Simulating a Passive Downdraft Evaporative Cool Tower

Liam Buckley[1]
[1] IES Ltd, Boston, MA, USA

Abstract

This paper is focussed on the concept, design and simulation methodology for a passive downdraft evaporative cool tower application. Passive evaporative cooling is a very efficient cooling application, but is often offset by fan energy. The cool tower concept utilises pressure differences (stack effect) to move air through the building. To further enhance this air movement, a negatively pressurised atrium creates an additional 'pull' so to correctly define the path of airflow, moving the cooler air into occupied areas that require cooling.

There is a common misconception in industry today, that the passive down-draft evaporative cool tower model cannot be explicitly modelled and requires "workarounds". This paper aims to clearly define an explicit workflow, devoid of workarounds.

This type of application can be used in many locations, but is especially useful in areas that can be simultaneously hot and dry; e.g. Calgary, AB. The presentation shall analyse the inputs required to simulate this innovative design such as louver intakes, airflow controls and bulk airflow. Finally, certain outputs shall be examined and compared by using this design, with variables such as building energy consumption and thermal comfort of occupants.

1 Introduction

This particular evaporative design strategy is suited to climates that experience simultaneous dry and hot conditions. For example, Denver in Colorado experiences such a phenomenon due to the adjacency to the Rocky Mountains and high altitude. Should one follow the path of the Rockies north into Canada, similar simultaneous conditions might occur.

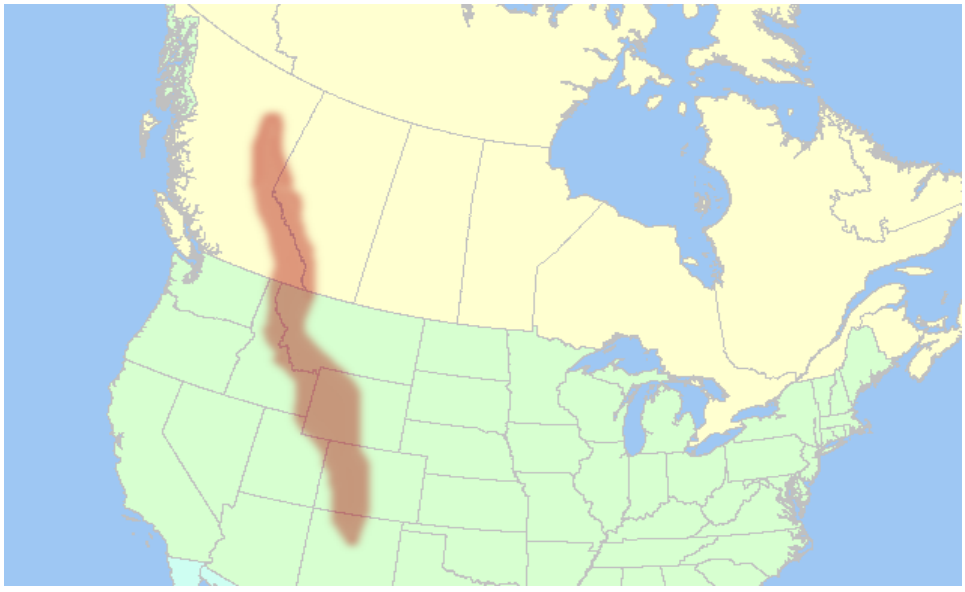

Figure 1: The Rocky Mountains in Alberta and BC.

Climatic Analysis

For the purposes of this paper, the location of Calgary, AB was selected for further investigation. A Mahoney Analysis ((Upadhyay, Yoshida) or 'monthly average' analysis of the Calgary CWEC (Canadian Weather for Energy Calculation) climate file in Figure 2 for Calgary indicates that the peak external dry-bulb temperature reaches 32.3°C during July.

The Mahoney analysis was used to examine swings between daytime and nighttime conditions for human comfort stresses. Figure 2 and Figure 3 further demonstrate that this climate may require air-conditioning for typical commercial applications.

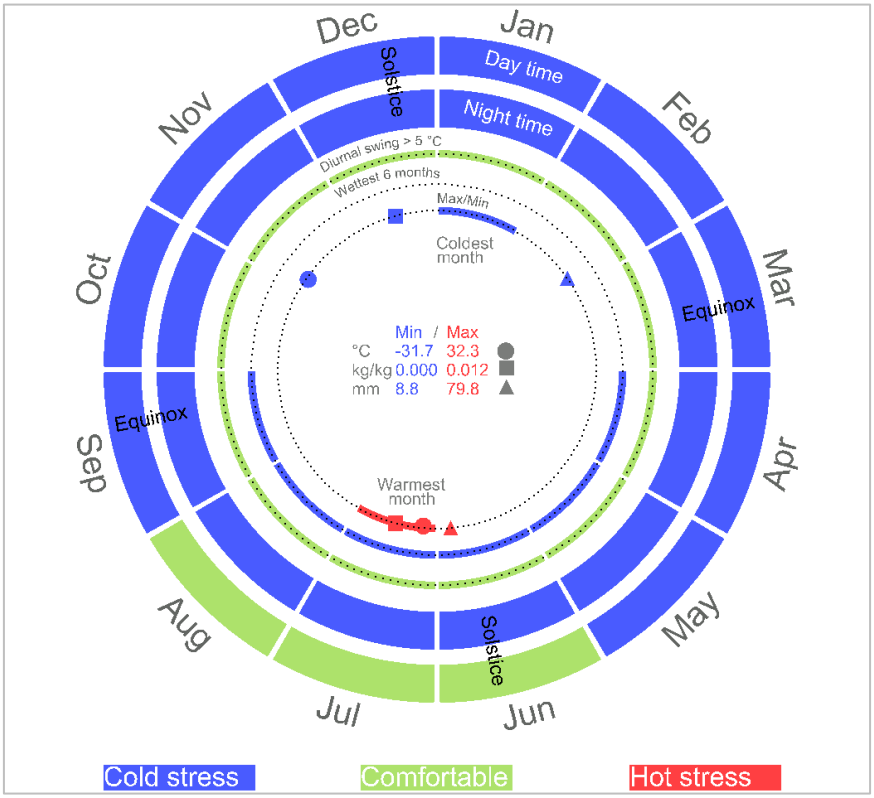

Figure 2: Mahoney Analysis for Calgary Alberta (CWEC Climate File).

The temperature ranges in Figure 3 indicate that external dry-bulb temperatures exceed 20°C for 668 hours and 30°C for 13 hours of the year. Note the peak hot stress is during July.

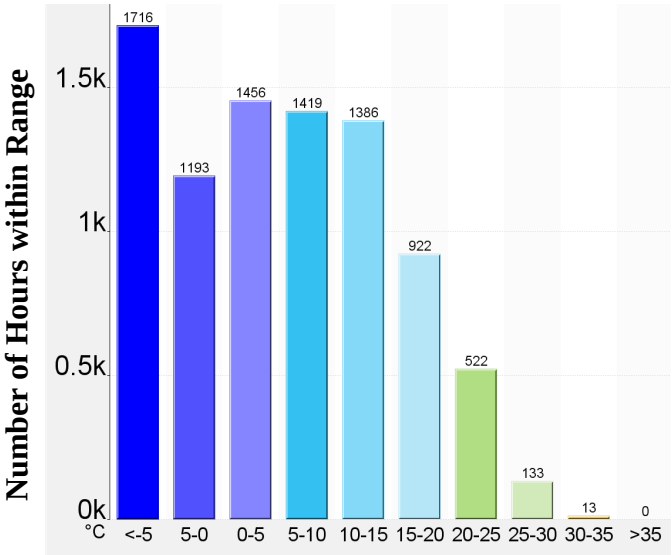

Figure 3: External Dry-Bulb Temperature Distribution

Figure 4 below demonstrates the simultaneous hot and dry conditions during the warmest month of July.

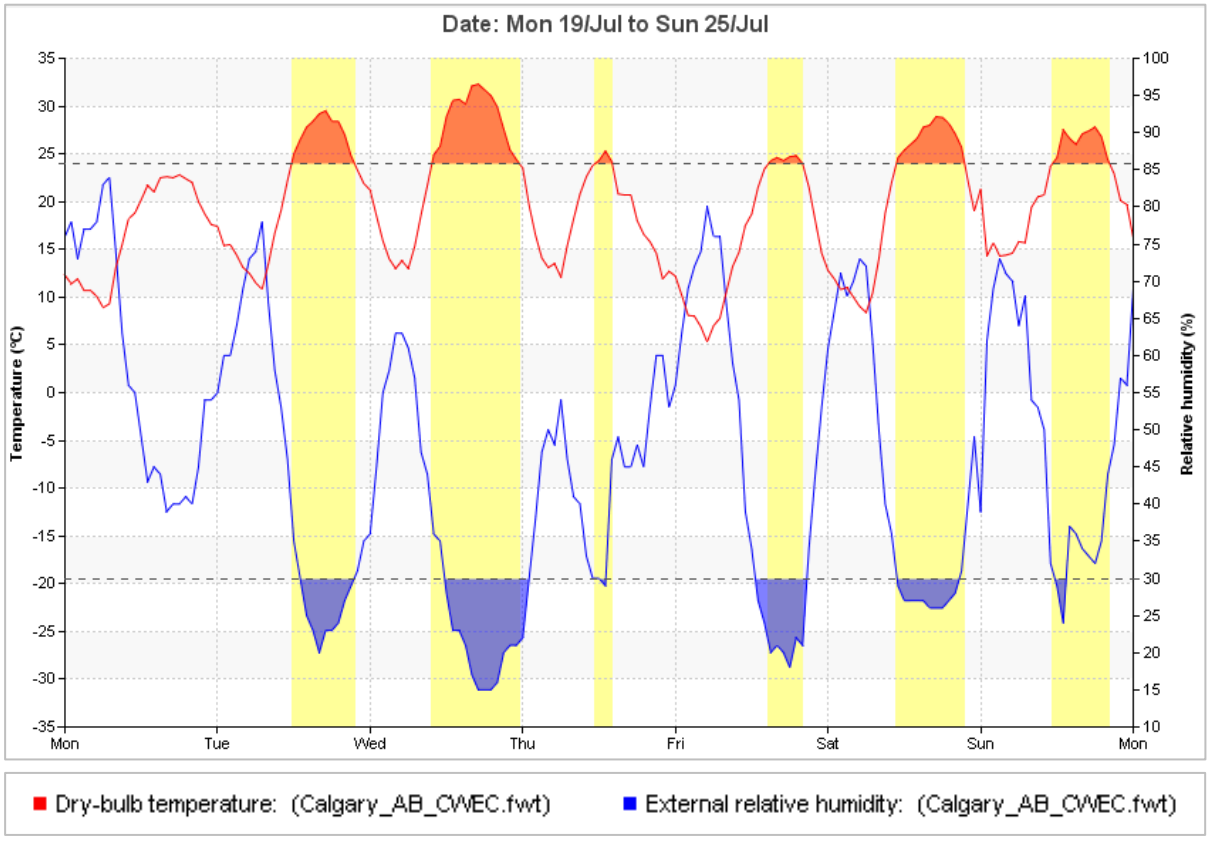

Figure 4: Alberta Experiences a Simultaneous Dry-Bulb Temperatures (red) exceeding 24°C and Relative Humidity (blue) below 30% RH.

The hours in which;

- External dry bulb temperatures (left Y-axis) that exceed 24°C are highlighted in red.
- External relative humidity (right Y-axis) that falls below 30% RH are highlighted in blue.
- The yellow areas highlight the phenomenon where the above conditions occur simultaneously.

Simulation Software Selection & Validation

Due to the common misconception in industry today, that the passive down-draft evaporative cool tower cannot be explicitly modeled and requires "workarounds"; an advanced simulation tool (IES-VE) and engine (ApacheSim) was selected so to accurately capture all of the thermodynamics, controls and heat/mass balances correctly at sub-hourly (e.g. 6 minute) time-steps. IES-VE is a fully ASHRAE 140 validated simulation tool (www.ashrae.org).

The IES-VE 2013 is also EPAct Qualification by the US Department of Energy (www.energy.gov); it is approved by the Canadian Green Building Council for LEED submittals; it is accepted by the cities of Toronto and Vancouver for building permits and is approved for the HPNC (High Performance New Construction) incentives provided by the Ontario Power Authority.

2 Methodology

A summary of the methodology is detailed is sections 2.1 to 2.8.

2.1 Zoning the Simulation Model

The three dimensional model was built in the energy modeling platform (IES-VE) and the model was thermodynamically zoned. See Figure 5 & 6.

The example model in Figure 5 was used for the analysis. The model in Figure 5 does not represent an actual building, but does represent the necessary simulation principles for successful building energy, airflow and thermal comfort analysis. On the left (west), two passive downdraft cool towers (north and south) are shown with external louvers on all four sides.

On the right (east), there is an atrium that has been subdivided into four zones. They are an underfloor plenum, an occupied zone, a central stratified zone and an upper stratified zone. Only the underfloor air plenum has any physical entity separating the vertically stacked zones; i.e. interzonal airflow is unrestricted and direct solar radiation is allowed to pass from zone to zone. The upper stratified atrium zone has two high-level openings on opposing sides, so that one window shall always be open on a leeward side of the building during passive cooling operation, thus creating a negative pressure in the atrium. These two openings operate in conjunction with one another; such that, if one is open, the other is closed. This changes dynamically dependant on the varying wind direction. Wind speeds and wind direction were read from the weather file.

There are office spaces on two floors. They each have an underfloor plenum (open to the cool tower), an occupied zone, a stratified zone and a return air plenum. The return air plenums are open to the negatively pressurised atrium.

Figure 5: The Passive Downdraft Evaporative Cool Tower Model Building

The passive downdraft cool tower itself is detailed in Figure 6. The adjacent underfloor zones of the cool tower are already negatively pressurised for reasons detailed later in the paper. The passively guided direction of airflow is further enhanced when the hot and dry

ambient air from outside moves freely through the inlet section of the cool tower; the ambient air encounters the spray section, thus adding moisture to the air and causing it to cool and dump downwards. The cool tower has now become a passive downdraft evaporative cool tower.

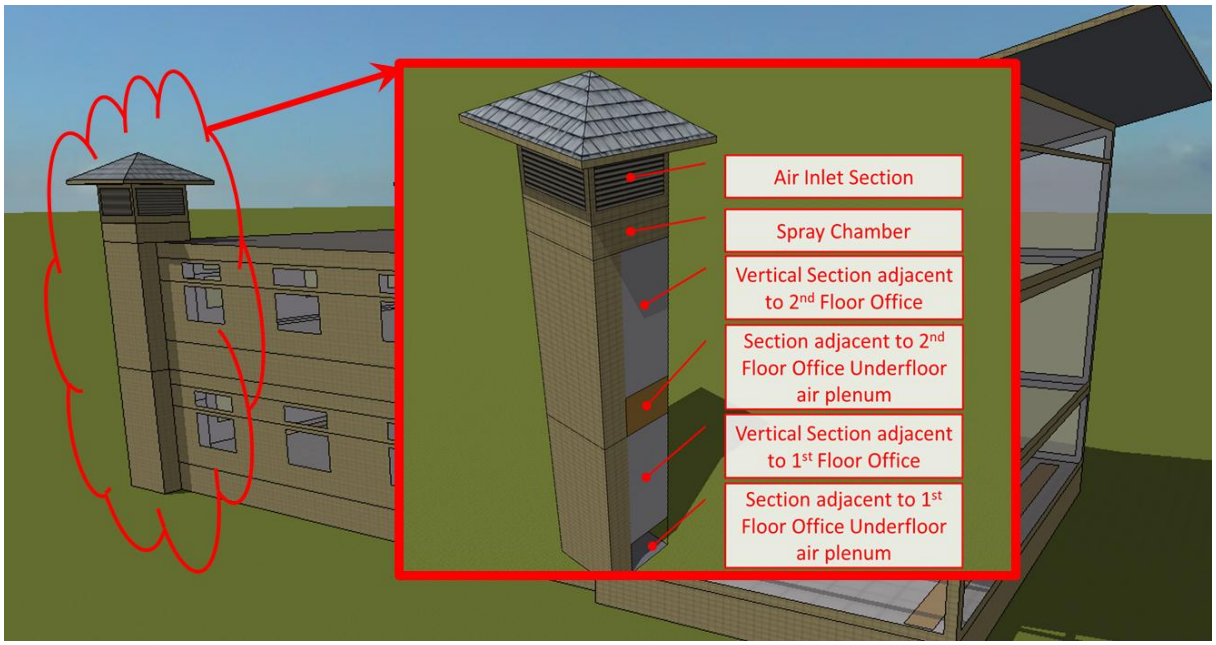

Figure 6: Detail of Passive Downdraft Evaporative Cool Tower

2.2 Climate and Orientation

The weather file and orientation were set as per Figures 2-4.

2.3 Calculate Dynamic Insolation (Incident Solar Radiation)

As shown in Figure 7, the incident solar radiation was calculated for every internal and external surface in the model at an hourly time step. Non-opaque surfaces allowed solar radiation to pass from zone to zone where applicable; e.g. through the atrium zones.

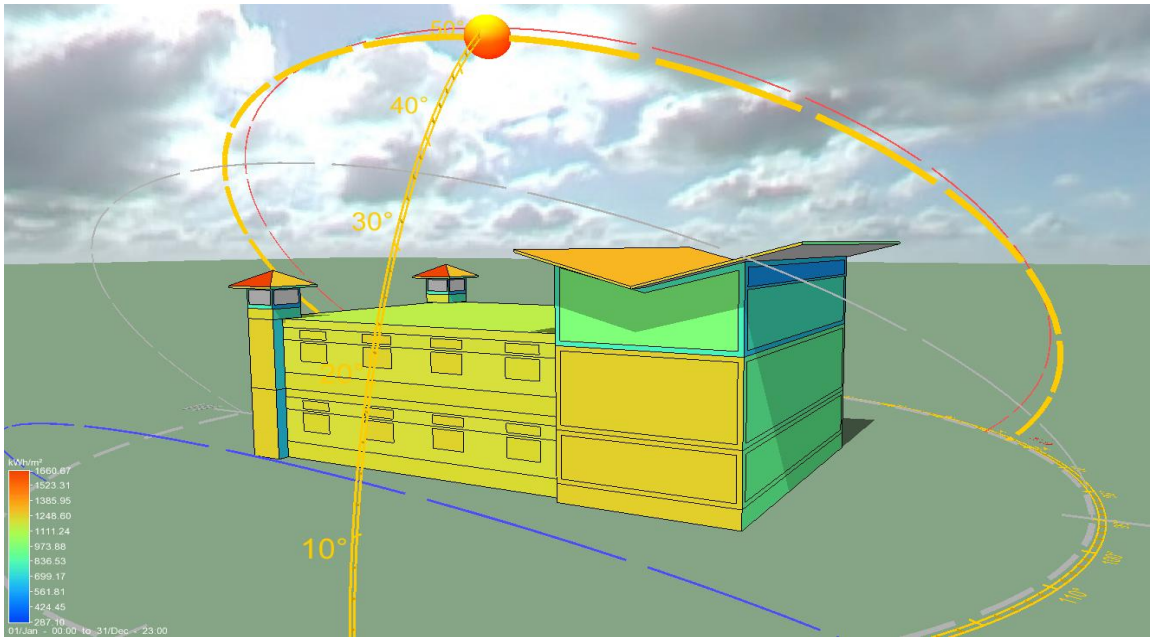

Figure 7: Incident Solar Radiation on the Three-Dimensional Model

2.4 Develop and Assign Envelope Thermo-physical Properties

The construction details were assigned as per Figure 8. Due to the fact that the envelope materials are not the primary focus of this paper, or simulation process, they are not detailed any further in this paper.

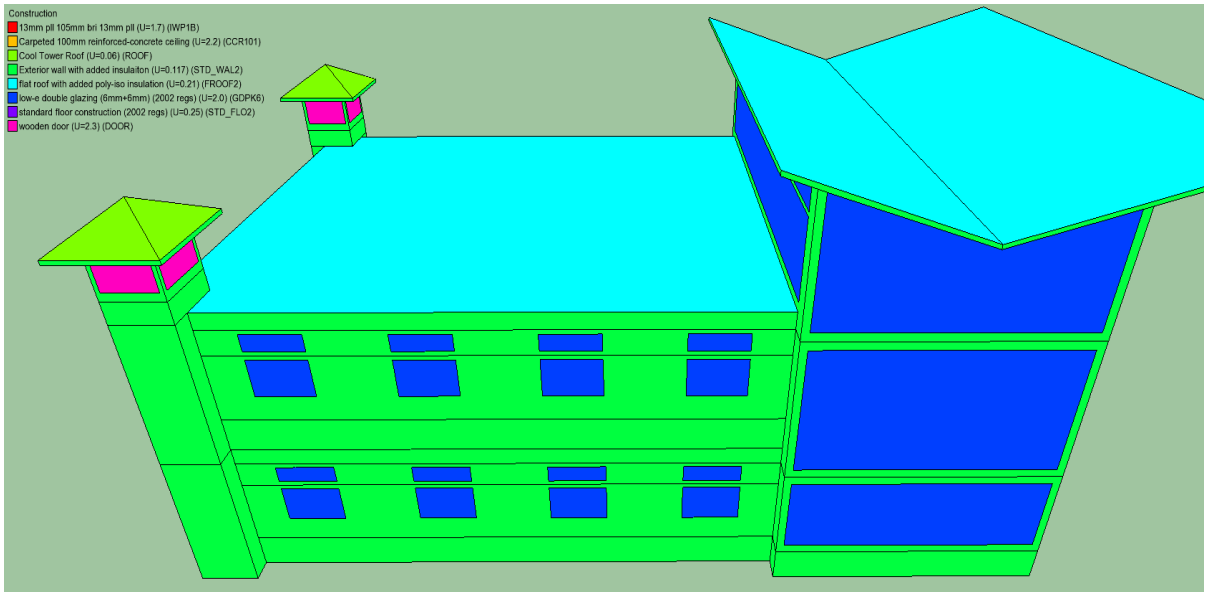

Figure 8: Envelope Constructions Assigned (U-values shown in the top-left corner)

2.5 Thermal Templates and Internal Gains

Note that both the office spaces and the atrium were sub-divided vertically into independent thermal zones, so to accurately capture the effects of displacement ventilation. This is shown in Figure 9.

Occupants and plug loads were assigned to the occupied zones. The lighting gains were assigned to the stratified zones. These zones are 'fully open' to one another which allows the effects of inter-zonal airflow as well as allowing daylight and incident solar radiation to pass from one zone to another where no physical obstruction exists. The radiant component of the lighting gains also passed to the occupied zones below.

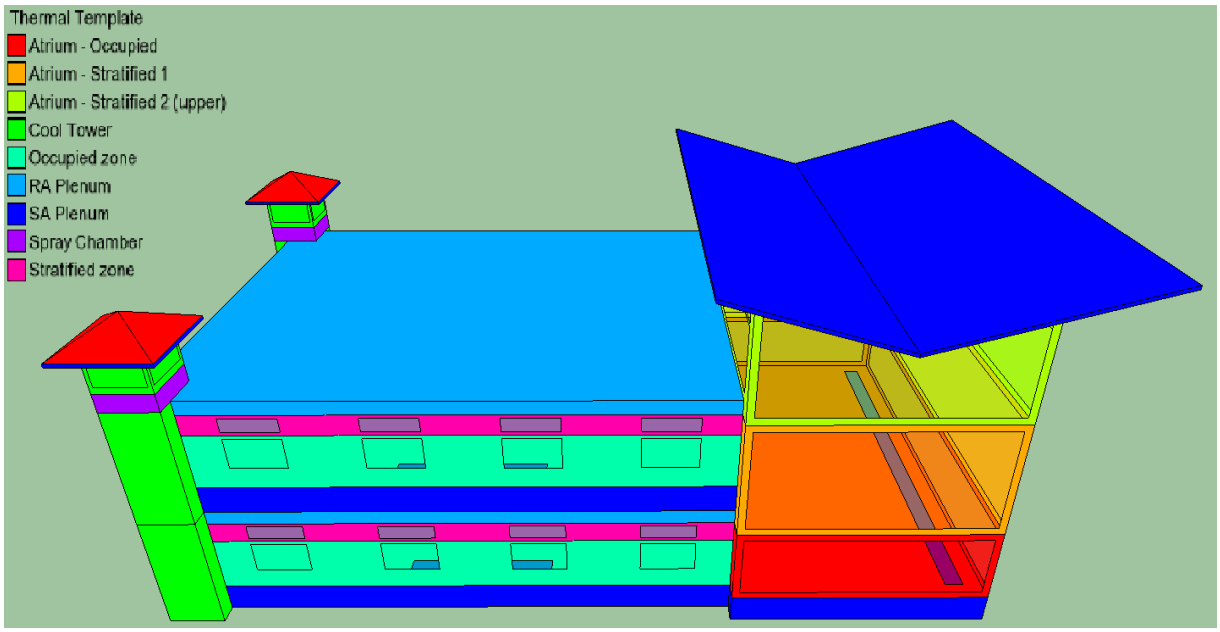

Figure 9: Assigned Thermal Templates

2.6 Fenestration Openings were assigned.

The site terrain type was considered to be suburban and both the magnitude and frequency of local wind speeds and wind directions were studied, and this was recorded below with a plan-view of the local wind rose.

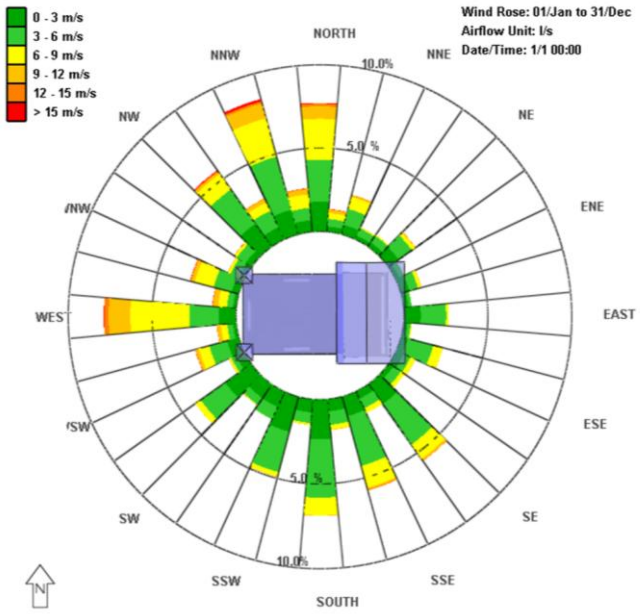

Figure 10: Site Wind Rose

The annual hourly wind data was discovered to be somewhat sporadic. Therefore a simulation solution for all climatic scenarios was required.

The external openings of the cool-towers were four sided and considered to be louvers with 80% free operable area, as typically specified by a manufacturer and shown in light green in Figure 11. These exposure types were considered to reference "sheltered wall" which impacted the wind pressure coefficients at varying angles of attack. These are further detailed in Appendix A and by the IES-VE MacroFlo Calculation Methods (www.iesve.com).

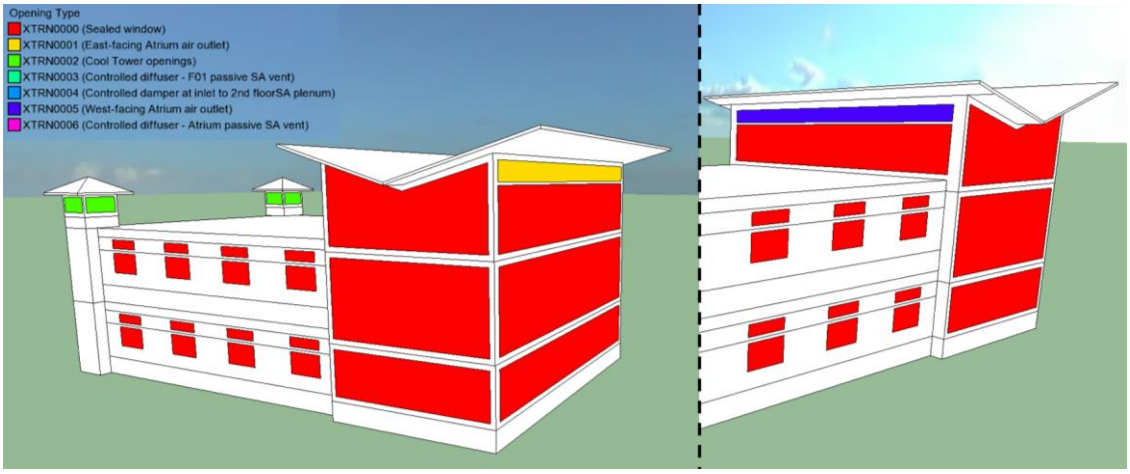

Figure 11: Assigned Fenestration Opening Types

The windows at high level of the atrium are also considered to reference a "sheltered wall" to account for worst case conditions. These two windows do operate in conjunction with one another, such that one is always open while the other is always closed. The window controllers react back and forth, dependent upon the sub-hourly wind conditions. Due to the fast response times required, they were simulated at a 2-minute time-step to account for all sporadic and dynamic wind conditions.

2.7 HVAC Airflow Network was configured.

The HVAC airflow network as shown in Figure 12 was setup with zero mechanical assist. That essentially meant having no fans present and also eliminating any mechanical airflow. There were a number of controllers placed below that had zero litres/second as an input. This was set up in order to allow any airflow to occur via passive means only.

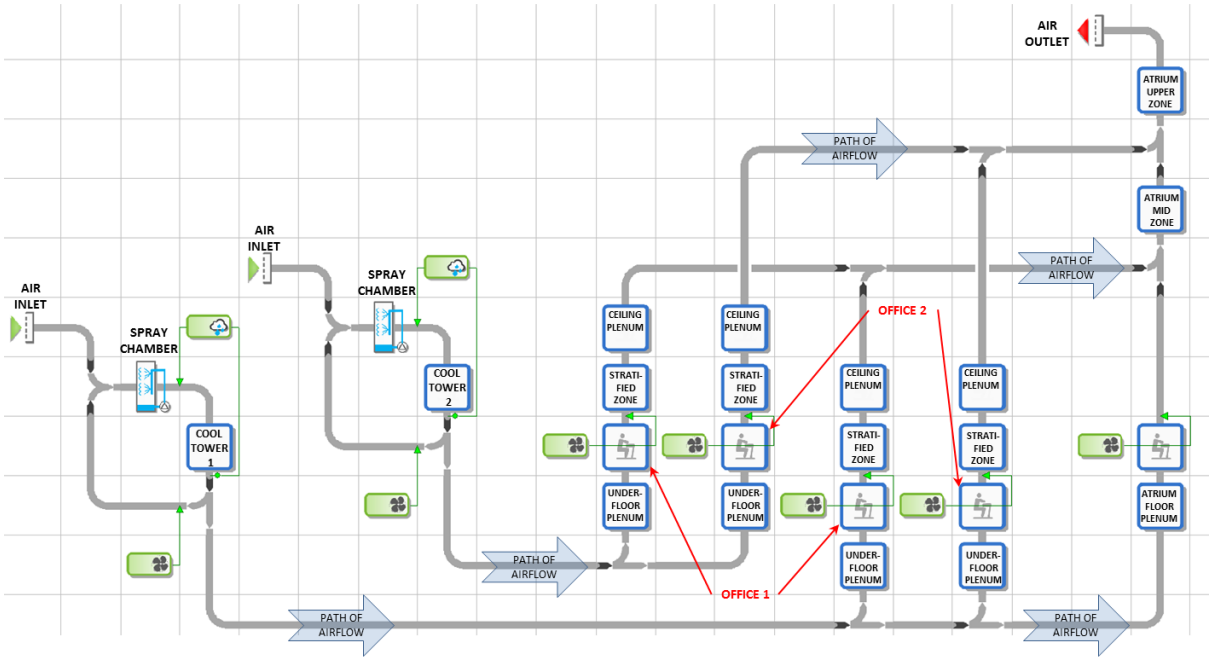

Figure 12: HVAC Airflow Network.

2.8 Perform energy simulation and analyse results.

A dynamic solar simulation and dynamic daylight simulation were performed first because they feed results into the energy simulation at a predefined time step. Then the annual energy/airflow simulation included the detailed HVAC network and the MacroFlo (bulk airflow) simulation at a 2 minute time step.

3 Results

Figure 13 shows the Dry Resultant Temperature during peak conditions. The occupied rooms ranged between 22-25°C. The external dry-bulb temperature during this period was 32°C.

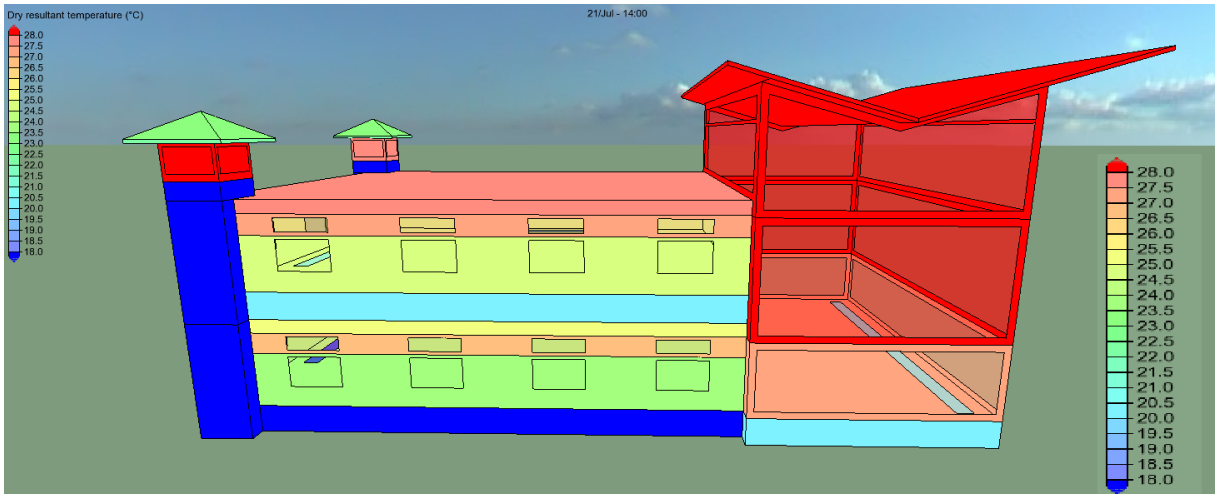

Figure 13: Dry Resultant Temperatures under Peak Summer Conditions

The Percentage People Dissatisfied during peak conditions of the occupied rooms ranged between 7-14.5% PPD (Percentage People Dissatisfied). This is shown in Figure 14.

Figure: 14: Percentage People Dissatisfied during Peak Summer Conditions

The occupied zone of the atrium did not perform as well as the occupied zone of the atrium due the substantial solar gain received in the atrium, which increased the mean radiant temperature of that zone.

During peak conditions, the daily profile of outside dry-bulb temperature reached over 32°C; meanwhile the internal temperatures of the two occupied office spaces remained lower than 25°C. During this period, the PPD remained below 20%, as required by ASHRAE Standard 55. This is shown in Figure 15.

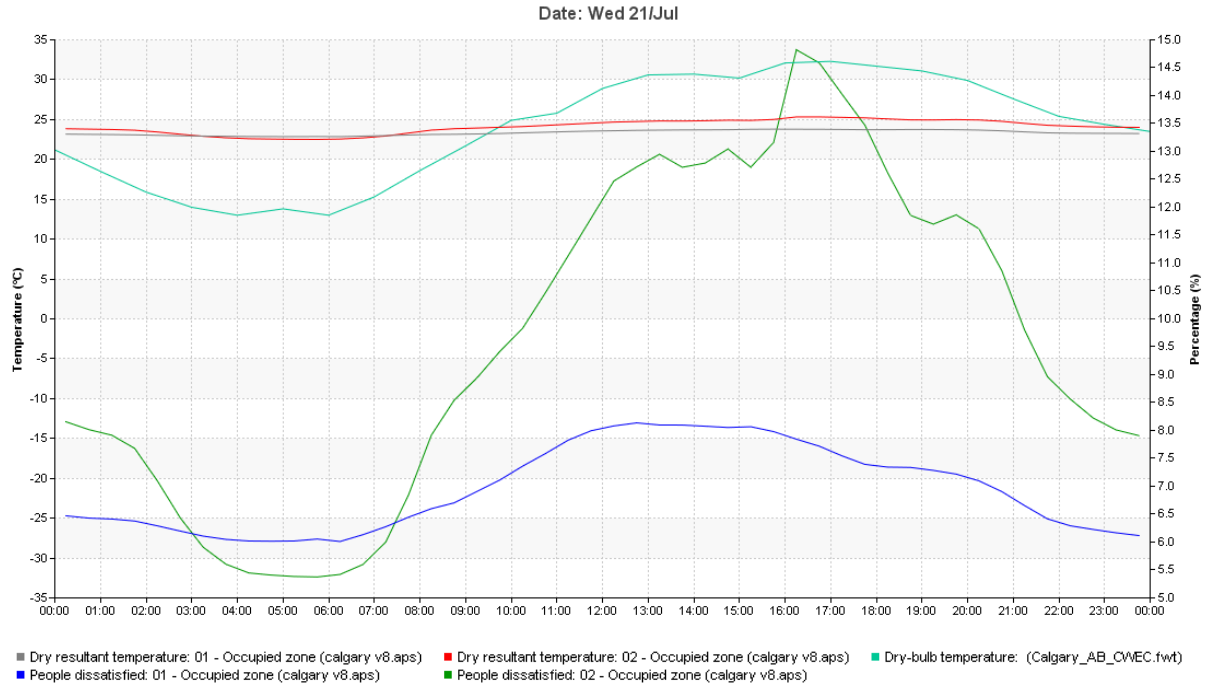

Figure 15: Daily Profile of PPD, Internal Dry Resultant Temperatures and External Dry-Bulb Temperatures

Note there are two Y-axes in the graph for Figure 15; temperature (-35°C to 35°C) on the left Y-axis and PPD (5% to 15%) on the right Y-axis. This analysis demonstrated a very visually effective high-performance building design strategy.

Further results analysis demonstrated the effective inter-zonal air flow down through the passive downdraft evaporative cool towers, through the underfloor plenums, occupied rooms, ceiling plenums and into the atrium, finally leaving the atrium at high level. This is shown in Figure 16 and 17 with airflow arrows demonstrating the direction of Interzonal air-flow.

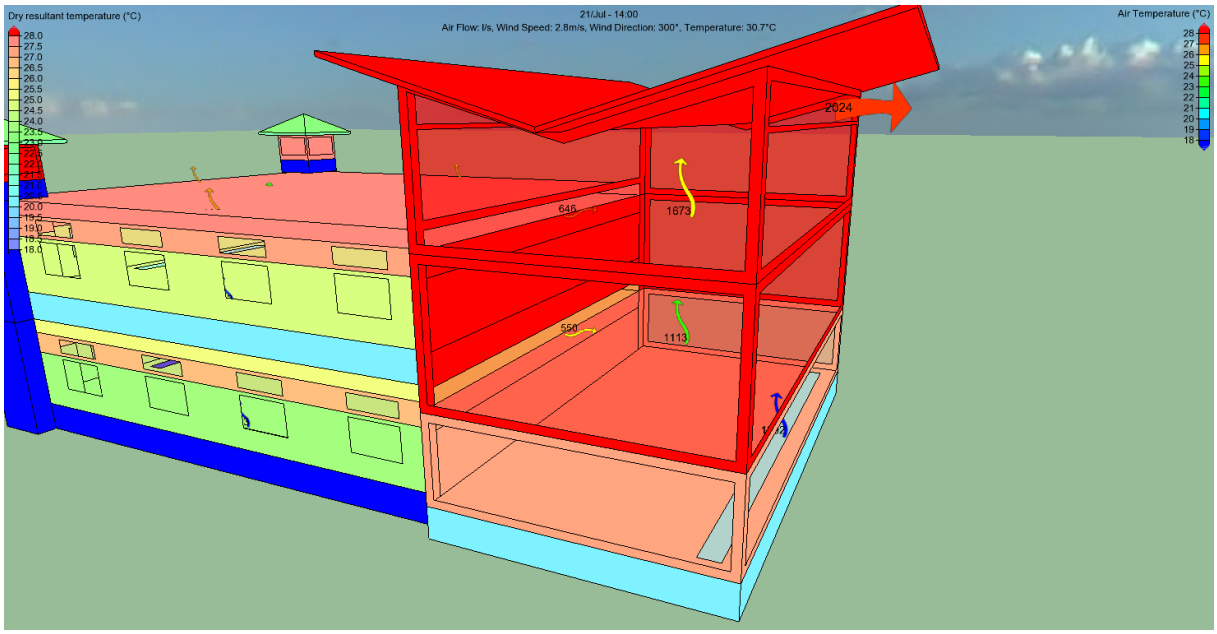

Figure 16: Atrium Interzonal Airflow

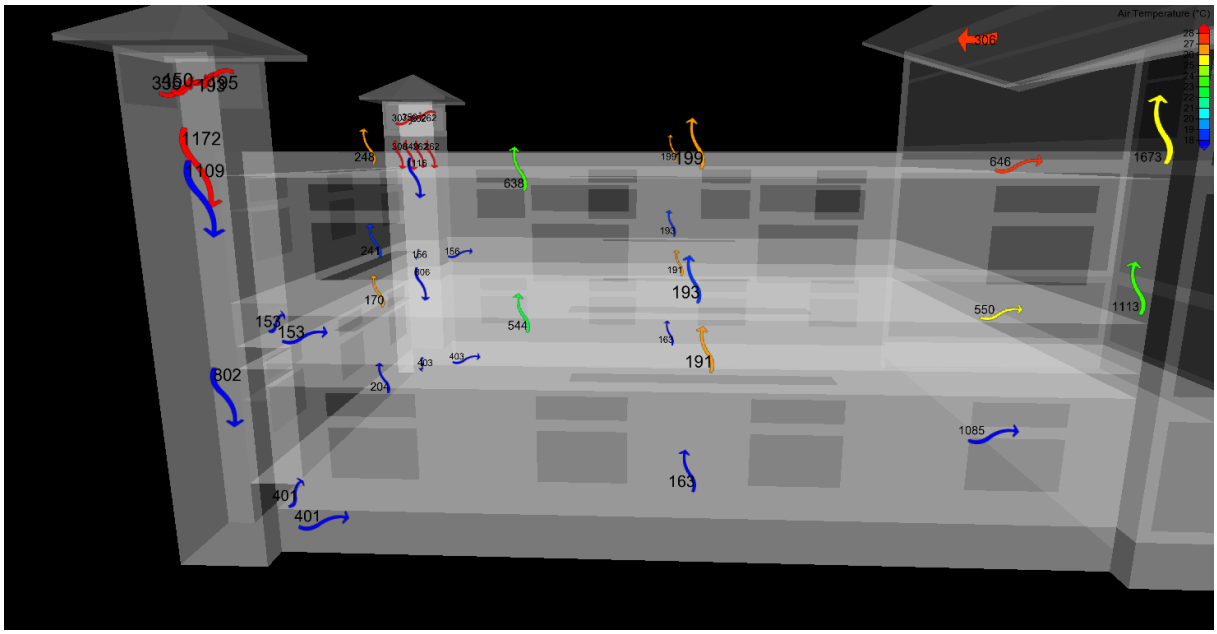

Figure 17: X-ray Effect of Passive Cool Tower Interzonal Airflow

Note the values beside the airflow arrows in Figure 16 and 17 represent the air quantity in litres per second.

The sizes of the arrows mirror their magnitude and the colour references the temperature between 18°C and 28°C. Figure 16 also demonstrates the temperature of each zone by colour.

4 Discussion

As demonstrated, this is a very effective design strategy for the reduction of energy and yields a positive effect on thermal comfort during simultaneous hot and dry ambient conditions.

For certain climates, ambient air leaving the cool-tower might be too moist and may be required to be dried. For this scenario, a reheat coil in the underfloor air plenums would alleviate this issue and also assist with the convective component of displacement ventilation.

For installations that struggle to generate enough negative air pressure in the atrium, an extract/exhaust fan at high-level in the atrium would overcome any unwanted static pressures and force air through the same airflow path.

For installations where mould in the cool-tower or where legionella is a risk, the spray chamber could be replaced with a cooling coil. There may however be an additional energy penalty.

Further areas of analyses might be a computation fluid dynamics analysis (CFD), in order to refine the design.

5 Conclusions

No simulation "workarounds" were required and the workflow process that is detailed in this paper can be used as a template for further future research and analysis. This was a major intent of writing this paper.

While considering a natural ventilation strategy for design of new construction projects promises low energy consumption; the strategy is often dismissed by design team members due to the potential lack of control building occupants will have. This paper intends to alert all members of design teams about the simulation process of this hybrid system and its control strategies, especially in the climates that warrant it. The passive cool-power evaporative cooling options should still yield low-energy consumption and acceptable thermal comfort of occupants. Yet, an element of building control is maintained and can be further improved for scenarios discussed in section 4.

6 Acknowledgements

This paper wishes to acknowledge a friend and colleague; Timothy Moore of IES Ltd., for sharing his HVAC simulation and controls expertise with the author and with the industry.

7 References

ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy.

American Society of Heating, Refrigeration and Air-Conditioning Engineers

www.ashrae.org

ASHRAE Standard 140: Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs.

American Society of Heating, Refrigeration and Air-Conditioning Engineers

www.ashrae.org

Canadian Weather Energy and Engineering Data Sets (CWEEDS); CWEC Weather Files. CWEEDS Appendix D.

EPAct Qualificatied Software, as per the US DOE.

http://energy.gov/sites/prod/files/2014/02/f7/qs_iesve_v2013_20140127.pdf

Integrated Environmental Solutions Ltd.

VE-GAIA and VE-Pro Software

www.iesve.com

MacroFlo Calculation Methods

http://www.iesve.com/content/downloadasset_4423

Upadhyay, A., Yoshida, J., Rajal, H., 2006. Journal of Asian Architecture and Building Engineering. May 2006.

Paper: “Climate Responsive Building Design in the Kathmandu Valley”.

8 Appendix A: Wind Pressure Coefficients of a Sheltered Exposure Type

Wind Pressure Coefficients

Angle of Attack

0.0°	22.5°	45.0°	67.5°	90.0°	112.5°	135.0°	157.5°
0.2	0.156	0.05	-0.091	-0.25	-0.285	-0.3	-0.274

Angle of Attack

180.0°	202.5°	225.0°	247.5°	270.0°	292.5°	315.0°	337.5°
-0.25	-0.274	-0.3	-0.285	-0.25	-0.091	0.05	0.156