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Ventilation Approaches for Shopping Malls – An Examination of Natural and Hybrid Strategies

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ABSTRACT

This paper will examine the challenges for energy-efficient ventilation that shopping malls present. In these buildings, the retail stores are often heated, cooled and ventilated separately from the mall central spaces, yet are connected to them by large, open doorways through which natural air exchanges occur, hence inextricably linking the two spaces. However, the central spaces of the mall are usually deemed to have the potential for more relaxed ranges of interior conditions than the retail stores adjacent to them, and regulatory requirements for these two types of space can also differ. The façade and roof access to the central spaces of malls mean that they have the potential to be ventilated naturally, or with a hybrid ventilation scheme. The extent to which this is beneficial depends on the local climate, as well as aspects of mall design such as glazing extents, and potential for low-level and high-level ventilation openings.

This study examines potential strategies for reducing energy use in such buildings by means of natural and/or hybrid ventilation of the mall central spaces. These strategies need to be formulated with the aim of reducing the whole building energy consumption, taking into account both the heating and cooling demands for the central space, and those of the adjacent retail stores interacting fluid mechanically with it. A numerical thermodynamic model has been developed to investigate this with respect to energy consumption and internal comfort of a hypothetical mall under various ventilation strategies. The influence of ventilation strategy on cost of plant (capital and maintenance) will also be discussed.

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INTRODUCTION

The retail stores within shopping malls are often tenant-controlled and have ventilation, heating and cooling systems which operate independently of the mall central space. Within the retail stores, balanced mechanical ventilation strategies are frequently employed and the shop floor areas are maintained within a narrow temperature band. In mall central spaces, there has been a tendency in the UK to move from tight temperature control towards allowing temperature and humidity to fluctuate over a wider range, with the driver for this being the desire to reduce energy usage and potentially plant maintenance and capital costs if equipment becomes redundant. As retail stores generally observe an "open-door" policy during shopping hours, then, in a mall where temperature control in central spaces is relaxed, these retail stores will contribute heat to the central spaces on colder days, and will cool the central spaces on warmer days. These effects have been identified in previous studies (Woods and Fitzgerald) – however the energy implications of these exchange fluxes on the net energy use of the building with different ventilation strategies warrants further investigation.

In this paper, the heating and cooling (sensible and latent) energy usage of the mall central spaces and the retail stores combined will be modeled for the cases:

1) Fixed minimum (outdoor air) ventilation to the mall central spaces, with heating and cooling as required for comfort.

2) Hybrid ventilation of the mall central spaces, where natural displacement ventilation at higher than minimum volumes can help free-cool these areas until there is a risk of overheating. At other times, minimum ventilation is employed with active heating and cooling as required.

3) Natural ventilation to free-cool mall central spaces, allowing upper temperature and humidity to float without limits.

In all cases, we have assumed that the retail stores are conditioned to 22°C (72ºF) and limited to 60% RH. The ventilation to the mall central spaces will be reduced to minimum outdoor air rates when there is a requirement for space heating. From these results, we will compare energy usage associated with these various strategies and predicted thermal comfort. Using this, we will examine the influence of mall design and climate in selection of the ventilation strategy which achieves the best combination of energy consumption and acceptable comfort.

METHODOLOGY

A numerical model was created from first principles to examine the sensible and latent energy balances within a hypothetical single–storey mall 250m (820ft) long by 15m (49ft) wide, with around 60 retail stores each of 160m^2 (1722ft^2) attached to a central space 10m (33ft) in height.

While a single-storey mall is not the most common configuration, we have made this assumption to simplify the modeling of natural ventilation flows between openings at various heights as well as issues of vertical stratification. To this end, we have examined the performance of the mall central space as a well-mixed space i.e. constant temperature throughout.

Exchange airflows which occur through open doorways linking the retail stores to the central space are an important effect in determining conditions in the central space. These exchange flows are driven by buoyancy due to temperature differences between the retail stores (held constant) and central spaces which are allowed to float over a larger range of conditions which vary between strategies. These exchange flows are demonstrated in Figure 1.

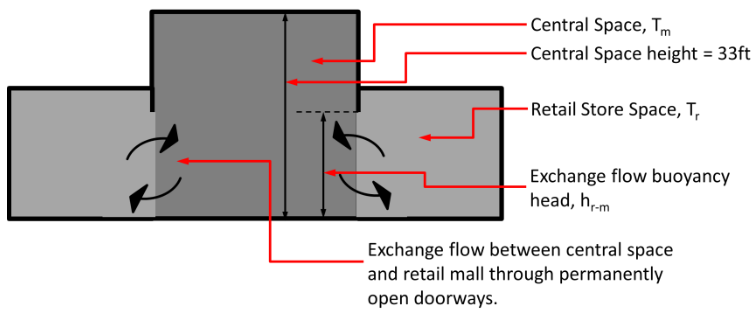

Figure 1 *Section through mall showing exchange flow through doorways.*

Volume flow rates of the exchange flows are described by Equation (1) (Linden), which examines the ventilation fluxes across open doorways of area A_{r-m} and height h_{r-m} between the central mall space and the retail stores, across which a temperature difference ΔT_{r-m} exists. T_{ref} is a reference temperature (taken as 295K).

$$V = \frac{1}{3} A_{r-m} C_D \sqrt{\frac{g h_{r-m} \Delta T_{r-m}}{T_{ref}}} \qquad (1)$$

The model formulated then performed hourly steady state calculations (for a whole year of operation) to determine the central space temperature resulting from this volume flux and accounting for the following factors:

- Internal gains outlined in table 1 below.
- Solar gain derived using hourly solar data.
- Conduction heat gain/loss through glazed rooflights derived using hourly ambient temperatures ($U=1.8W/m^2/K$ \ $1.04BTU/hr/ft^2/°F$), (UK Building Regulations).
- Ventilation air exchanges in both retail stores and central space indicated in Table 1 below.

Having determined the central mall temperature and accompanying exchange air flow it is possible to determine latent energy exchanges and determine also the relative humidity of the central space.

Energy requirements for sensible cooling, dehumidification and heating could then be calculated to compare the performance of each strategy (note that 80% efficiency total energy recovery on mechanical ventilation systems was utilized when appropriate),

Table 1. Model Assumptions

Input	Retail Store	Mall Central Space	Notes
Occupancy (Persons/m^2 \ Persons/ft^2)	0.15 \ 0.014	0.4 \ 0.037	
Sensible Gain / Occupant (W \ BTU/hr)	80 \ 273	80 \ 273	
Latent Gain / Occupant (W \ BTU/hr)	60 \ 205	60 \ 205	
Lighting Gain (W/m^2 \ BTU/hr/ft^2)	25 \ 7.9	6 \ 1.9	
Minimum Ventilation Rate (l/s/person \ cfm/person)	10.1 \ 21.3	5.9 \ 12.4	(ASHRAE Standard 62.1) + 30% for LEED

In terms of exchange flows between retail stores and the mall central space, we have assumed that 35% of the shopfront facades are open doorways of 3m (10ft) height (h_{r-m}), and 50% of the roof area of the mall central space has been assumed to be glazed, in line with experience of recent mall designs. It has been assumed that the mall and retail stores are open 9am-7pm daily.

The model actually calculates the central mall temperature for two distinct cases. The first assumes that air exchange between the mall and external environment is limited to that required for ventilation of the space, i.e. a dedicated outdoor air supply. The second case assumes the central space is naturally ventilated and calculates the ventilation flow assumed to be predominantly buoyancy-driven, with 8m (26ft) buoyancy head between low-level (e.g. mall entranceways) and high-level openings (most often included as dampered vents or actuated rooflights). The first case is then used to determine conditions when the central space is mechanically ventilated with heating and cooling supplied as needed to maintain the required comfort conditions in the mall.

The model has been set up such that ventilation strategies 1) and 2) apply both upper and lower bounds on the mall central space temperature and an upper bound on the internal relative humidity, prior to conditioning of the mall air being instigated. The two strategies then differ in that 2) can allow the mall to be naturally ventilated when it is favorable to do so and comfortable conditions can be provided without the need for heating and cooling. Approach 3) employs a lower temperature limit, but does not impose an upper limit on temperature or relative humidity, which may lead to periods of thermal discomfort in certain climates. It is therefore recognized that different locations will permit different ventilation approaches, and this will be examined in the results.

Figure 2 shows diagrammatically the three strategies modeled. The coloured arrows represent schematically the ventilation flows to the central space and retail stores, while the curved arrows represent the presence of air exchange between the central space and the retail stores. The size of the arrows qualitatively indicates the size of the ventilation volume fluxes, showing whether the scheme is operating at minimum ventilation by mechanical ventilation or regulated natural ventilation (smaller arrows), or potentially at much higher ventilation levels by means of maximizing natural ventilation flows (larger arrows). The colors of the arrows indicate qualitatively the temperatures of the incoming or outgoing air, from blue (cold) to red (hot). In Figure 2c) the ventilation regime on the hottest days may often be downflow displacement ventilation where the mall central space is cooler than the exterior due to the effect of the retail stores' cooling systems. The dashed image to the bottom right of Figure 2c shows a possible extension to Strategy 3), of restricting natural ventilation flows to minimum levels on the hottest of days. In this approach, the mall central space can benefit from cooling from retail stores, resulting in cooler conditions than would be achieved with unrestricted ingress of hotter external air. This image shows reduced natural ventilation flows as a result of restricting openings – whilst the dominant flow mode will be natural downflow displacement ventilation for these times, there may be some air exchange with the atmosphere also occurring at high level, due to the restricted low-level openings and the internal stratification that may occur. This extension to the natural ventilation scheme has not been modeled as part of the strategies above, but can be shown to result in further energy savings and improvements in peak temperatures internally.

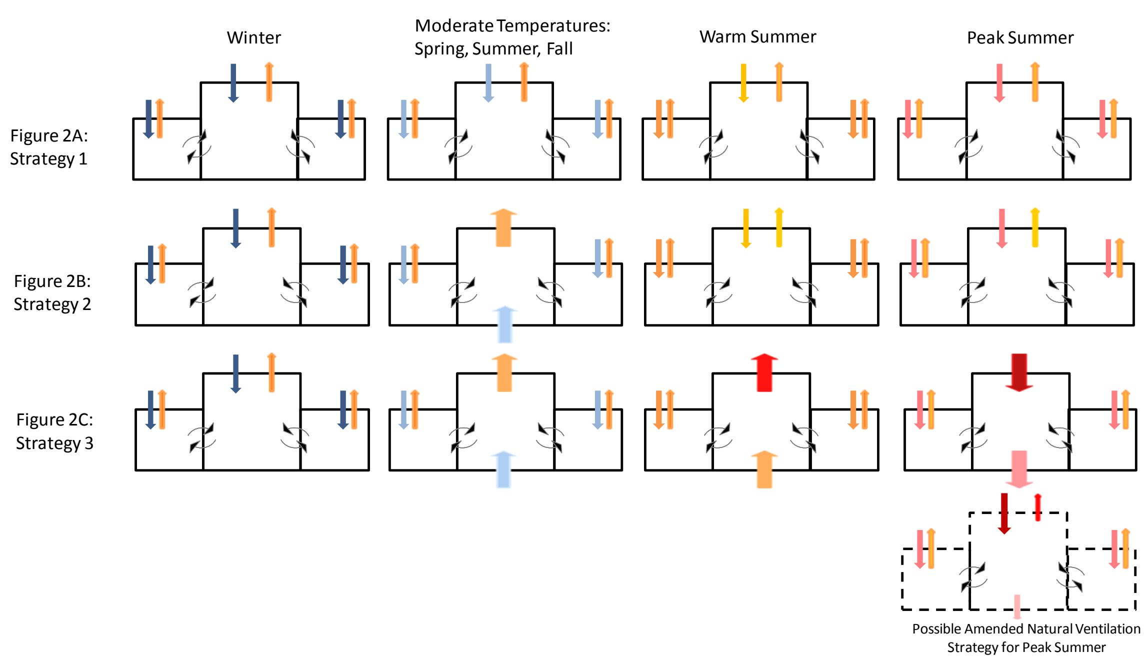

Figure 2 *(a) Strategy 1: Minimum ventilation strategy year-round. (b) Strategy 2: Minimum ventilation (first, third and fourth images) and free cooling by natural displacement ventilation when the mall central space can be maintained within an appropriate temperature range (second image). (c) Strategy 3: Minimum ventilation (first image) until external temperature sufficiently warm to permit natural displacement ventilation thereafter (second, third and fourth images).*

Calculations have been made for three locations: London, UK, San Francisco, USA, and Chicago, USA. These are described by ASHRAE Standard 90.1 as being in climate zones 4, 3 and 5 respectively.

RESULTS AND ANALYSIS

Figure 3 shows the combined thermodynamic demand associated with heating, cooling and dehumidification for the hypothetical mall and retail stores with the various ventilation strategies. It should be noted that these comparisons exclude the following:

- Fan power (excluded in order to ensure a conservative demonstration of the potential for energy savings by means of a hybrid or natural ventilation strategies, which would clearly utilize less fan power than a fully mechanical ventilation strategy).
- Heating energy needed to get the mall and stores up to the minimum temperature prior to the start of the occupied day.
- Electrical energy use from lighting or small power (although the heat gains from such sources are modeled).

The latter two of these items are independent of ventilation strategy used. In Figure 3, the energy consumption is shown for both low and high solar gain cases (G-values of 25% and 50%[1]) as well as different ventilation areas[2] (1% and 2.5% of mall central space floor area at both low-and high- level) under natural or hybrid ventilation cases. The results have been scaled in comparison with the base case of strategy 1 (a mall central space employing a year round strategy of ventilation at the stated minimum ventilation rates, plus heating, cooling and dehumidification as appropriate). In these initial results, strategies 1) and 2) have been modeled with upper limits on temperature and relative humidity of 24ºC (75ºF) and 60% respectively – in strategy 3) these have not been applied.

It is worth noting that daytime heating loads for both retail stores and mall central spaces, in each location, were negligible, due to high internal gains. From our experience, this is true in practice of modern, well-insulated UK shopping malls, many of which are able to retain sufficient heat overnight for year-round comfort conditions without heating prior to morning start-up.

[1] G-value indicates the percentage of incident solar thermal radiation admitted to the space, equivalent to the solar heat gain coefficient.
[2] The ventilation areas are taken to be effective opening areas once aerodynamic losses are accounted for.

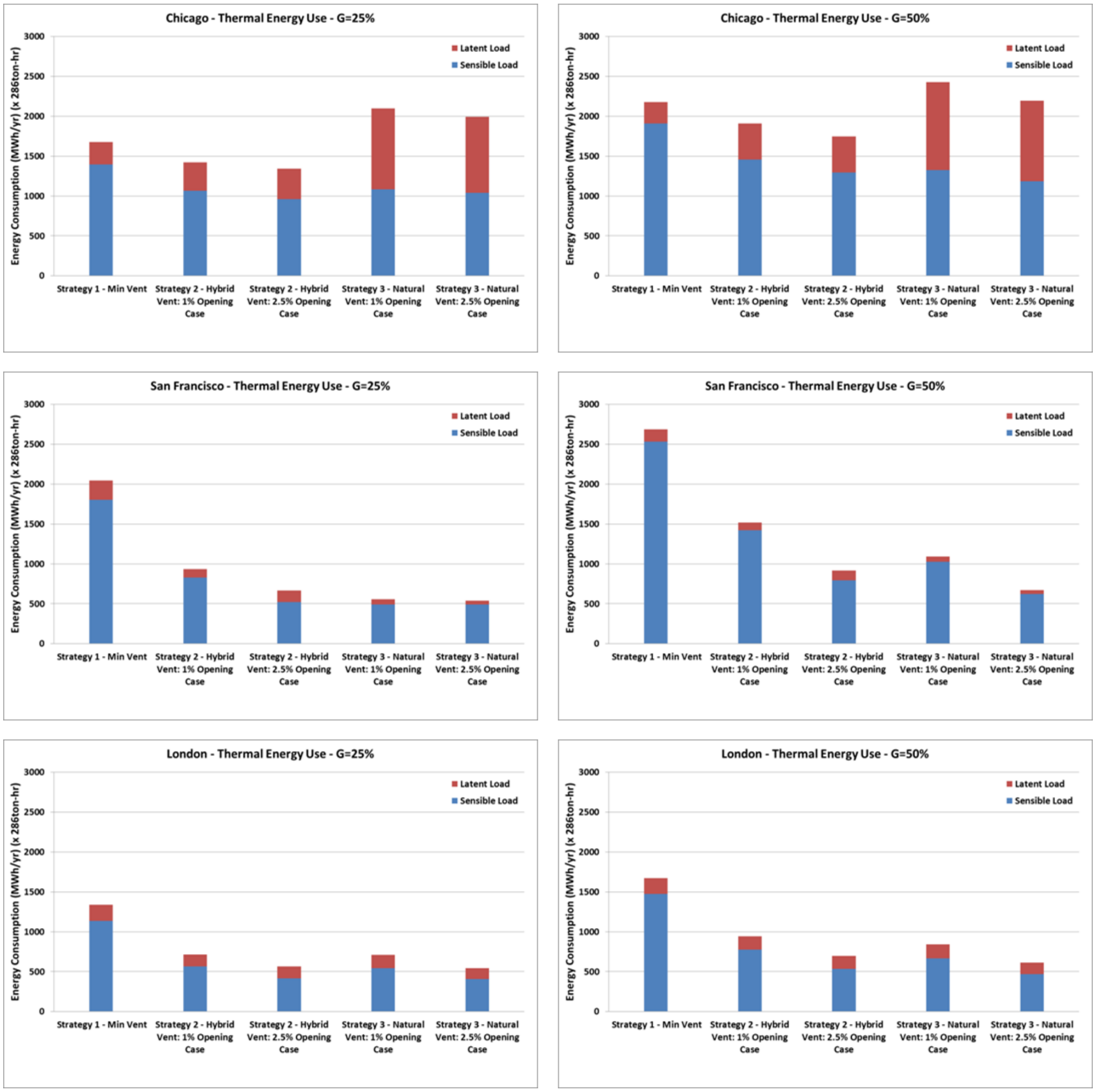

Figure 3 *Mall (central space and retail stores) thermal energy use with different ventilation strategies in Top: Chicago, Middle: San Francisco and Bottom: London. Left-hand column shows case with twice the solar gain of the right-hand column.*

The results show significantly reduced HVAC loads for the ***hybrid*** strategy (strategy 2) particularly in the less humid locations of London and San Francisco relative to the year-round minimum ventilation case. This is due to the potential for free cooling of the mall central spaces for large portions of the year when these areas are not at risk of overheating. Under this strategy, it is possible to maintain the mall central spaces at cooler internal conditions for longer, reducing the cooling load imposed on the retail stores by the exchange flows. This is also true for Chicago, but to a reduced extent due to the warmer and more humid summer conditions necessitating increased cooling and dehumidification in this location to avoid uncomfortable conditions within the mall central spaces.

The ***natural ventilation*** strategy (strategy 3) suggests that substantial energy savings are achievable with this approach in both San Francisco and London, although thermal comfort criteria would need to be relaxed. Table 2 shows the number of hours per year that various comfort criteria are exceeded in the mall central spaces in the natural ventilation cases. In London and San Francisco, these exceedences are relatively few, and certainly with the trend towards “covered street” and outdoor mall schemes in the UK, these are worthy of consideration for the lower running costs that they imply. Reducing solar gain and increasing opening areas for natural ventilation strategies can substantially enhance the energy savings realizable and improve mall thermal conditions. In Chicago, the peak predicted relative humidity in the mall central spaces reaches 100% under this strategy, and hence would preclude a purely natural strategy, although there appears to be significant benefit in a hybrid approach. The very high cooling loads shown in Figure 3 for Chicago under a natural ventilation strategy result from the increased demand for cooling and dehumidification placed on retail stores due to air exchange across their open doorways with the unconditioned mall central area.

Table 2. Internal Conditions Under Natural Ventilation in Mall Central Spaces (G=25%, Ventilation Openings at 1% of Floor Area)

Location	Hours/yr over 26ºC (79ºF)	Hours/yr over 70% RH	Max. Temperature (ºC \ ºF)	Max. RH (%)
London	72	168	28.7 \ 83.7	84.9
San Francisco	90	69	29.4 \ 84.9	80.0
Chicago	584	433	30.5 \ 86.9	100.0

Figure 4 shows in more detail the predicted temperature profile in a naturally ventilated mall (strategy 3) in San Francisco. This strategy allows internal conditions to float without limits unlike strategies 1 and 2 where peak temperature and relative humidity are limited. It can be seen that the number of hot humid hours internally are relatively few.

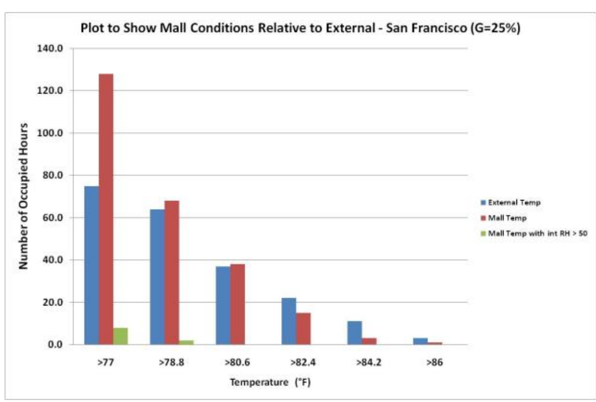

Figure 4 *Temperature profile for naturally ventilated mall (strategy 3) in San Francisco.*

PRACTICAL CONSIDERATIONS

Various building and plant design considerations arise from the discussion above, and are briefly discussed below.

Solar Gains and Daylighting

Recent mall designs favor large areas of glazing over common areas, with central voids allowing natural light to lower levels. This provides excessive daylighting, (with average daylight factors[3] in excess of 8%, even on lower, shaded levels in one recent project) and results in large solar gains which are typically offset by mechanical cooling. Controlling these gains can be very important towards reducing cooling usage and extending the envelope for natural ventilation. Published guidance suggests design light levels for shopping centers in the range 50-300lux (4.6-27.8fc) (CIBSE Guide A). Our experience within the UK suggests that values of 250lux (23.2fc) or lower are acceptable, and that tenants may prefer lower light levels in the mall central spaces, as this makes more brightly lit retail stores the focus. As an example, for London weather data with a daylight factor of 3%, 250lux (23.2fc) would be exceeded for 75% of office hours (0900-1730) (CIBSE Guide A).

Daylight modeling of existing malls using the Radiance Module of the software package IES VE suggests that solar heat gain may be significantly reduced (by around 50%), whilst still maintaining good daylighting (3% daylight factor). Solutions for retrofitting to existing malls generally focus on improving solar shading, which can be achieved by a variety of means including films, external shades, and blinds. A sensible design strategy for new buildings would seek to balance provision of daylight to provide adequate natural light for the majority of the year, with reduced heat gains.

Plant Capital and Maintenance Costs

In UK shopping malls we have surveyed, air handling units have been around $8m^3/s$ (17000cfm) capacity to serve internal central space floor area of approximately $800m^2$ ($8600ft^2$). An indicative installed unit cost (including chillers and burners) is \$250k, with an expected lifespan of 20 years (CIBSE Guide M), and annual maintenance costs of around 3% of purchase cost. By contrast, the purchase cost of natural ventilation openings to serve a similar mall floor area could be around \$80k. Several additional factors should also be considered:

1) At least in the UK, high level natural ventilation openings can sometimes also be used for smoke ventilation systems. The capital expenditure on these openings should then be considered as either split between the two applications, or as a sunk cost, as smoke ventilation would be required regardless of the HVAC system.
2) AHUs and associated plant occupy a substantial footprint which may be useable, for example for additional parking

[3] The ratio of inside illuminance over outside illuminance, expressed as a percentage

spaces, increasing the property value and raising revenue.

3) Natural ventilation equipment generally has a lower maintenance and replacement regime than mechanical equipment.

4) In a hybrid system, the cooling capacity required will still need to meet the peak design day loads as with a fully mechanical system, although the mechanical component can be simplified to space conditioning with regulated natural supply of air. This suggests that without careful design, a hybrid system could lead to high capital costs through the duplication of systems. Hybrid system operating costs are reduced by the periods of passive conditioning of the space that can be realized, which are a function of the size of natural ventilation openings. Increasing the amount of natural ventilation openings leads to a law of diminishing returns in terms of hours of fully passive operation. Hence, a cost-effective hybrid solution should consider the balance of capital cost against these operating costs (the level of passive operation).

Entrance Design

In cooler seasons, malls can suffer cold draughts around entranceways in winter, often due to wind tunneling between openings in different parts of the building. The main requirements identified for effective entrances are:

1) Providing a pressure barrier between air within the mall and outside air, when the ambient temperature is colder or warmer than desirable.

2) Providing sufficient opening area for natural ventilation in seasons when the ambient temperature is desirable.

A range of strategies have been attempted to address the difficult conditions at entrances, including air curtains, overdoor heaters, lobbies, revolving doors and baffles. Revolving doors with retractable dividers and controllable louvers above them appear the most robust solution that satisfies the requirements above, noting that disabled access may also necessitate provision of adjacent swing doors. Air curtains and overdoor heaters are generally ineffective when there is pressure communication between entrances, as they are unable to temper or stop the large volumes of air involved. Lobbies are most effective when they can operate to keep one set of doors closed at all times. Actual experience and study of footfall patterns indicate that for a number of cases the high footfall associated with shopping malls lead to both sets of lobby doors being open simultaneously for large proportions of the day.

CONCLUSIONS

HVAC energy use of shopping malls has been examined for three different ventilation strategies for the mall central spaces. The design of such systems has historically often neglected natural exchange fluxes between retail stores and these central spaces, although these have been shown to be significant. This poses a dilemma for designers, as maintaining a similar degree of control of the environment within the mall central spaces to that in the retail stores itself requires significant energy use (and is perhaps unnecessary), but reduces loads on the retail stores which exchange air with the mall central space. Natural ventilation for part or all of the year provides free cooling to mall central spaces. On hotter days, a natural ventilation strategy in the mall can lead to increased loads on retailers' systems, although this problem can be minimized by the mall adopting a minimum ventilation strategy in high summer. A positive consequence of this is that the mall central space would benefit maximally from retailer cooling (see Fig 2c dashed line diagram). Overall, our modeling concludes that hybrid systems will reduce HVAC energy use in three climate zones considered, and that in two of these, there is a case for purely natural ventilation of mall areas as long as upper temperature and humidity comfort criteria can be extended for a limited number of hours per year. The appropriate application of hybrid and natural ventilation strategies to such buildings have been shown to be inherently linked to building design, particularly regarding glazing and entranceways, and can lead to plant and maintenance savings.

NOMENCLATURE

V = Ventilation flow rate

$A_{r\text{-}m}$ = Area of opening between retail store and mall central space

C_d = Discharge coefficient

g = Acceleration due to gravity (9.81m/s^2 \ 32.17 ft/s^2)

$h_{r\text{-}m}$ = Doorway height between retail store and mall central space

$\Delta T_{r\text{-}m}$ = Retail store – mall central space temperature difference

T_{ref} = Reference temperature (22ºC \ 72ºF)

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