of the earth tube parameters were varied from their design phase estimated values. These were:

- Static tube/air heat transfer coefficient (kJ/h.m^2.K)
- Velocity dependent tube/air heat transfer coefficient (kJ/(h.m^2·K)/(m/s))
- Soil thermal conductivity (kJ/h.m.K)
- Soil thermal capacity (kJ/h.m^3.K)
- Tube material thermal conductivity (kJ/h.m.K)
- Tube material thermal capacity (kJ/h.m.K)

During the design phase, the tube heat transfer coefficients were calculated using minimum and maximum expected face velocity, Moody Diagrams, and a corrlelation for heat transfer on the inside of a pipe under forced convection from Incorpera and DeWitt (Incorpera, 1990). Soil properties were estimated using published values for wet sand. Earth duct properties were estimated using published values for lightweight concrete. Table 1 below summarizes the design-phase (preconstruction) and calibrated (post occupancy) values for each earth tube parameter identified above.

Table 1
Pre and Post Calibration Values

PARAMETER DESCRIPTION	DESIGN PHASE VALUE	CALIBRATED VALUE
Static tube/air heat transfer coefficient	4.614	76.0
Velocity dependent tube/air heat transfer coefficient	187.26	55.45
Soil thermal conductivity	1.26	2.52
Soil thermal capacity	1282	1300
Tube material thermal conductivity	1.512	2.512
Tube material thermal capacity	2646	1000

Based on the September calibration, the tube and soil thermal conductivities as well as the static heat transfer coefficient were originally underestimated. This would suggest that stagnant (or slow moving) air in the tube comes to equilibrium with the ground temperature much more quickly that had originally been estimated and that over the long term, the soil temperature will not build up much temperature stratification near the tubes (ie the temperature of the soil near the tubes will not be goverened by energy given up to or absorbed from the air in the tubes). The tube and soil thermal capacities and the velocity dependent tube/air heat transfer coefficient were originally overestimated. This would indicate that from an energy transfer perspective there is not as much benefit to running the air quickly through the tubes and not as much detriment to running air slowly though the tubes (recall that the air system is variable volume and only runs at its peak flow rate on peak occupancy days). The high soil thermal capacitance would indicate that the soil / tube / air system will change outlet temperature less rapidly with changing long term (deep earth) conditions than had been expected.

The original design simulations were then conducted with the calibrated earth duct parameter file to determine whether the original decision to include them in the system held up with better knowledge of their actual performance.

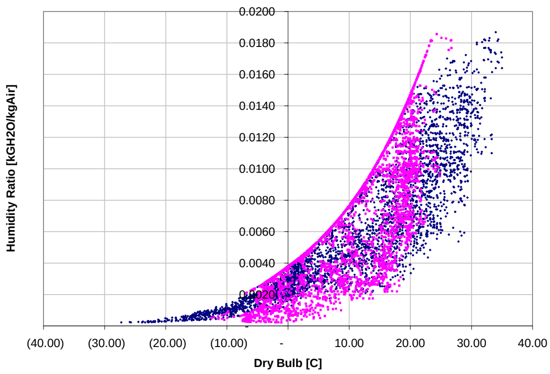

Figure 7: Inlet/Outlet Air Conditions (Calibrated Earth Duct pre-treatment)

Comparing the earth duct performance prediction shown in Figure 7 (post calibration) with that shown in Figure 4 (pre calibration) indicates that the cooling and heating performance, especially at extreme conditions is not as good as had been originally predicted. This suggests that the design model slightly overpredicted energy savings from the earth duct.

There are of course a number of weaknesses with the calibration exercise that has thus far been carried out.

First, confidence that the measured ambient conditions are representative of the conditions of air entering the earth ducts is needed. Second, the calibration needs to be carried out over a much longer period than one month. Third, the September period used for calibration was dominated wholly by cooling operation and included approximately two (non consecutive) days when the data logging equipment was nonoperational for an unknown reason.

CONCLUSION

A number of studies have been carried out to determine whether buildings that undergo a "green high performance" design process such as that prescribed by the LEED™ rating system actually use less energy than an average building. A recent study carried out by the National Building Institute suggested that LEED™ rated buildings use 30% less energy than average buildings (Turner, et. al, 2008). A critique of that same study analyzed the same data set with some different criteria and suggested that in fact LEED™ buildings use more energy than their average counterparts (Gifford, 2008). One of the central arguments in the critique is that designing with a nearly exclusive emphasis on comparative performance *prediction* is a mistake and that the only true measure of building efficiency is post occupancy energy use measurement. In the opinion of the present paper's authors, however, predictive simulation must play a part in the design of high performance buildings and that post occupancy measurement and verification is the feedback that improves subsequent designs. The question for the design team then becomes; during the design phase simulation work, when do you trust the model and when do you not?

In the three cases highlighted in this paper, simulation led the design team correctly in the case of the heat pump / radiators (al be it with the late addition of a buffer tank to the system) and correctly in the case of the earth ducts (this time with an over prediction of performance on the earth ducts.) Simulation actually led the design team correctly in the case of the heat pipe as well except that the modellers did not believe that the model was telling them that the system was not viable.

Prior to reassessing the systems post-occupancy, the modellers suspected that the earth-tube system was working better in simulation than in real life simply because of the number of assumptions that had to be made in setting up the model. They did not, however, have a good sense as to whether the model was vastly over predicting performance or just over predicting performance a little. The modellers did not expect that the heat pump system in the low-occupancy meeting wing of the building would fail and were fairly confident in their design-phase assessment of that system. The heat pipe simulation bears further study. It is clear that the simulation predicted that the heat pipe would not work and it is clear that indeed it did not. What remains unclear, however, is whether the heat pipe failed for the reasons predicted by the simulation or for entirely unrelated reasons.

It would seem from this experience that the key to high performance building design is in the use of simulation early to inform design, and perhaps more importantly, in the use of post-occupancy measurement and model calibration to verify design and build a more solid experience base. In the case of the present work, further designs of earth duct systems have been carried out with a performance derating factor. As more data is available from the Legacy Centre system, better prediction methods of the static and velocity-dependent tube/air heat transfer coefficients are being developed. In more recent designs of heat pump systems, it has become a matter of course to include more significant thermal buffering than is typically recommended by manufacturers' representatives.

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