Passive Downdraft Systems: A Vision for Ultra-Low Energy Heating, Cooling and Ventilation

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ABSTRACT

In modern buildings, fans used to move air around for ventilation, heating and cooling represent a significant component of energy consumption. As a means of reducing this energy consumption, buildings with conventional overhead air conditioning systems have pushed the limits on air quality and thermal comfort by limiting the quantity of air supplied.

Similarly, natural ventilation systems, with their limited capacity to provide temperature control to meet expectations, especially in cooling are very rarely adopted as design solutions outside of the residential sector, even though they can be extremely energy efficient.

Some designers have sought to overcome this by providing hybrid systems with both natural ventilation and air conditioning backup. Often the cost of two systems results in both systems being or poorer quality with the result still being a building of average performance.

This paper reviews new techniques in a fourth way – enhanced natural ventilation through the use of the passive downdraft, also known as buoyancy HVAC system. The approach has the potential to significantly reduce building energy and enhance air quality (through significantly increased outside air rates (P. Wargocki et al, 2000)) in many building types and especially in relatively mild climates.

Introduction

Just as the use of natural ventilation is as old as buildings themselves, the concept of using buoyancy forces is also thousands of years old.

In ancient Persia, bagdir towers combined with water for evaporation were used to capture wind and use it to push and pull ventilation through buildings in the hot summers, cooling the air as it entered the space.

Similarly the ancient Romans used hot water to heat ventilation air entering large buildings passively in the winter time.

More recently, there are quite a few examples of the use of evaporative cool towers that are used to augment and drive natural ventilation systems and some academic institutions in particular are making efforts to promote this as a design approach. This work and some examples of existing projects will be summarized in the first section of this paper.

The strategy proposed in this paper takes that concept further. It considers the use of cooling and heating coils in the passive air stream, the added control this provides in terms of comfort, the amount of energy needed to drive air flow and how that energy can then also be generated in a highly energy efficient manner.

It then also considers how these strategies might be applied to larger buildings with multiple stories.

Overview of Passive Downdraft Cooling Systems Using Evaporative Cooling

The passive downdraft concept comes from vernacular architecture that has been used for thousands of years. Iran offers some of the best vernacular examples of passive downdraft towers, some of which used evaporation to supplement the use of thermal mass for cooling as part of a natural ventilation strategy. (A. Sayigh, 2011)

In the past 20 years, there has been a resurgence in passive downdraft buildings using evaporative cooling in cool towers to augment the performance of the natural ventilation cooling.

The ventilation path starts with a height differential and usually a tower designed to capture breezes that supplies the air either directly to the space at low level or into an underfloor plenum.

Air is exhausted also at high level, usually using a combination of solar and wind effects to enhance the passive buoyancy effects and flow of air. Dampers or controlled openings are used to modulate the flow of air to meet a temperature set-point and ventilation requirements inside.

As long as outside air temperatures are in a range where they can provide cooling (and do not require additional heating) – 12-22C (55-72F), then spaces can be naturally conditioned without any energy.

When temperatures rise above the desired space set-point, there are 2 options. In buildings with good thermal mass, controlled glazing and low internal loads, air flow can be dialed down to a minimum flow required for ventilation and the building's mass is used to ride out warm periods.

In buildings with high internal loads and possibly less massive facades, water is sprayed or misted into the air stream. The evaporation of the water reduces the temperature of the air (and makes it more humid). If cool water is used, there are usually some convective cooling effects as well. Depending on the expectations of the occupants, this cooling might allow the building to be kept comfortable up to external temperatures of around 30C, possibly even higher if the outside air is very dry.

These systems are often used in either mild or in hot, dry climates. They do not work very well in humid climates because the capacity of the air to release heat through the evaporation of water in the actual air stream is limited.

If heating is needed, it can easily be provided either in the space directly or at the point where the air stream enters the building (or both).

Design Challenges

There are some fundamental challenges in implementing systems with direct evaporative cooling in modern buildings which has no doubt limited the growth of this design approach.

Some of these challenges include:

- Managing the use of water in large components of the building. This includes drainage, internal water-proofing and splashing of water at the base of the cool tower.
- Using evaporative cooling directly in the air-stream, particularly relating to mold and legionella.
- Providing cooling capacity to meet space loads and the contraints this places on architectural form and envelope.

- Water use of evaporative cooling (although annual water use may not be significantly more than cooling towers would use in a 100% outside air fan driven displacement system – the cooling load of all conventional systems with cooling towers is dissipated through evaporation)
- Managing heat build-up in the water source used to provide the evaporative cooling (this is problematic if water used in an evaporative process such as a shower is not all evaporated and therefore reused because the water collects heat convectively as well);
- Managing poor cooling performance when outside conditions are too hot or humid for the evaporative cooling to work.
- Air filtration and removal of outside air pollutants (although shower systems can be good at removing larger particles such as dust and pollen);
- Designing a system to work in buildings with more than 1 storey.

Although these challenges sound daunting, there are examples of where many of the challenges have been overcome.

Case Studies

Some well documented case studies that use both architectural intakes and exhausts to drive buoyancy and evaporative cooling processes include the following projects

- Wendouree Performing Arts Center, Ballarat Victoria, Australia (see below)
- Zion National Park Visitor Center, Southwest Utah, USA (P. Torcellini, 2002)
- Torrent Research Building, Ahmedabad, India (L. Thomas)
- School of Environmental and Informational Sciences at Charles Sturt University, Thurgoona, Australia (Architectural Review)
- Global Ecology Center Foyer, Stanford University, Palo Alto, CA, USA (Greensource)
- Interactive Learning Center Library at Charles Sturt University, Dubbo, Australia (Architecture.com.au)

Some of these projects have had more success than others in overcoming the design challenges associated with passive downdraft evaporative cooling. For example, Charles Sturt University recently decommissioned the passive downdraft towers at the Interactive Learning Center mainly because the system was not able to maintain acceptable temperatures.

Case Study: Wendouree Performing Arts Center

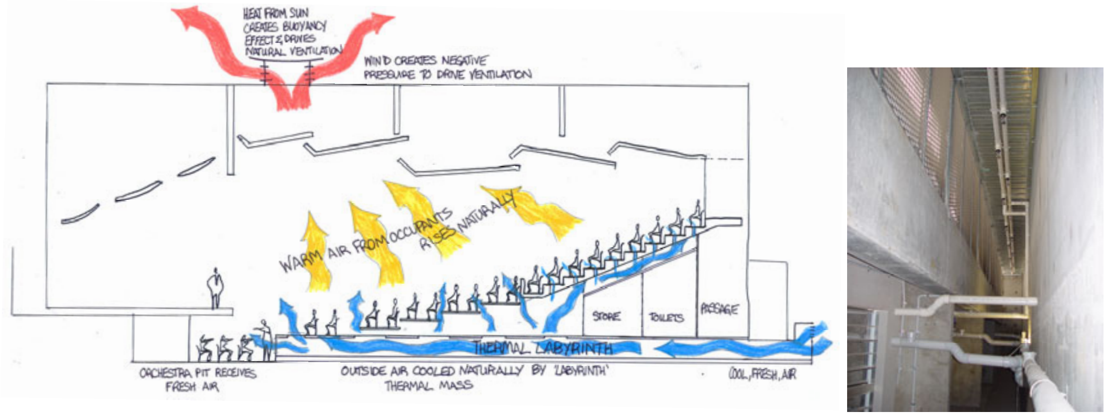
One case study that has been quite successful is the Wendouree Performing Arts Center in Ballarat, Victoria (Australia). The information provided below is from reporting and analysis reports by Built Ecology and subsequent post-occupancy feedback with the building operator.

The project is a concert hall at a private school in a climate with warm, dry summers and cool winters at an altitude of about 350m.

An early concept sketch is shown in Figure 1. Air enters through waist high intakes down into a series of underground tunnels.

Direct evaporative cooling is provided by showers at the top of the intake, with drainage to a nearby recircualtion tank and water treatment system. This keeps the evaporative cooling elements out of the building and eliminates problems of water ingress.

Figure 1: Passive Ventilation Concept Diagram (left) and Evaporative Cooling Showers (right) at Wendouree Performing Arts Center



The underground tunnels run up to twice the length of the building. Acoustic treatment in the tunnels removes all noise from the outsie. The tunnels open into plenums and vertical risers that serve the different zones in the auditorium and associated spaces such as lobbies and rehearsal space

At each point, there are heating coils to provide zone-level air-heating and modulating dampers to control the flow of air. Small fixed openings between the plenum and the occupied spaces, then allow even distribution of air across the building. At the roof, acoustically controlled passive outlets with control dampers allow the air to escape.

There is also heating in the occupied space (provided by in-slab radiant piping) for warm-up or heating in low occupancy situations.

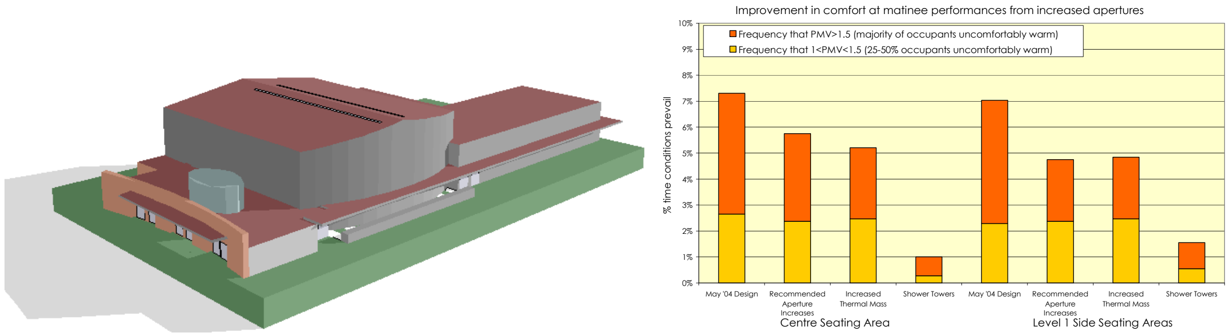
Analysis and Design

One of the best ways to study the performance of natural ventilation designs is through the use of bulk air flow modeling. Two examples of software tools that use bulk air flow modeling are IES VE and TAS (by EDSL).

Bulk air flow modeling can be used to establish cooling and heating loads that can then be processed to determine energy consumption for cooling and heating. Most importantly bulk air flow modeling can be used to calculate hourly air flows and temperatures through the system so that comfort and ventilation performance can be understood and the design can be optimized.

The images below show the 3-d rendering of the thermal model used to study the Wendouree building, a sample of hourly temperature outputs. (for more information on passive downdraft analysis refer to Corney A, Taniguchi T, 2011).

Figure 2: Thermal Model and Comfort Results Obtained from Bulk Air Flow Model



The results established that the addition of evaporative cooling to a passive buoyancy ventilation system (with air supplied low via a labyrinth and then exhausted high) reduced the frequency of uncomfortable hours from 7% to 1.5%. The ultimate prediction of comfort is a good anecdotal match of the building operator's assessment of when the building is comfortable based on outdoor temperatures.

Heating energy (the only main source of heating required) was estimated to be approximately 12 kbtu/sqft/yr. Based on anecdotal feedback, this is probably higher than actual. The reason is most likely because the analysis model was based on full ventilation rates necessary in winter. In such a high-volume space in practice, it is unlikely CO2 levels build up enough to actually require that much outside air.

Performance and Improvements

The building has been operating for 5 years now. The building management provided the following feedback on the performance of the building:

- The spaces which use passive downdraft cooling and heating were not metered separately from the adjacent classroom building. However the facilities management is very happy with the energy use of the facility as a whole.
- The evaporative cooling system works effectively in that climate until outside air temperatures reach about 30 degrees C. At higher temperatures the Faclities Management tend to try to pre-cool the building and limit the flow of outside air to ventilation rates only but it is difficult to maintain comfort.
- The acoustic control of the building and absence of HVAC noise is so good that the concert hall is used by musicians from Melbourne 2 hrs away for recording.
- The building took a considerable amount of time to get to a point where it could be operated optimally.
- Hardly any maintenance has been required on the system components in the past 5 years.
- The primary energy use from the heating and cooling of this building is limited to heating hot water. Most of this load would be applied to heating the ventilation air. CO2 sensors are used on the space to control the intake of outside air for ventilation. It is very likely these CO2 sensors require less than the code-minimum amount of outside air because the space has a large volume and is only occupied for relatively short periods.
- Based on the climate, the frequency of uncomfortable conditions in about 3% of operating hours. This problem could probably have been overcome through the addition

of cooling to the water used for evaporative cooling. This could increase the convective cooling effect of the showers and allow the air entering the tunnels to be cold enough for cooling. Because the frequency of this would be low (about 3% of events), the efficiency of the cooling unit used would be less critical for energy.

The project demonstrates how many of the constraints of passive downdraft evaporative cooling can be overcome. This building's ventilation and cooling system only requires electricity for pumping, dampers and water treatment and is almost negligible, making it an ultra-low user of energy. Even if cooling was added for 3% of hours, energy use would be low.

Unfortunately many building forms will struggle to implement underground tunnels and intakes at ground level. The limitations of using direct evaporation for cooling are real. The next section of this paper reviews options that remove the evaporative nature of passive downdraft cooling.

Use of Cooling and Heating Coils in Passive Downdraft Systems

Many of the design issues associated with passive downdraft evaporative cooling are linked to the use of water in the air stream and the control of the damaging impacts of the water on the building.

One design approach to significantly reduce the amount of water in the system is to use cooling coils rather than direct evaporative cooling in the air stream. This has the significant benefit over the use of evaporative coils that cooling is done sensibly rather than through evaporation. This means that it is much easier to supply air with enough latent cooling capacity to condition occupant loads in a space properly. Although condensation would still collect on the coils and would need to be drained. Ultimately by using cooling coils, the system could be used in more humid climates and also potentially in much hotter climates.

There are a handful of buildings employing this approach including the following:

- National Institute of Dramatic Art Foyer, Sydney Australia, 2001 (Hassell and WSP);
- NELHA Visitor Center, Kona, Hawaii, 2004 (Ferraro Choi and WSP);
- Australian War Memorial Café, Canberra, Australia (Johnson Pilton Walker and WSP)
- School of Slavonic and East European Studies in Bloomsbury (Short & Associates)

The greatest challenge in using cooling coils in the air stream is that the pressure drop created by the coils is significant and constrains the flow of air in all conditions. This can either be overcome by increasing the height of the intake, the driving force of the exhaust or the amount of cooling provided by the coil (to increase downdraft). A secondary challenge is dehumidification and how it can be done efficiently.

In the case studies developed further below, great care was taken to ensure that the pressure drop across cooling coils was limited to less than 25Pa at a design flow of 1m/s (200 fpm). In all instances, the design off-coil temperature is no greater than 14C (57F) to allow dehumidification if needed.

Case Study – NELHA Visitor Center, Kona, HI

The NELHA (National Energy Laboratory of Hawaii) Visitor Center in Kona, HI is a small, mixed use function space of about 3,500 sqft. WSP provided MEP and Passive Downdraft consulting. The architect was Ferraro Choi (Honolulu).

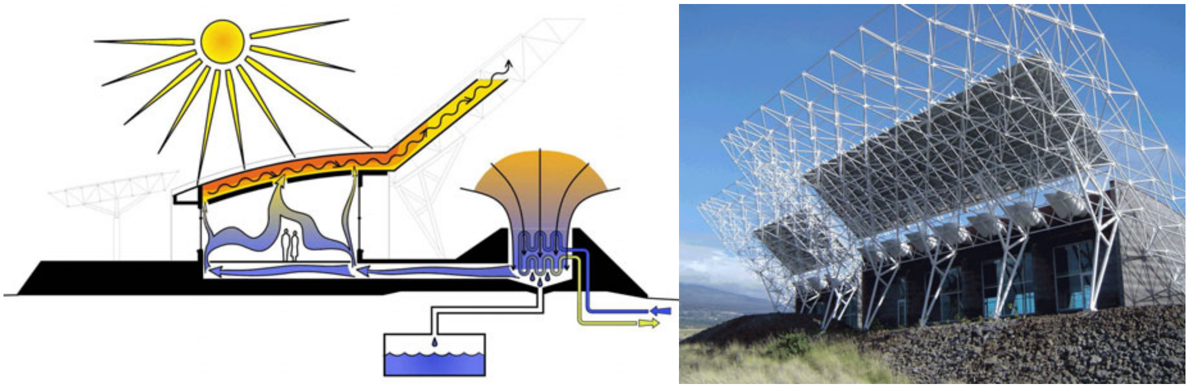
The building has been operating since 2005 and uses a passive-downdraft cooling system to provide cooling, dehumidifcation and ventilation. It is a net positive building, generating more energy on-site than it uses.

The sketch in Figure 3 shows a section and photo of the building and how the passive downdraft system works. The concept has some unique design aspects:

- Cooling is done with chilled water running through an array of pipes that cross the air-stream;
- The chilled water used for cooling is supplied via a district deep sea water loop. This means the cooling energy is predominatly about pumping.
- The air off the cooling coils is dehumidified and cold (about 10 degrees Celcius) so the air is passively mixed with unconditioned outside air before being supplied into the building's raised floor plenum (so the supply temperature is not to cold).
- The air movement is more driven on the exhaust side, through a solar chimney and also through the wind, than through bouyancy forces of cold air on the supply side.

The building is quite well known and has received many awards, including an AIA COTE top 10 in 2007.

Figure 3: Concept Sketch and Photo for NELHA Visitor Center, Kona, HI



Performance and Improvements

The climate the building is located in has high humidity and high outside air temperatures (usually around 30° C) for most of the year.

Despite the high temperatures, this natural ventialtion system is able to maintain an indoor condition of 24° C with less than 60% Relative Humidity in most conditions.

Interestingly, the only times the building has trouble maintaining conditions are when there is not enough solar gain to drive the exhaust system, or when the typically consistent trade winds change direction and push air into the outlets. Although these occurrences are very occasional, there is a long-term strategy to overcome this by increasing the height of the exhaust outlets.

In terms of energy, the building is very energy efficient, operating at a measured EUI of 19 kbtu/sqft/yr excluding the energy generated by renewable energy.

Over 10 kbtu/sqft/yr is for pumping energy to bring the chilled water up from the ocean into the building. There are a number of reasons for this. Firstly, the chilled water is brought from 200ft below sea level and brought a considerable distance across land to the facility. Secondly, the pumping system does not have very sophisticated controls, such as Variable Flow controls or even after hours on/off controls. Chilled water is pumped through the coils 24 hours a day. So although the energy needed to generate chilled water is free, the pumping energy is significantly higher than it needs to be.

The fact that the chilled water is collected through a deep sea well makes this project very unique. This was not estimated in original energy calculations and is not currently being measured. 3 air changes of 100% dehumidified outside air cooled to 50F / 10C and then remixed with the same amount of outside air to achieve 65F/18C supply temperature would require approximately 16kbtu/sqft (50kWh/m2/yr) with an efficient water-cooled chiller.

The lack of detail in these operating factors means that the primary lessons from the NEHLA case study are as follows:

- Passive Downdraft cooling can be used effectively not only in mild and dry climates with evaporation, but also in hot humid climates with chilled water coils and still be able to maintain comfortable temperatures equivalent to air-conditioning without needing fans.
- Architectural impacts on how the system will perform carry even more significance than in fan-driven systems for building conditioning.
- The key to making passive downdraft systems energy efficient in more humid climates is to find efficient means of generating chilled water.

Three Design Case studies – Conrad N. Hilton Foundation Headquarters (ZGF Architects, LA), De Anza College Mediated Learning Center (MLC) (Ratcliff Architects) and NOAA Pacific Regional Center (PRC) (HOK Architects, San Francisco)

To demonstrate the energy savings potential of passive downdraft in current projects, we are finally going to review 3 case studies we are currently working on, all of which are due for completion in 2012/early 2013. Each project uses passive downdraft HVAC for a significant proportion of the floor area. Each project is in a different climate but used the same design process and are benchmarked for energy using the same methodology (ASHRAE 90.1 (2004)).

The table below summarizes the characteristics of each building.

Passive Downdraft Design Case Studies						
Building	Location	Climate	Type	Size (sqft)	Chilled Water Source	Heating Hot Water Source
De Anza College MLC	Cupertino, CA	Warm, Marine (3C)	Classroom	55,000	District CHW (COP 4)	60% Campus HHW, 40% solar thermal
Hilton Foundation	Thousand Oaks, CA	Warm, Dry (3B)	Office	20,000	Water-cooled Chiller with Cooling Tower (COP 5.6)	69% solar thermal, 31% electric
NOAA PRC	Ford Island, HI	Very Hot, Humid (1A)	Office	300,000	Water-cooled Chiller with Harbor Heat Rejection (COP 7.3)	Condenser Water

The two projects with design, bid, build delivery methods (NOAA PRC and De Anza MLC) were both bid significantly under budget, however it is not possible to know what the premium cost attributable to the system is.

The sketches below provide section diagrams of the airflow for the buildings. Each building uses the same fundamental principal – a passive downdraft tower with wind catchers and cooling coils at the top is the intake for the ventilation, heating and cooling air in the building. The towers are connected to a raised floor plenum, where heating coils heat the ventilation air if necessary for comfort. Air is distributed via the raised floor plenum into a central atrium space where it is exhausted passively, through a combination of stack, solar chimney and wind effects.

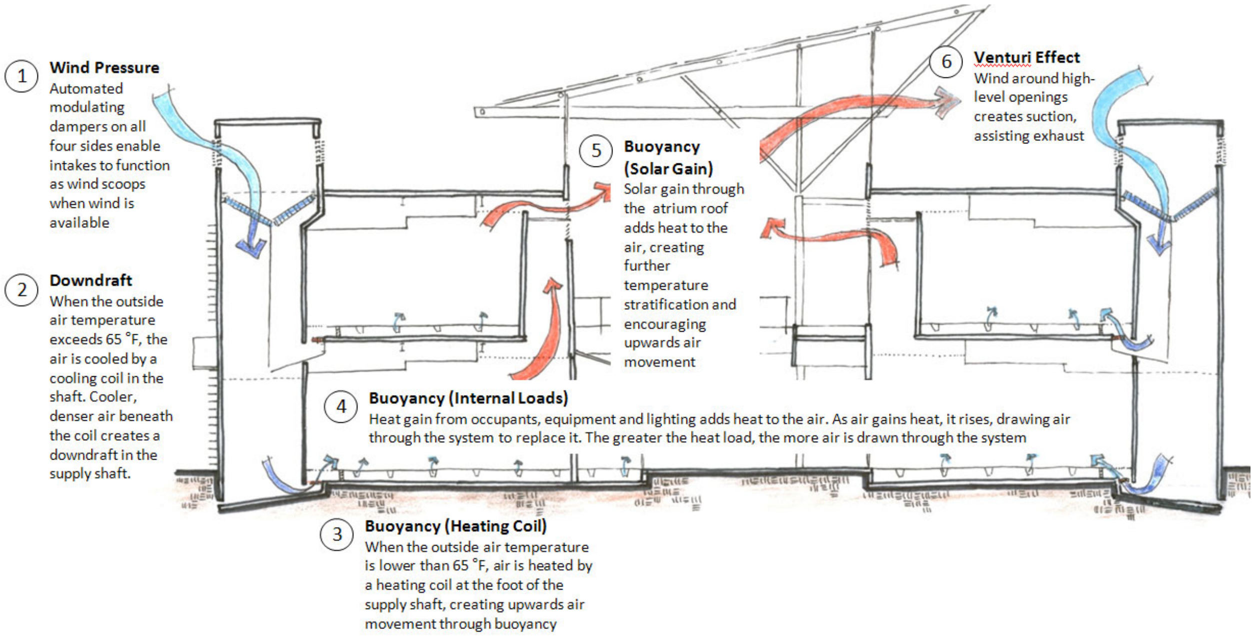
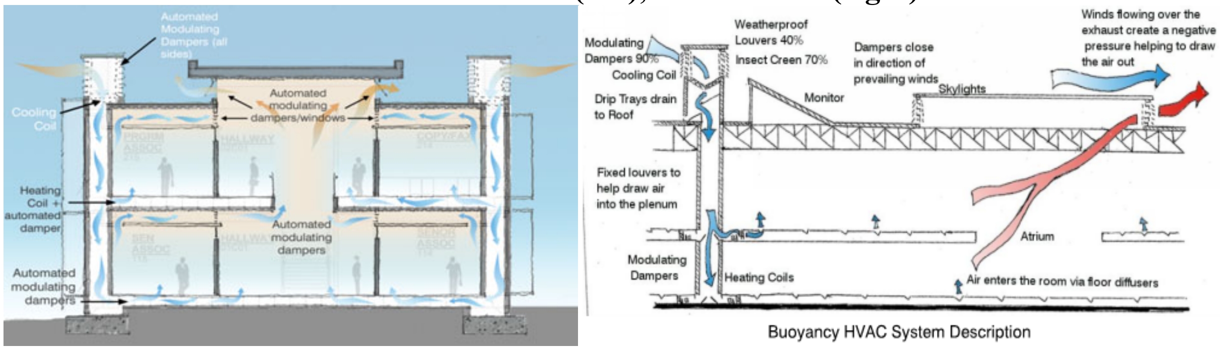


Figure 4: Diagrams Showing Passive Downdraft Concept for De Anza College (top), Hilton Foundation (left), NOAA PRC (right)



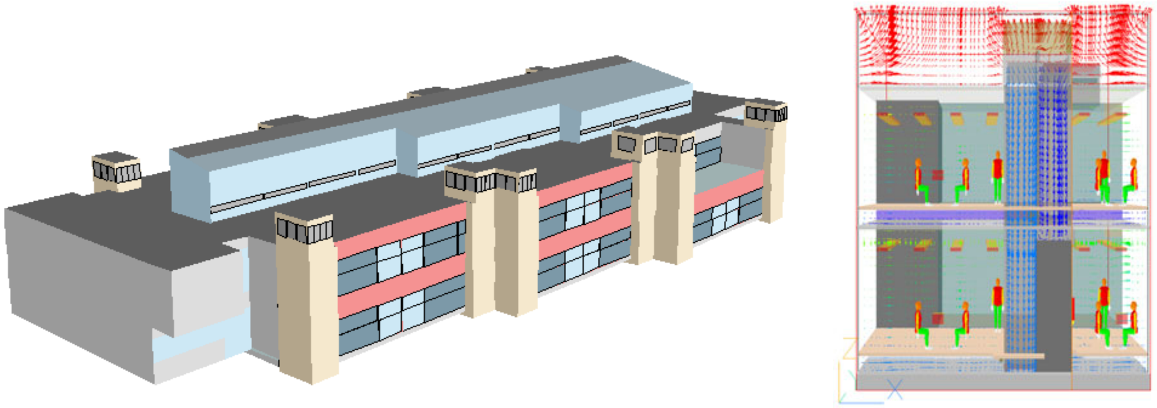
The performance of each project was studied using two methods:

- Bulk Air Flow Modeling (EDSL TAS) for annual ventilation, comfort and energy load performance (produces hourly results);

- Computational Fluid Dynamics modeling (Phoenics) for design condition comfort and ventilation performance verification.

The CFD results and thermal model example below show the sort of information obtained by this analysis. For detailed information on the analysis process, refer to the paper titled “Performance Analysis Methods for Passive Downdraft Systems” (Corney, Taniguchi, www.ibpsa.org, 2011).

Figure 5: Thermal Model of De Anza MLC (left) and CFD Model of Hilton Foundation (right)



The following table summarizes the predicted energy performance of these three projects. Although the projects are in 3 climates, not all the same building type, and used different techniques to achieve energy savings, the passive downdraft approach was able to achieve between 56% and 64% HVAC energy savings against an ASHRAE 90.1 (2004) baseline.

Figure 6: Summary of Design vs ASHRAE Energy Performance for Select Passive Downdraft Projects

Annual Energy Summary of Passive Downdraft Projects											
Building	Benchmark	Fans		Cooling		Heating		Pumps		TOTAL	
		kbtu/ft2	kWh/m2	kbtu/ft2	kWh/m2	kbtu/ft2	kWh/m2	kbtu/ft2	kWh/m2	kbtu/ft2	kWh/m2
De Anza College MLC	ASHRAE 90.1 (2004)	15.8	49.7	6	18.9	12.2	38.4	0	0.0	34.0	107.0
	Design	1.8	5.7	4.9	15.4	5.04	15.9	0.6	1.9	12.3	38.8
Hilton Foundation	ASHRAE 90.1 (2004)	6.6	20.8	9.1	28.6	0.3	0.9	0	0.0	16.0	50.4
	Design	0	0.0	3.9	12.3	1.5	4.7	1	3.1	6.4	20.1
NOAA PRC	ASHRAE 90.1 (2004)	5.0	15.7	12.1	38.1	0.0	0.0	3.5	10.9	20.5	64.6
	Design	0.0	0.0	6.1	19.1	0.0	0.0	2.9	9.1	9.0	28.2

There are important design lessons from these projects:

- Passive downdraft cooling has the potential to be equally effective in multiple climates, from hot humid tropical (Hawaii) to hot dry seasonal (Los Angeles) to maritime (Cupertino).
- The approach is more sensitive to the central plant strategies that provide heating hot water and cooling for the system.
- All buildings incorporated good solar control (and in the case of NOAA, a very deep floor plate with predominantly center zones). CFD analysis for the NOAA project identified a 2.5 fold increase in air flow needed at un-shaded perimeter zones to satisfy comfort. With a passive downdraft system, this is effectively 2.5 times the energy consumption for perimeter zones.
- All projects identified a need to separate cooling distribution to each floor, so there is a separately controlled cooling coil for air serving the second floor compared with the first.
- Apart from some sections of the NOAA PRC, the projects were only 2 stories with relatively high ceilings. CFD analysis on the NOAA project identified that 3rd floor spaces would need to be supplemented with fans due to the build up of heat from the two floors below.
- All projects were atrium buildings with the atrium forming the primary exhaust path.

Next Steps in Passive Downdraft System Design

We see the validation of projects coming on line in the next 6-12 months as critical in growing the recognition of passive downdraft systems as a legitimate means for achieving significant energy savings. The projects will need to both provide comfort comparable or better than conventional air conditioning and live up to predicted savings.

With the concept further validated, we see the following as exciting further developments of the strategy:

- Rationalization of the concept to limit the number of shafts required for a given floor plate and therefore limit the cost of the system;
- Application of passive downdraft systems to multi-storey buildings and even high-rises, possibly through the use of towers connected at the façade.
- Application of renewable combined heat, power and cooling systems to provide all the building's energy demands through one energy generation system, or through other very low carbon strategies for generating waste heat and cooling.

Conclusions

Natural Ventilation remains an enormously untapped opportunity to save energy and improve air quality in non-residential buildings. However it will not become an acceptable design strategy as long as it is not able to maintain acceptable comfort conditions in spaces where people are engaged in industrious activity.

Passive Downdraft systems have enormous potential to bridge the gap between natural ventilation and conventional air conditioned buildings.

Most of the modern applications of passive downdraft cooling have used evaporation as the means of enhancing natural ventilation. The challenge has been convincing mainstream architecture that the obvious shortcomings of using water in buildings can be overcome. There are some examples (such as the Wendouree Performing Arts Center) that provide examples of how those issues can be overcome. Perhaps with cooling of the water used in misting and air-washing systems, these buildings can provide comfortable environments for their occupants even in very hot or humid conditions.

There is a new way that has not been implemented on many projects thus far, but that will have case studies for review later in 2012. It involves combining passive downdraft systems with cooling coils rather than evaporative cooling. Although these systems use slightly more energy, they are more practical in their application to modern buildings and have fewer constraints in terms of humidity control.

These systems enable energy efficiency outcomes 55-65% better than ASHRAE 90.1 when combined with creative solutions for providing heating hot water and chilled water efficiently. By transferring fan energy to heating energy (and some extra cooling energy) they enable buildings that are able to produce chilled water and hot water efficiently to gain enormous energy savings.

They also permanently provide 100% outside air to the occupants of buidlings, which in developed countries with good control of outside air pollution means a healthier indoor environment.

For these reasons in the future, particularly in areas with efficient district heating and cooling systems, possibly powered by waste heat, there could be cause to believe that these systems might lead to significantly more energy efficient and healthier buildings.

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