FEASIBILITY OF CONTROLLED HYBRID VENTILATION IN MID RISE APARTMENTS IN THE USA

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ABSTRACT

Natural ventilation is generally accepted as the preferred ventilation option as it is a healthy and energy-efficient means of supplying fresh air to a building. In the USA it is seldom being applied as most climate zones are considered unsuited to apply natural ventilation, mostly due to perceived uncontrollability and very humid and hot or very cold seasons. For mid and high rise apartment buildings the option of natural ventilation is virtually disregarded because the tradition of full air conditioning is so well established. This paper challenges this disregard and hypothesizes that controllable ventilation openings are a realistic option for apartment buildings in some climate zones. As envelopes without operable openings pose fewer security and facility management concerns, a convincing case has to be made before people are willing to experiment with non fully air conditioned solutions.

KEYWORDS

Ventilation, control, thermal comfort, hybrid ventilation

INTRODUCTION

Natural ventilation has been shown to be one of the most healthy and energy-efficient means of supplying occupants with fresh air. The approach has received increasing attention and has been tried out in new innovative designs. It has in fact become a key target in passive solar designs of high performance buildings in terms of energy saving and IAQ improvement. Past researches show that there is a potential for 5 to 50% percent energy savings if natural ventilation is introduced to fully replace traditional mechanical ventilation in some locations of the United States (Spindler, Glicksman et al. 2002; Walker 2006). According to the residential energy consumption survey 2001 there are around 16.9 million apartments in buildings with five or more units which make up about 16% of the total housing units in US. Around 20% of them are on floor 5 or higher and 5.3% of them are 10^{th} floor high or more. Table 1 summarizes housing unit characteristics of apartments in buildings with five or more units in terms of climate zone (EIA 2001).

Table 1: Housing Unit Characteristics by Climate Zone –Apartments in Buildings with Five or More Units, Million (CDD = Cooling Degree Days; HDD = Heating Degree Days).

	CDD < 2000				CDD≥2000
	HDD>7000	5500<HDD<7000	4000<HDD <5499	HDD< 4000	HDD < 4000
Housing unit	0.7	4.2	5	3.5	3.5

As shown in Table 1 more than 20% of apartments in buildings with five or more units have critical cooling requirements (CDD >=2000) and this percentage is still increasing due to the currently blooming new housing starts (predominantly condos) in the southern part of the US. In order to respond to demands for energy conservation, maximizing the use of natural ventilation for cooling becomes an option worth looking at. In view of security and facility management concerns, high-rise buildings typically have avoided operable openings. This choice has both favorable and unfavorable impacts to IAQ inside buildings. It will bring less outside pollution into the apartment if buildings are located in industrial cities but if that is not the case, most occupants generally rate the natural ventilation satisfaction higher than full air conditioning. One of the reasons for this reduced level of satisfaction is that HVAC systems in high-rise buildings tend to supply the minimum rate of ventilation. Niu (2004) discussed several key issues in high-rise residential buildings based on Hong Kong's situation including pollutant dynamics surrounding buildings but also pointed out that our advanced design and manufacturing technology on modern-windows can help natural ventilation while mitigating its possible adverse impact on IAQ. This, and other studies suggest that small size openings (for example around the perimeter of windows), that are automatically controlled could provide the best natural ventilation option. In many climate regions it is unrealistic to assume that this solution can provide sufficient ventilation at all times, or could replace a mechanical cooling the whole year. In such cases one can introduce low cost help units in each apartment that only are turned on when needed. Trials in Europe in the early nineties have shown that pressure feedback control of the amount of air intake can save energy. A product that entered the market in 1993 was developed for that purpose, working at low pressures.

Our research starts from the premise that a similar product can be installed in window frames, as an integrated pre-fabricated component, with pre-installed sensor and actuator. Each product can be configured on site to obey a desired pressure-flow characteristic. This paper evaluates the feasibility of applying this type of technology in mid-rise apartments in the US. A prototypical building has been chosen taking a popular design of a typical mid-rise apartment in the current market. This apartment type will be used to test our hypotheses through simulations and evaluations.

CURRENT STATUS

Natural ventilation in residential buildings has been researched a lot in Europe but relatively little work has been conducted in the United States. Axley (2001) reviewed residential passive ventilation systems in Europe and tried to give an answer to the question: “can European passive ventilation be adopted in North American dwellings to provide ventilation in an energy conservation manner?”. His technical report gives an excellent review of residential passive ventilation system and provides important general guidelines for designing and evaluating residential passive ventilation system, especially one and two-family dwellings. Emmerich and Crum (2005) conducted another similar study to identify and realize the potential of advanced natural and hybrid ventilation technology in the U.S., specifically on low- to mid-rise commercial buildings. It is one of the key findings of this study that some U.S. cities, including San Francisco and Los Angeles, are capable of relying purely on natural ventilation with an extended tolerance on IAQ, which, matches the conclusion of another natural ventilation study by Spindler and Glicksman (2002). These and other application studies are mostly limited to buildings below 7 stories. Application of standard natural ventilation provisions in taller buildings typically meets serious security concerns.

PROTOTYPICAL BUILDING

The prototypical building is chosen to represent the current trend in mid-rise apartments in terms of popularity (GNA). It is 15-story high with a flat roof. Each floor has eight identical apartment units. The overall dimension is about 71 m × 18 m. Figure 1 shows the layout of one single apartment unit.

Physical properties, including envelope characteristics, internal gains and corresponding schedules, are determined according to ASHRAE standard 90.1 (ASHRAE 2004a) and 90.2 (ASHRAE 2004b). Table 2 shows the maximum envelope conductance and solar heat gain coefficient (SHGC) for windows required in each of the 8 climate zones in the US (ASHRAE 2004a). Most of the climate zones involved in this study have multiple climate classifications: A (Moist type), B (Dry type), and C (Marine type).

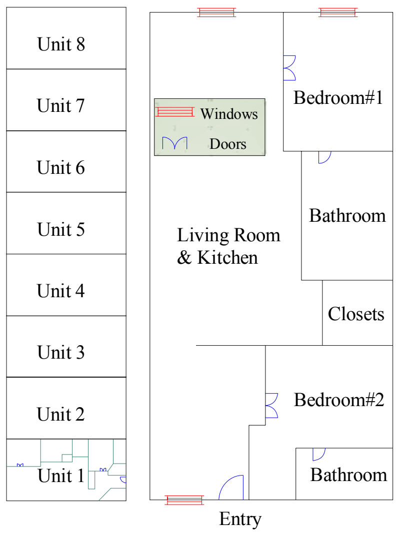

Figure 1 Building configuration and detailed plan of an individual apartment

Every unit has two external facades, located on the two opposite sides of the apartment building.

Table 2 Envelope properties of the prototypical building in different climate zone

Climate Zone	**Wall-Assembly Max. U**	**Window-Assembly Max. U**	**Window-Assembly Max. SHGC**	
	W/(m^2-K)	W/(m^2-K)	All Ori.	North Ori.
1 (A, B)	0.70	6.928	0.25	0.61
2 (A, B)	0.70	6.928	0.39	0.61
3 (A, B)	0.48	3.237	0.39	0.49
3 (C)	0.48	6.928	0.61	0.82
4 (A, B, C)	0.36	3.237	0.39	0.49
5 (A, B, C)	0.36	3.237	0.49	0.49
6 (A, B)	0.36	3.237	0.49	0.64
7	0.36	3.237	0.49	0.64
8	0.31	2.612	NR	NR

Ventilation openings

Throughout the feasibility study it is assumed that there are no other ventilation openings in the façade than a line opening integrated in the window frame. At both facades the opening is assumed to be around the window perimeter except at the bottom frame of windows. The width of the opening is assumed to be between 0 and 10 mm, either fixed at a particular width or controllable.

AIRFLOW MODELS

There are three main airflow components involved in this study: window integrated vents, exhaust fan(s), and air volume dampers.

The vent is modeled as a function of the pressure difference across the vent by the semi-empirical relation as shown in equation 1.

$$Q = C_d A\sqrt{2\rho\Delta p} \qquad (1)$$

Where

ρ the density of air

A the area of the vent

Cd the discharge coefficient

Δp the pressure difference across the vent.

The pressure p on a certain position at the building envelope can be estimated based on the potential wind speed at the meteorological station using equation 2:

$$p(x) = \frac{1}{2}\rho C_p(x)(\gamma U_{pot})^2 \qquad (2)$$

Where

U_{pot} potential wind speed, i.e. (hourly average) wind speed measured at an ideal meteorological station at 10m above ground level

$C_p(x)$ wind pressure coefficient

γ wind reduction factor.

The exhaust fan is designed based on requirements for mechanical exhausts defined in Table 403.3 in Section 403 of IMC (2006): one single bathroom has to have a mechanical exhaust capacity of 50 cfm intermittent or 20 cfm continuous and kitchens must have 100 cfm intermittent or 25 cfm continuous. For simplicity this study chooses every bathroom has a continuous mechanical exhaust of 20 cfm and the kitchen has a continuous mechanical exhaust of 25 cfm. A fan performance curve is choosen from the specification sheet of an existing fan type in the market with a design flow at 65cfm.

BOUNDARY CONDITIONS

The boundary conditions can be classified into two groups: local climate and wind pressure coefficients.

The feasibility study is conducted for a number of cities across the US. For the local climate data a TMY2 weather file for each considered city is used. The wind pressure coefficients are simulated by CPCALC+ (Calculation of wind pressure coefficients on buildings) which was developed within the European Research Program PASCOOL (Passive Cooling of Buildings). It is based on the FORTRAN 77 Berkeley Laboratory within the COMIS workshop on infiltration and ventilation (Grosso 1995). The software was used to calculate wind pressure coefficients for our apartment at floors 5, 10, and 15. The results were then fed in the airflow simulation model described in the following section. Figure 2 shows the wind pressure coefficient profiles for the considered apartment unit (unit 1) as well as adjacent apartment units on the same floor (floor 5) as one of the outcomes. Based on this outcome it was decided that it the consideration of unit 1 would be representative for all the apartment units.

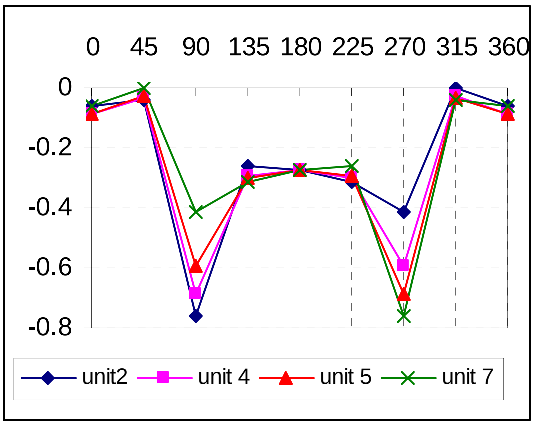

Figure 2 Wind Pressure Coefficient Profile for vents in Unit 1, 4, 5, 8 at a story of 5

Together with wind pressure coefficients another factor, the wind reduction factor is estimated to handle effects of local terrain. Equation 3 shows the relationship between wind reduction factor and local terrain characteristics.

$$\gamma = \frac{U_H}{U_{pot}} = \left(\frac{\delta_{pot}}{H_{pot}}\right)^{\alpha_{pot}} \left(\frac{H}{\delta}\right)^{\alpha} \qquad (3)$$

Where

U_H wind speed measured at local reference height;

δ_{pot} wind boundary layer thickness for the meteorological station;

α_{pot} wind exponent for the meteorological station;

δ wind boundary layer thickness for the local building terrain;

α wind exponent for the local building terrain.

SIMULATIONS

Evaluation criteria

The objective of this simulation study is to investigate the potential of external wind pressures to supply sufficient ventilation through small (controlled) openings and verify the increased energy performance of hybrid ventilation. In order to focus simulation efforts the following evaluation criteria were chosen:

- The resulting pressure distribution as a result of wind pressures on the facade openings combined with a mechanical exhaust system as required by IMC (2006), will lead to a resulting ventilation amount. The amount of time that the required minimum ventilation can be delivered is evaluation criterion 1
- The combined ventilation system can be controlled to supply extra cooling when needed; the amount of time that the apartment can be cooled to an adequate comfort level is criterion 2;

The following performance parameters are introduced to evaluate the mentioned citeria:

- Ventilation performance

  h_vent: the total number of hours through a year when minimum ventilation according to ventilation code has been met. In this case the required minimum ventilation rate is 95 cfm, including 15 cfm per occupant, 25 cfm for kitchen, and 20 cfm per bathroom.

- Cooling performance

  h_suff: the total number of hours through a year when increased natural ventilation through the ventilation opening (with assistance from mechanical exhaust system) fully offsets space internal gains;

  h_insuff: the total number of hours through a year when maximum natural ventilation through the ventilation opening (with assistance from mechanical exhaust system) can only partially cover space internal gains.

Simulation Method

Our simulation study has adopted a method called climate suitability analysis technique developed by NIST (Axley 2001) to evaluate the potential impact of natural ventilation through window vents in a given climate. This technique is based on a general single-zone thermal model that is operated to make optimal use of ventilative cooling. Details of this approach are presented in earlier publications (Axley 2001; Axley and Emmerich 2002). As some of the assumptions are not met when applying this technique in a residential building this study uses a slightly modified way by feeding a time varying solar gain which is estimated from solar radiation data in the weather file, building orientation, and building envelope characteristics. Thermal mass is also taken into account in the simulation scenario 3 (explained below). The heating set point and cooling set point are set to be 20˚C and 26˚C respectively.

Simulation Plan

The climate suitability analysis method has been applied to seven different climate zones defined by ASHRAE (ASHRAE 2004a) under the following three scenarios:

- Scenario 1: constant opening of window vents (between 0 and 10 mm) and no constraints on moisture;
- Scenario 2: constant opening of window vents but with consideration of constraints on moisture. In general there is no mandatory code on moisture but ASHRAE standard 55 defines an acceptable moisture level based on thermal comfort zone chart: the dew point temperature of a controlled space shall not be smaller than 2˚C and not greater than 16.8˚C. In this scenario this constraint has been applied to ambient air under the assumption that there is neither a moisture source nor moisture sink in the apartment.
- Scenario 3: "perfectly" controlled window vent. The perfect control strategy is: 1) always increase vent opening if ventilation is not adequate (until maximum opening is reached); 2) ventilation flow is never allowed to be greater than minimum requirement if space needs heating; 3) always increase vent opening as long as increase in ventilation adds net usable cooling to space; 4) ventilation flow is never above minimum requirement if ventilative cooling is not effective or ventilation increase pushes indoor dew point temperature above 16.8˚C.

Scenarios 1 and 2 represent uncontrolled, i.e. static ventilation openings (possibly changed once a year between summer and winter operation). In scenario 3, the perfect control will be evaluated in terms of its energy performance and ventilation performance against a traditional mechanical system. Unlike scenario 1 and scenario 2, scenario 3 simultaneously solves the energy balance equation (equation 5) and moisture balance equation (equation 7) considering average thermal mass and moisture sources/sinks in the apartment. Assuming mass-less exterior walls and a combined interior thermal mass node scenario takes a thermal mass of 2.5Btu/˚F (11140 kJ/K) per square foot of conditioned floor area (ASHRAE 2004b). Abstract heating will be used to keep the indoor temperature above the heating set point of 20˚C.

$$M\frac{dT}{dt} = K(To - T) + Qsol + Q\text{int} \quad (4)$$

$$K = \sum UA + \dot{m}c_{pair}(To - T) \quad (5)$$

Where

M Thermal Capacity, J/kg-K

Qsol Solar gains, w

Qint Internal gains, w

UA Envelope conductance

$\dot{m}$ Ventilation, kg/m^3

c_{pair} Air specific heat transfer coefficient

$$V\frac{dC}{dt} = Wp + \dot{V}(Co - C) - \frac{A_s}{3600} \times V(C - Ceq) \quad (6)$$

Where

C Humidity ratio, kgw/kgda (w =water; da = dry air)

Ceq Equilibrium humidity ratio, kgw/kgda

V Room mass, kgda

$\dot{V}$ Ventilation mass rate, kgda/s

A_s Moisture absorption of internal mass, 1/hr

In scenario 1 and 2 (uncontrolled vent width) 7 different (constant) vent widths were studied: 10mm, 7mm, 4mm, 2mm, 1mm, 0.4mm, 0.1mm.

SIMULATION RESULTS

Scenario 1

In this scenario our most familiar city, Atlanta, GA, was studied in depth, taking different floor heights and positioning the apartment building along different orientations (orientations are measured with respect to the façade having two window vents, see figure 1). A simple climate analysis was conducted using Ecotect. Four orientations, including north (N), southwest (SW), northwest (NW), and west (W), were studied in particular. It showed that W is wind directions with highest frequency. Figure 3 and Figure 4 show the impact of different floor locations (i.e. different heights above ground); results for Floors 5, 10 and 14 are shown. Clearly the higher the location, the larger the total hours that ventilation code can be met by the proposed hybrid ventilation system, and the higher the total hours that the proposed system can fulfill space cooling needs. Figure 5 and Figure 6 show the impact of different orientations. As we can see from the graphs, orientation seems to have little impact on the ventilation performance. However considering the load impact that orientation will bring, NW has been chosen as the prevailing orientation for our feasibility study in climate zone 3 to which Atlanta, GA belongs. Figure 7 shows the distribution of h_suff and h_insuff for NW orientated building in Atlanta, GA. As we can see when ventilative cooling is usable it can hardly fully offset space internal gains except winter season and early spring when there is no big cooling load existing.

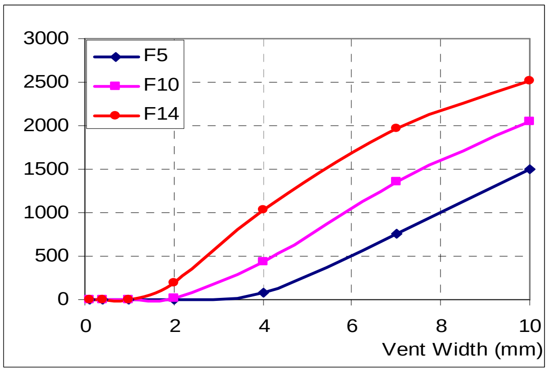

Figure 3 Profile of h_suff along different vent widths for building in Atlanta, GA for NW orientation

Similar climate analyses were carried out on representative cities in each climate zone in U.S. Table 3 lists these representative cities and their corresponding building orientations for the following potential evaluations.

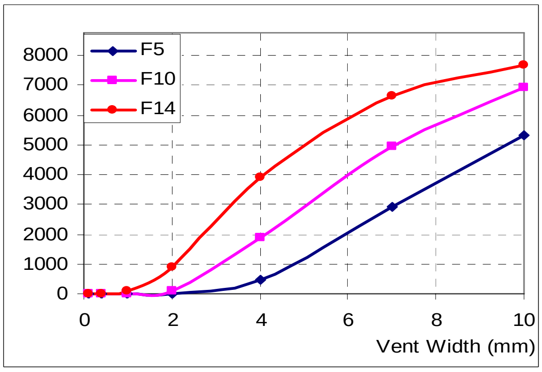

Figure 4 Profile of h_vent along different widths for building in Atlanta, GA fort NW orientation

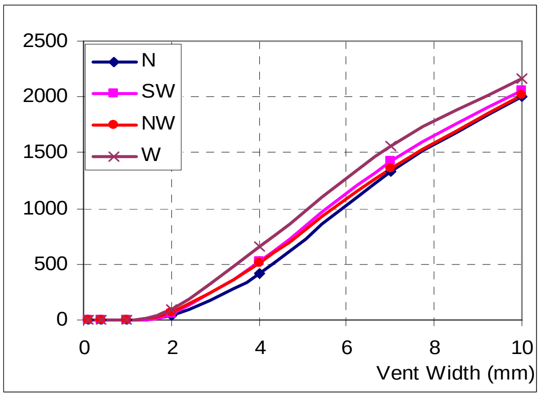

Figure 5 Profile of averaged h-suff along different widths for building in Atlanta, GA for different orientations

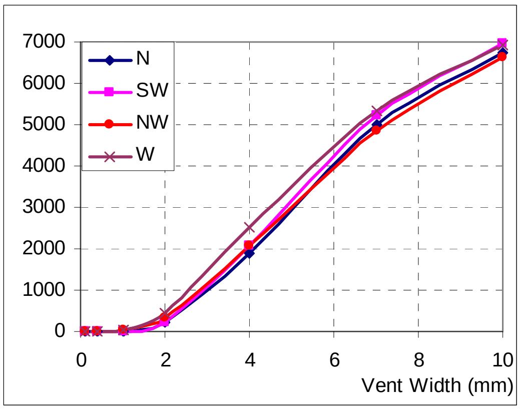

Figure 6 Profile of h_vent along different widths for building at Atlanta, GA for different orientations

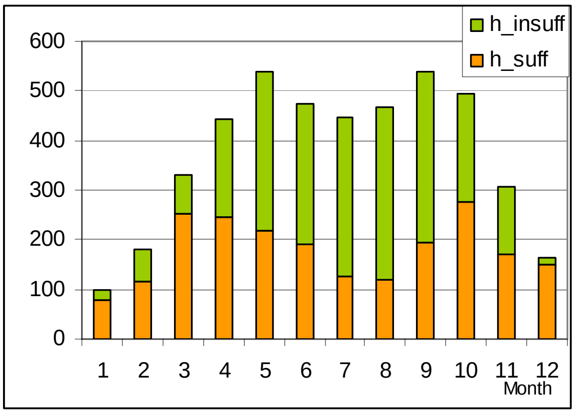

Figure 7 Distribution of h_suff and h_insuff for Atlanta, GA with NW orientation

Figure 8 and Figure 9 show the performance of window vents of different but constant widths in 14 cities in the U.S. Clearly Boston, MA (6A) has the longest time period during which ventilation code can be fully met while San Diego (3B) has the longest period during which space cooling can be fulfilled by the proposed hybrid ventilation system.

Table 3 Representative cities for each climate zone in the U.S.

Climate Zone		Representative City	orientation
1	A	Miami, FL	NW-SE
	A	Austin, TX	N-S
2	B	Phoenix, AZ	NW-SE
	A	Atlanta, GA	NW-SE
	B	San Diego, CA	NW-SE
3	C	SANFRAN, CA	NW-SE
	A	New York, NY	N-S
	B	Prescott, AZ	N-S
4	C	Seattle, WA	N-S
	A	Chicago, IL	NE-SW
5	B	ColoradoSprings, CO	N-S
	A	Boston, MA	NE-SW
6	B	Alamosa, CO	N-S
7	A	Duluth, MN	NW-SE

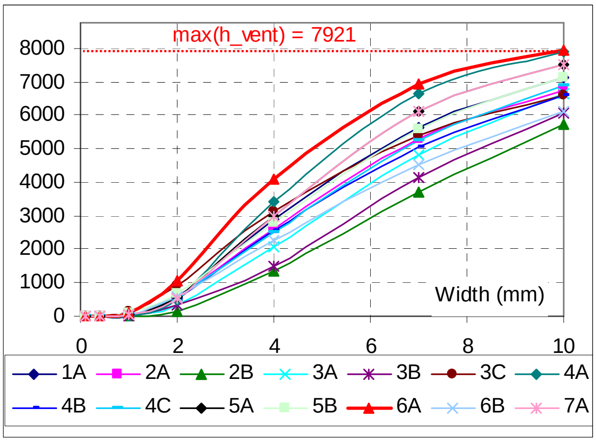

Figure 8 Profile of averaged h-vent along different widths for a building in different climate zones

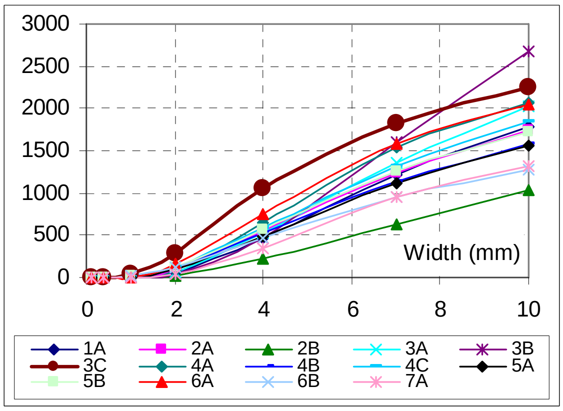

Figure 9 Profile of averaged h-suff along different widths for a building in different climate zones

Scenario 2

If the moisture constraint is taken into consideration some usable wind in terms of temperature won't be beneficial any more because of the moisture constraint kicks in. Figure 10 shows the cooling performance of the window vent system in different climate zones under the cut-off moisture constraints which means that the extra ventilation beyond minimum ventilation rate won't be welcome if the ambient dew point temperature is above 16.8°C. The city of San Diego still takes the leading position even its performance has been compromised by the cut-off moisture constraints. There are five cities that are not impacted by the moisture constraint. They are: San Francisco (3C), Prescott (4B), Seattle (4C), Colorado Springs (5B), and Alamosa (6B). As we can see from difference between Figure 9 and Figure 10 Miami (1A) obviously is affected a lot by the moisture condition. Around 782 hours of beneficial cooling in terms of temperature do not pass the moisture constraint.

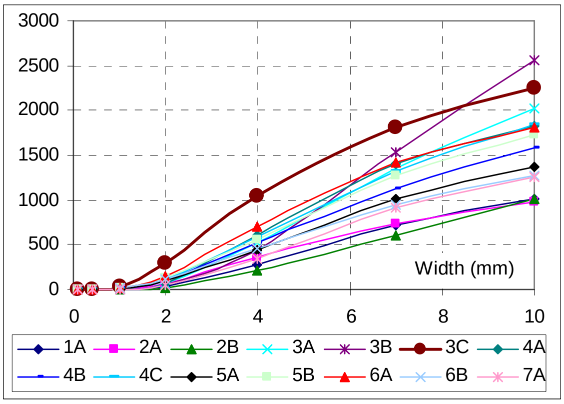

Figure 10 Profile of averaged h_suff along different widths for a building in different climate zones under cut-off moisture constraints.

Scenario 3

Our standard apartment was simulated for scenario 3 in six cities whose h_suff at maximum width under moisture constraints are more than 1800 hours. They are: San Diego, San Francisco, Atlanta, Seattle, New York, and Boston. Figure 11, Figure 12, Figure 13, and Figure 14 show the distribution of space temperature values for four of them. If we assume that the chosen vent system serves as the only (natural) cooling system, San Francisco (Figure 14) has the smallest number of hours during which the space temperature cannot be controlled under 26˚C and thus shows to have the best thermal performance. Atlanta, Boston, and San Diego both have relatively large numbers of hours during which space temperatures is higher than 26˚C, especially Atlanta and San Diego which have a hot and humid climate. In terms of influence from moisture control, Atlanta has a total of 647 exceeding hours while Boston has 98 and San Diego has 4 when cooling performance is diminished by the moisture constraint. As stated earlier, San Francisco has the mildest climate and its cooling performance is not diminished by the additional moisture constraint. Table 4 shows a monthly temperature and ventilation statistics for San Francisco. As we can see in San Francisco the apartment has a large percentage of hours of under-ventilated during heating seasons but when ventilative cooling is effective the apartment is mostly adequately ventilated except September. A small ventilation help system might help San Francisco improve its thermal performance and ventilation performance to meet criteria perfectly. It should be remembered that the evaluated apartments are equipped with envelopes that only meet the minimum thermal resistance requirements in the climate zone where they are located. Envelopes of new apartments are likely to surpass these requirements. Improving the properties of the envelope could in fact improve thermal performance to meet criteria perfectly. This was investigated through extended simulations for San Francisco (3C) but using the envelope required for San Diego (3B). This showed that even a minor improvement of the envelope would reduce uncomfortable hours from 330 hours to 139 hours.

Simulations also show that application of controlled ventilation will not increase space heating load. The controllability distinguishes it from other non-controlled or self-regulated ventilation provisions. Moreover its application is not limited to mid-rise apartments. Since vents are integrated in window frames they can be installed in high-rise apartments as they do not raise any security concerns.

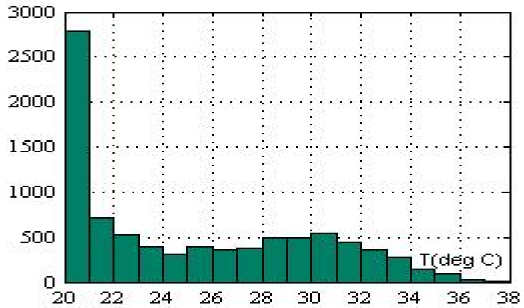

Figure 11 Distribution of indoor temperature values in Atlanta, GA

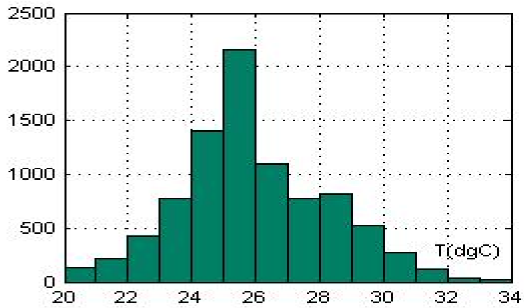

Figure 12 Distribution of indoor temperature values in San Diego, CA

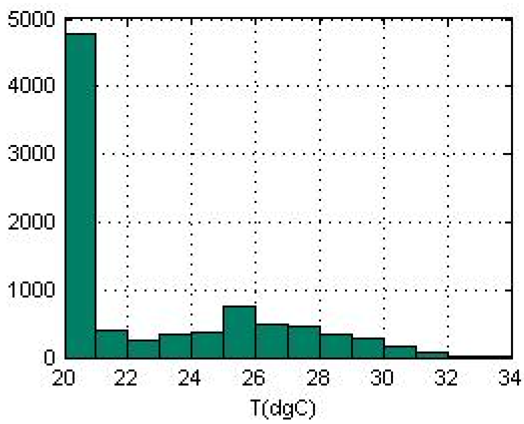

Figure 13 Distribution of indoor temperature values in Boston, MA

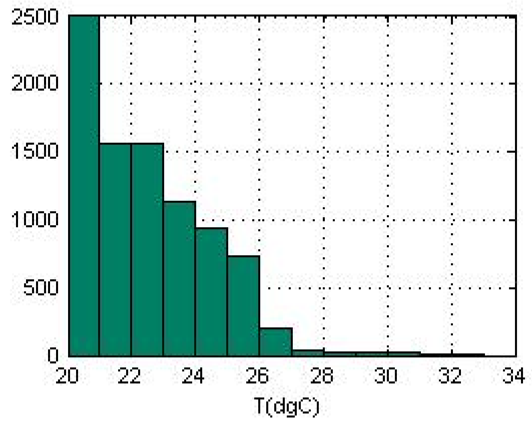

Figure 14 Distribution of indoor temperature values in San Francisco, CA

Table 4 Monthly average space temperatures for San Francisco

month	Tavg (?C)	% of hours above cset	% of hours below Vmin
1	20.67	0.0%	51.6%
2	21.49	0.0%	36.8%
3	21.30	0.0%	14.9%
4	21.84	0.0%	16.5%
5	22.21	0.0%	7.8%
6	22.61	2.2%	3.6%
7	23.92	6.1%	6.3%
8	24.13	4.7%	8.1%
9	25.09	20.4%	20.8%
10	23.92	11.7%	25.7%
11	21.71	0.0%	41.5%
12	20.55	0.0%	28.1%

CONCLUSIONS AND FURTHER WORK

The results show that there is good potential to integrate controlled natural ventilation in mid rise apartments in several climate zones of the US. However, it is not feasible, except in rare circumstances to count on the controlled ventilation system to meet ventilation and thermal comfort requirements on its own. The next phase will therefore concentrate on the combination of low cost ventilation and cooling units and window frame integrated controlled natural ventilation. The combination with water based heating systems could be a promising approach. Effective control of the opening width poses a set on interesting challenges: (1) what sensor signal to use for wind pressure and moisture (requiring study of calibration and placement of the sensor), (2) calibration of the complete apartment pressurization system (requires study of how exhaust fans, help unit and controlled ventilation opening operate together) and (3) feedback control from effective ventilation of living quarters. In addition, the design of the ventilation opening configuration poses special challenges in designing the most effective opening shape – flow - pressure characteristic.

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