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ATRIUM BUILDINGS: THERMAL PERFORMANCE AND CLIMATIC FACTORS

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ABSTRACT

The atrium has been documented as having high energy costs, but it has also been reported to have "inherent" passive cooling and heating potential. The impact of the atrium's physical parameters on its thermal performance is not well understood. Recommendations for enhancing its thermal performance often emphasize the shading control of atrium fenestration, which might counteract the daylighting and sunlighting strategy. Thermal mass in the atrium's walls can play a significant role in absorbing excess heat caused by oversized glazing. The objective of this study is to identify the impact of the atrium's physical design parameters and climatic region on its thermal performance. Thermal performance was evaluated using computer simulation (TRNSYS) for cold and warm climates. Variations included atrium proportion, top-glazing area, and atrium wall mass. Results show that the atrium's physical parameters can significantly alleviate or aggravate its thermal performance in both cold and warm climates.

INTRODUCTION

Emergence of Atrium Buildings

The landscaped atrium of today attracts the public. This appeal is recognized in commercial benefits despite some reported higher operational costs (Bednar 1989). Besides being removed from urban congestion, the atrium provides an open space where weather is not a factor, thus enhancing promenading, social interaction, and working relationships, making it a popular building type in both cold and warm climates (Saxon 1990; Bednar 1986, 1989). The atrium offers better design solutions than a mere shelter; it brings in daylight (and direct-beam sunlight) but keeps out wind and rain. The atrium is now found in many building types, including banks, hotels, offices, apartments, and shopping malls.

Thermal and Energy Factors in an Atrium

The atrium evolved from the traditional (and unprotected) courtyard, which has largely been a climatic solution in regions with predominantly warm seasons. The modern glazed atrium offers more amenities, such as protection from rain and snow, and consequently is found in many commercial and office buildings, especially in cold regions. However, through this "evolution," the passive thermal potential of the "courtyard" has been compromised by a lack of massive walls and natural ventilation, trapped heat in the space, high internal load, and application of the "covered courtyard" in cold climates. In fact, atrium buildings are not built to save energy, but the configuration and sizing of the atrium's physical parameters can enhance or aggravate its thermal performance.

Daylighting represents one of the most important values of an atrium. This implies the use of extensive areas of glazing at the top of the atrium. The energy and thermal performance of an atrium has been reported in two distinct ways. On one hand, the atrium has been reported as having generally extensive energy costs, although offset against higher income due to improved marketability (Jones and Luther 1993; Kainlauri and Vilmain 1993). On the other hand, research and case studies reported the "inherent" passive cooling and heating potential of an atrium and even reported the possibility of unconditioned atria (Navvab and Selkowitz 1984; Bednar 1986; Watson 1982; Gillette and Treado 1988). At the same time, sizing tools related to the atrium's physical parameters are still not available and the magnitude of their impact on the atrium's temperature and thermal loads with respect to climate is not understood.

Problem Statement

Recommendations for enhancing the thermal performance of an atrium have often emphasized the use of shading control of atrium fenestration. While some shading may be useful, it potentially counteracts the abundance of daylight and sunlight that creates the aesthetic value of an atrium. Climatic variations also affect the thermal performance. Therefore, it is important to examine the impact of atrium physical parameters, other than the top glazing, on the thermal performance with respect to climates. The thermal mass of the atrium walls (and the floor) can play a significant

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role in absorbing excess heat, thus reducing the peak cooling loads (Boerreson and Harsem 1985; Utzinger and Bochek 1985). The extent to which mass can reduce the thermal loads as a function of the top-glazing area is not well understood. Furthermore, most thermal analyses on atria are based on monthly or annual results (e.g., average atrium temperature) or total annual thermal loads. While this is useful, it does not provide the fine-grain hourly temperatures and thermal loads that are important for evaluating thermal comfort and for sizing the mechanical system. The objective of this study is to identify the extent to which the atrium's physical parameters and the climate can affect atrium temperatures and the heat transferred from the atrium into the conditioned occupied spaces.

METHOD

Procedure and Atrium Parameters

Using the computer software TRNSYS 13.1 (Transient System Simulation) (SEL 1990), the thermal performance was evaluated for two distinct climatic regions: Ottawa, Canada (latitude 45.5°), as a predominantly cold region, and Fresno, California (latitude 36.8°), as a predominantly warm region. Four types of atria were tested: four- and two-story atria, each with square and linear configurations. Table 1 shows the dimensions of these atria. Figure 1 shows a schematic description of the atria. The area of the horizontal glazing was varied from 50% to 100% of the total horizontal roof area. The opaque part of the atrium roof (in the case of the reduced top-glazing area) was massive and well insulated. Vertical south-facing glazing was also tested for the warm climate only, where shading is needed. The tilt angle of the shading devices was 45°, which was considered an average angle for shading while still allowing some shading

TABLE 1
Thermal Characteristics and Mass of the Atrium Surfaces

Type of surface	Description	U-value, Btu/hr·ft^2·F (W/m^2·°C)	Mass, lb/ft^2 (kg/m^2)
Heavyweight wall	8-in (20 cm) heavyweight concrete with 3/4 in (1.9 cm) gypsum	0.490 (2.776)	106 (517)
Lightweight wall	Standard frame wall without insulation	0.438 (2.482)	16 (78)
Solid roof	6-in (15 cm) heavyweight concrete with 2 in (5 cm) of insulation	0.118 (0.668)	72 (351)
Very lightweight wall	1 in. wood	0.391 (2.21)	3 (14)
Glass of horizontal top-glazing	Clear glass 1/4 in. (6mm)	Summer* 0.83 (4.70) Winter** 1.23 (6.96)	---
Glass for vertical glazing	Clear glass	1.04 (5.89)	---
Floor	4-in (10 cm) heavyweight concrete	0.585 (3.312)	63 (307)

* 7.5 mph (12 km/hr) outdoor air velocity; 89 F (32 C) outdoor air; 24 C (75 F) inside air, natural convection
** 15 mph (24 km/hr) outdoor air velocity; 0 F (-18 C) outdoor air; 70 F (21 C) inside air, natural convection
Source: ASHRAE 1977, pp. 25.28-25.35; ASHRAE 1981, p. 26.15.

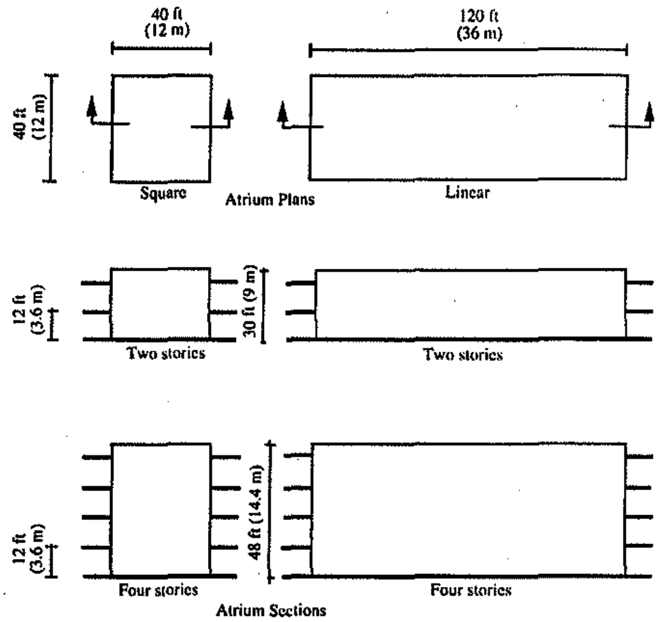

Figure 1 *Dimensions of the generic shapes of atria for the thermal simulation.*

penetration. Figure 2 shows a schematic description of this shading type. For the walls, two opaque-to-total-area ratios were considered for each type of atrium: 30% and 67%. Figure 3 shows a schematic description of mass distribution in the linear atrium.

The effect of mass was tested for both lightweight and heavyweight materials. Table 2 shows the thermal characteristics and mass (in lb/ft^2 [kg/m^2]) of the atria's physical parameters. For the simulation of the wall configuration, the area of each component of the wall (i.e., solid

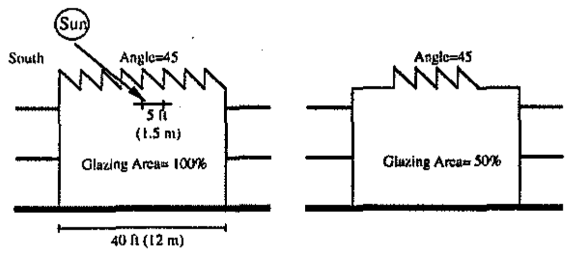

Figure 2 *Different alternatives for the vertical, south-facing top-glazing areas.*

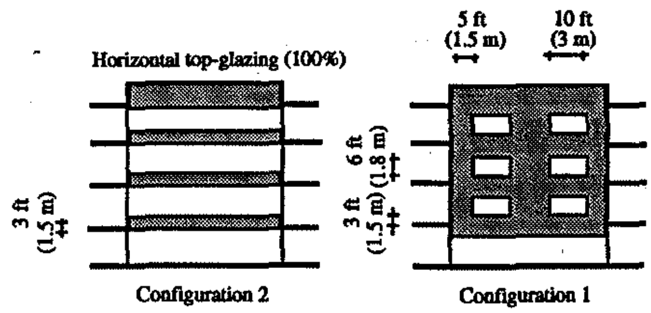

Figure 3 *Schematic description of mass distribution for the square atrium.*

TABLE 2
Thermal Characteristics and Mass of the Atrium Walls

Type of wall	Configuration 1 (solid area of 67%)		Configuration 2 (solid area of 30%)	
	Overall U-value, Btu/hr·ft²·F (W/m²·°C)	Overall mass, lb/ft² (kg/m²)	Overall U-value, Btu/hr·ft²·F (W/m²·°C)	Overall mass, Btu/hr·ft²·F (W/m²·°C)
Heavyweight	0.559 (2.947)	75 (366)	0.641 (3.631)	30 (146)
Lightweight	0.524 (2.972)	11 (54)	0.626 (3.546)	5 (24)

Source: ASHRAE 1977, pp. 25.28-25.35
ASHRAE 1981, p. 26.15

wall and glass) was used as a weighting factor to determine the average heat transfer coefficient and average absorptivity of the atrium walls. This was to accommodate the limitations of the algorithms embedded in the TRNSYS library. The average U-factor of the atrium walls, for example, was obtained by dividing the sum of the product of each wall component area and its respective U-factor by the total area of the atrium walls. This concept has been frequently used, particularly in ASHRAE Standard 90A-1980, in which the U-factor of all vertical walls has been used to calculate the average U-factor of all walls. Each wall (and roof) assembly was described (to TRNSYS) by its conduction function coefficients (ASHRAE 1977, 1981). The overall reflectivity of the atrium walls was assumed to be equal to 0.3.

The atrium can be considered either a cooling or a heating load to the adjacent spaces. The thermal fluxes in the atrium are the result of the thermal balance among the ambient environment, the atrium, and the adjacent spaces. The thermal simulation of heat transfer in an atrium included solar gains, external conductive heat between the atrium and the ambient environment, internal conductive heat transfer between the atrium and the adjacent spaces, internal heat gains, and the heat transfer through ventilation (Utzinger and Bochek 1985; Bochek 1984). Hourly temperatures and thermal loads were calculated for June 21 for Ottawa using the WYEC2 data for Ottawa (WSL 1992) and for Fresno using TMY data. The daily simulation was run the week of June 14-21 to eliminate any error that could have been caused by the input of initial values. TRNSYS generated the hourly atrium temperature and the thermal flux through the walls between the atrium and the adjacent conditioned spaces for each hour.

Ventilation Strategy

The ventilation strategy included the supply of the required fresh air in the atrium space. The ventilation mass flow rate was about 10 cfm (4.72 L/s) per person. This flow rate is rather small compared to the suggested 15 to 20 cfm for malls and arcades because the atrium was assumed to be a waiting room and a circulation space for surrounding office spaces. To test the full thermal impact of the atrium's physical parameters, the temperature of the atrium was allowed to fluctuate freely. Furthermore, it was important to examine the practicality of the atrium without air conditioning. The supply of fresh air was operated under a control system for the atrium temperature, ambient air temperature, and cooling setpoint temperature. This control system was operated under the following conditions: (1) when the atrium temperature was above both the cooling setpoint and the ambient temperature, the ventilation flow stream was delivered from the ambient air; and (2) when the atrium temperature was below the cooling setpoint temperature but above the ambient air temperature, then the ventilation flow stream was delivered through an air-to-air heat exchanger with a steady-state heat recovery of 70% (Bochek 1984; Utzinger and Bochek 1985).

The temperature of the adjacent spaces was a time-dependent function, varying from 66°F (18.9°C) in the winter to 76°F (24.4°C) in the summer. The temperature of the adjacent spaces was set back to 80°F (26.6°C) during unoccupied hours in the summer. The cooling setpoint temperature of the atrium was 76°F (24.4°C) and was set back to 80°F (26.6°C) during unoccupied hours. The humidity control was modeled but was not part of this evaluation.

Internal Load and Operation

The atrium space was operated from 8 a.m. to 7 p.m. The activity level of users was based on standing/walking activity. The occupant density was one person per 100 ft² (one person per 10 m²) (ASHRAE 1989; Treado et al. 1987). This rate of occupancy was raised at 8 a.m., noon, and 5 p.m. to account for the morning arrivals, lunch breaks, and afternoon departures (Bochek 1984). The power density of electrical lighting had to account for the daylighting contribution. Due to the lack of algorithms for the daylight contribution to lighting loads, the power density was estimated based on daylighting measurements and daylight and sunshine availability. The daylighting experiment consisted of horizontal illumination measurements (nine test points) collected at the atrium floor in a sky simulator for diffuse clear sky. The average illumination was then compared to an illumination target of 92 fc (1,000 lux), i.e., the minimum recommended illumination for plant growth (for at least 12 hours a day) (IESNA 1981). The electrical power density base case (in the case of no daylight contribution) was 1.5 W/ft² (16.7 W/m²). In case of no electrical lighting demand, there was a minimum power density of 0.5 W/ft² (5.6 W/m²). Therefore, the power density of electrical lighting was dependent on the daylighting measurement and varied from 0.5 to 1.5 W/ft² (5.6 to 16.7 W/m²), depending on the atrium cover and the time of year (Atif 1992). Table 3 shows the power density for electrical lighting estimated in different atrium configurations on June 21.

Atrium Temperature and Thermal Stratification

Temperature stratification in an atrium is mainly due to convection flows, including flows from heat sources such as

TABLE 3
Estimated Power Density for Electrical Lighting in the Atrium Space on June 21 (W/ft² [W/m²])

Atrium type	Top-glazing area (percent of projected roof area), %			
	Horizontal		Vertical south-facing	
	100	50	100	50
two-story square	0.5 (5.6)	0.5 (5.6)	0.6 (6.7)	0.7 (7.8)
four-story linear	0.5 (5.6)	0.6 (6.7)	0.7 (7.8)	0.9 (10.0)
four-story square	0.5 (5.6)	0.6 (6.7)	0.7 (7.8)	1.0 (11.1)

top glazing and other surfaces heated by the sun, and also flows downward across surfaces that have temperatures lower than the average atrium temperature. The temperature stratification difference could reach as high as 27°F (15°C) in a 65-foot-high linear atrium without a mechanical system during a warm summer day in regions with predominantly cold seasons (Jones and Luther 1993). Several studies have carried out temperature measurements to study the stratification process in an atrium. These studies show that the temperature gradient is nonlinear and the two zones of warm and extremely warm are clearly separable (Jones and Luther 1993; Simmonds 1994; Kolsaker and Mathisen 1992; Hedjazi-Hashemi 1989). Computer simulations of atrium performance/thermal performance with a one-zone model show that the predicted "uniform" (average) atrium temperature is at the border between these two zones, making the one-zone simulation model more suitable for thermal performance comparisons than for thermal comfort studies (IEA 1994).

This study applies mainly to a low-rise (four-story maximum), well-ventilated atrium, where the temperature is about the same throughout the atrium. This assumption seems rather logical in low-rise atria with fully mixed air. Furthermore, the calculated indoor temperature was based on a detailed analysis of a single zone, where the building components (ceiling, floors, walls, glazing) were modeled according to the ASHRAE transfer function approach (ASHRAE 1981).

RESULTS

Effect of the Top-Glazing Area

Figure 4 shows the atrium temperature profiles of a four-story, four-sided atrium on June 21 for Ottawa as a function of the top-glazing area and the mass in the atrium walls. Figure 5 shows the daily thermal loads per unit of floor area for June 21 in Ottawa. With low mass in the atrium walls, the reduction of the top-glazing area by 50% decreased the atrium temperature range by 11°F (6.1°C) for Ottawa. With the high mass, the same reduction of the glazing area decreased the atrium temperature range by only 4°F

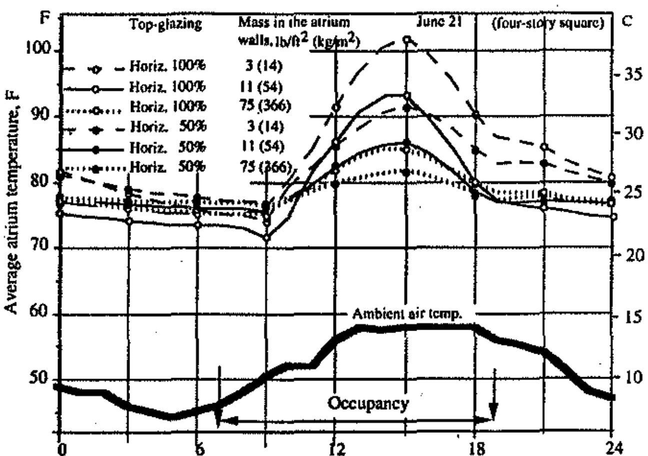

Figure 4 *Average atrium temperature profiles on June 21 in Ottawa.*

(2.2°C) and decreased the peak atrium temperature by only 3°F (1.6°C). The reduction of the glazing area by 50% reduced the heat transferred (per day) from the atrium into the adjacent spaces by as much as 60% with low mass and 40% with high mass.

Simulation results for the relatively warm region of Fresno were similar to those obtained for Ottawa, but the magnitude of the thermal impact was more pronounced. This is due to higher ambient temperatures and higher solar loads in the summer. Figure 6 shows the atrium temperature profiles of a four-story, four-sided atrium on June 21 for Fresno as a function of the top-glazing area and the mass in the atrium walls. Figure 7 shows the daily thermal loads per unit of floor area for June 21 in Fresno. The reduction of the top-glazing area by 50% with low mass decreased the atrium temperature range by 18°F (9.4°C), reduced the peak atrium temperature by 18°F (10°C), and decreased the heat transferred (per day) from the atrium space into the adjacent spaces by 40%.

Impact of Mass in the Atrium Walls

The increase of mass in the atrium walls reduced the atrium diurnal temperature range, decreased the peak maximum atrium temperature, and reduced the heat transferred

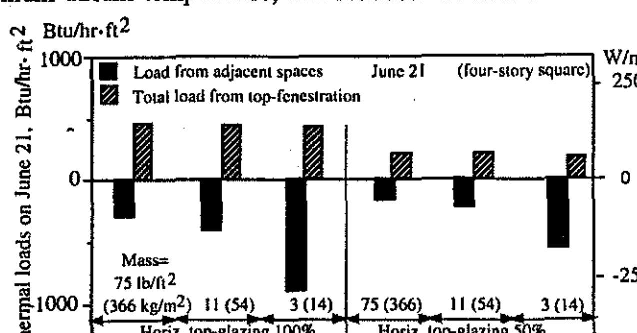

Figure 5 *Typical daily heat transfer of an atrium in Ottawa as a function of mass and top glazing.*

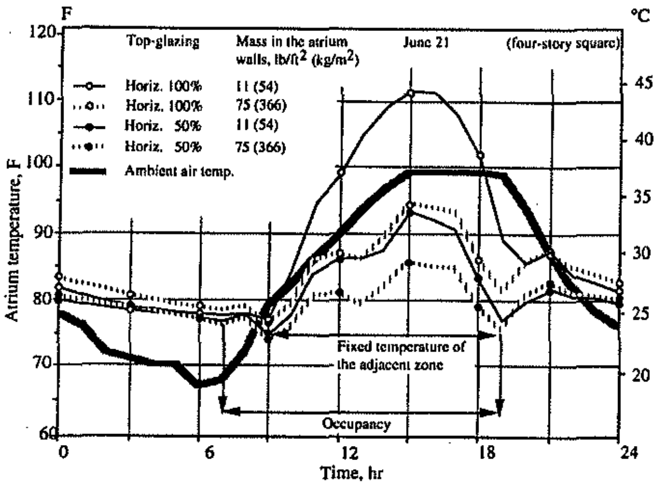

Figure 6 *Average atrium temperature profiles on June 21 in Fresno, CA.*

TABLE 4
Deviation of the Peak Atrium Temperature from the Atrium Design Temperature on June 21

Four-sided square atrium			
Max. atrium temp. deviation from the desired (design) atrium temperature	Mass lb/ft² (kg/m²)	Top-galzing area, percent	
		100 %	50 %
in Fresno F (°C)	Light mass= 11 lb/ft² (54 kg/m²)	36 (20)	17 (9.4)
	Heavy mass= 75 lb/ft² (366 kg/m²)	19 (10.6)	10 (5.6)
in Ottawa F (°C)	Light mass= 11 lb/ft² (54 kg/m²)	17 (9.4)	10 (5.6)
	Heavy mass= 75 lb/ft² (366 kg/m²)	6 (3.3)	5 (2.8)

Note. The atrium design temperature is 76 F (24.4°C). The atrium temperature was calculated for June 21. The temperature of the adjacent spaces is 76 F (24.4°C).

into the adjacent occupied spaces. The lower peak atrium temperature occurred during occupied hours. In an atrium with a fully glazed cover in Ottawa on June 21, the increase of the mass by a factor of seven decreased the atrium's diurnal temperature range by 12°F (6.7°C) and the peak temperature by 9°F (5°C). As expected, the effect of mass was more significant with greater top-glazing areas. Table 4 shows the deviation of the peak atrium temperature from the indoor design (target) temperature (76°F [24.4°C]).

It is important to note that the increase of the mass by a factor of seven in the climate of Ottawa was about as efficient as the decrease of the top-glazing area by 50%. Furthermore, the medium mass listed here (i.e.) 11 lb/ft² [54 kg/m²]) has by far more heat capacity storage and a lower U-factor than that of a fully glazed wall. In fact, Figure 4 shows that the maximum atrium temperature with a wall of 3 lb/ft² (14 kg/m²) (3-in. [7.5-cm] wood wall) could be as high as 45°F (25°C) above the maximum ambient temperature of 58°F (14.4°C).

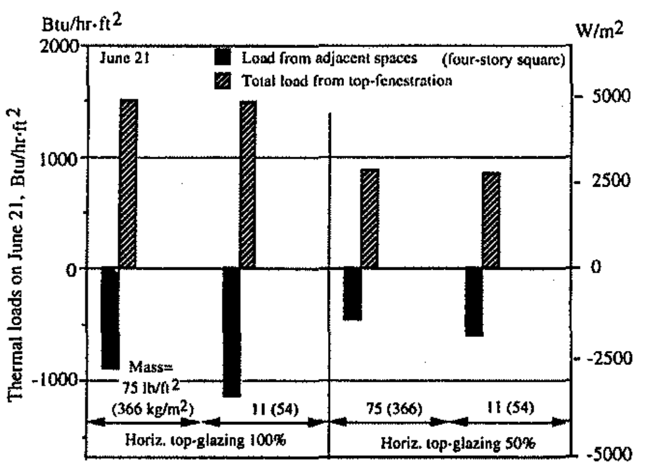

Figure 7 *Typical daily heat transfer of an atrium in Fresno as a function of mass and top glazing.*

The effect of the mass was more significant on June 21 in Fresno. In an atrium with a fully glazed atrium cover, the increase of the mass by a factor of seven decreased the daily atrium temperature range by 17°F (9.4°C) and the maximum atrium temperature by 16°F (9.3°C). However, the decrease of the top glazing by 50% was more beneficial than increasing the mass by a factor of seven.

Effect of the Atrium Proportions

The atrium proportions had an impact on the atrium temperature. Results show that the mass and/or the reduction of the top-glazing area is more relevant in lower and larger atria. With a fully glazed atrium cover, the maximum temperature of the two-story atrium in Fresno (on June 21) was 10°F (5.6°C) above that of the four-story atrium. In fact, the heat transferred to the adjacent spaces in the four-story atrium, per unit of floor area, increased only slightly with the two-story atrium despite the decrease of the wall area by almost 50%. This is because there is more mass in a four-story atrium than in a two-story atrium with the same plan-aspect-ratio.

Effect of Shading

The vertical south-facing top glazing, as compared with the horizontal top glazing, decreased the daily atrium temperature, the maximum atrium temperature, and the heat transferred into the adjacent spaces (simulated only for Fresno). The temperature profile with the shaded fenestration was flatter and its maximum was as much as 27°F (15°C) below that without shading. However, this is likely to counteract the daylighting value of an atrium.

RECOMMENDATIONS AND CONCLUSION

The study shows that, in a cold climate such as that of Ottawa, reducing the horizontal top-glazing area by 50%

was about as efficient as increasing the mass by a factor of seven, i.e., 75 lb/ft^2 (366 kg/m^2). Because sunlighting is so desirable in the cold climate, designers and engineers tend not to reduce the area or the transparency of the top glazing. Therefore, mass is needed to reduce overheating and thermal loads. This study also suggests that in the warm climate, such as that of Fresno, reducing the horizontal top-glazing area by 50% was slightly more efficient than increasing the mass by a factor of seven. The reduction of the area and/or the shading coefficient of the top glazing is obviously more relevant in warm climates. However, atrium wall mass can be used to avoid overheating in cases where more atrium "transparency" is needed. Tilted glazing (between the vertical and horizontal) would be an intermediate solution for views to the sky and should be tested for its thermal performance.

An optimum combination of reduction of glazing area and mass is recommended, especially in warm climates. In lower atria, reducing the area by "blocking" the sun penetration through the middle of the fenestration is more appropriate; it reduces the direct solar radiation on the atrium floor. It is important to reduce the direct solar radiation as much as possible away from the atrium floor, especially in the summer, because it will be more difficult to achieve thermal comfort (or reduce glare) when people are in direct solar radiation in the summer.

From the thermal performance point of view, it is not recommended to use fully glazed atrium walls in extremely sunlit atria. Moreover, the design of the atrium walls is not only related to the thermal performance, but it also responds to acoustics and especially fire codes. In fact, special care should be given to reduce noise from the atrium into the adjacent spaces and to prevent fire and smoke propagation between the atrium and adjacent spaces. In this case, heavy walls may be mandated by the code and thus can be included in the thermal strategy.

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DISCUSSION

Paul Tseng, Chief Engineer, Montgomery County, Rockville, MD: The thermal mass benefits are clearly in cold climates but are not well articulated in warm climates. Can you elaborate?

Morad R. Atif: The application of the thermal mass in atria in warm climates has several cooling benefits. Figure 6 clearly shows that the increase of the thermal mass by a factor of 7 reduced the maximum atrium temperature by 16°F (9.3°C) and the daily atrium temperature range by 17°F (9.4°C) on a typical June 21 day in Fresno. This has a direct impact on the reduction of the atrium temperatures and the diurnal temperature fluctuations in the atrium space. This, in turn, reduces the size of the equipment required for cooling and also reduces the cooling operational costs. However, it is important to notice that the decrease of the top glazing by 50% was more beneficial than increasing the mass by a factor of 7 and that the high thermal mass value, simulated at 75 lb/ft^2 (366 kg/m^2), can be very expensive to accomplish. This high mass value is usually found in the atrium walls at the top floor, where there are usually mechanical rooms, and where there is less need for large perimeter apertures. This mass is more efficient if it receives direct incoming solar radiation before it reaches the lower floors and the atrium floor.