Methodology towards developing skylight design tools for thermal and energy performance of atriums in cold climates

Laouadi, A.; Atif, M. R.; Galasiu, A. D.

Publisher's version / Version de l'éditeur:
https://doi.org/10.1016/S0360-1323(02)00009-4
Building and Environment, 38, January 1, pp. 117-127, 2003-01-01

Methodology towards developing skylight design tools for thermal and energy performance of atriums in cold climates

Laouadi, A.; Atif, M.R.; Galasiu, A.

NRCC-44248

A version of this document is published in / Une version de ce document se trouve dans :
Building and Environment, v. 38, no. 1, Jan. 2003, pp. 117-127

METHODOLOGY TOWARDS DEVELOPING SKYLIGHT DESIGN TOOLS FOR THERMAL AND ENERGY PERFORMANCE OF ATRIUMS IN COLD CLIMATES

A. Laouadi, M.R. Atif and A. Galasiu

Indoor Environment Research Program

Institute for Research in Construction

National Research Council Canada

Montreal Road Campus, Ottawa, Ontario, Canada K1A 0R6

Email: aziz.laouadi@nrc.ca

Tel. (613) 990 6868

Fax (613) 954 3733

ABSTRACT

This is one of two papers that outlines the methodology used to develop, through computer simulation, skylight design tools for thermal and energy performance of atriums in cold climates. The methodology identified important design alternatives that included skylight and atrium physical variables, and a series of thermal and energy performance outputs that may serve as selection criteria for an energy-efficient design. New prediction models were developed to overcome some computer-simulation limitations, which included models to deal with airflow between an atrium and its adjacent spaces and temperature stratification within an atrium space. The developed airflow network model is a technique used to predict the mutual influence between the atrium and its surrounding spaces without requiring additional geometrical information on the surrounding spaces. The developed temperature stratification model is consistent with airflow network models and the zone concept used in building thermal-simulation programs since it takes into account radiation (overlooked in airflow network models) and convection heat transfer at the same time. This was done through treating fictitious surfaces that separate the thermal zones in a similar way as real surfaces. Fictitious surfaces were assigned a high emissivity, high solar transmittance, high thermal conductivity and convection film coefficient of 10 W/m^2 °C. These values were found to yield reasonable solar radiation absorption, convection and radiation heat balances for the real surfaces irrespective of the number of the thermal zones. The developed models were integrated into a simulation computer program, and then validated against field measurements of a case study atrium. The predicted indoor temperatures were within ±2°C of the measured ones in both winter and summer days.

INTRODUCTION

The atrium is proliferating, with an increasing frequency, in new, renovated, and converted office and commercial buildings, especially in cold climates. Atriums revive the indoor space by admitting natural light, simulating the outdoors, and increasing people interaction. Atriums have also been reported to increase the marketing values of many buildings, beside their psychological and physiological effects on increasing the morale of people and exposure to daylight. However, these amenities may be counteracted by excessive solar heat gains in summer, high total energy consumption and expensive operation.

Physical characteristics of atriums affect the indoor environment conditions, thermal loads and daylighting performance. Daylighting has the potential to reduce electrical lighting and cooling energy consumption [1,2]. However, in most atrium buildings, electrical lighting operation is not controlled based on daylight availability. Furthermore, the sizes and forms of atrium spaces lend themselves to complex skylight shapes and surface areas that result in excessive solar heat gains in summer and high heat losses in winter. The impact of skylight and atrium physical parameters on the atrium thermal and energy performance has not been well understood. Therefore, there is a need to develop design tools to take full advantage of atrium potential daylighting, improve thermal performance, and optimize the total energy consumption for lighting, heating and cooling.

Prediction of thermal and energy performance of atriums is strongly related to the availability and accuracy of prediction tools and modeling techniques. Atriums are known to be subject to significant temperature stratification due to their large size and high solar heat gains through their fenestration, particularly in summer. Temperature stratification influences thermal comfort and increases thermal loads of the mechanical system. Atriums also have complex air flow patterns, due to buoyancy effect and to the interaction among the atrium space, the adjacent spaces, the mechanical system, and the outside environment. Prediction of temperature stratification and airflow pattern needs accurate and detailed modeling techniques. Computational Fluid Dynamics models (CFD) may be used to predict temperature stratification and air flow pattern under steady state and known boundary conditions [3-9]. However, CFD models are not practical for dynamic simulations since they require excessive calculation time and powerful hardware. Alternatively, zonal airflow models may be used to predict inter-zonal air flows under dynamic conditions for either known flow patterns –without mass-pressure coupling [10,11], or unknown flow patterns –with mass-pressure coupling [3,12-15]. However, zonal airflow models integrated in whole building simulation ignore radiation exchange between zone surfaces and, therefore, they do not accurately predict temperature stratification.

OBJECTIVES

The purpose of this paper is to outline the methodology and models used in the computer simulation to develop skylight design tools for thermal and energy performance of atriums. The specific objectives are:

1. To select design alternatives for skylights and atriums;
2. To identify design performance outputs, criteria to assess energy-efficient designs;
3. To develop models to overcome some computer-simulation limitations, namely models to predict air flows between an atrium and its adjacent spaces, and temperature stratification within an atrium space; and
4. To validate the developed models against field measurements in a case study atrium.

SELECTED DESIGN ALTERNATIVES

The selected design alternatives include design parameters for the atrium and its fenestration and the mechanical and electrical system control strategies. The atrium variables of interest are the atrium shape and the interaction of the atrium with its adjacent spaces. The shape of an atrium is important to take full advantage of the atrium potential benefits for daylighting and to minimize thermal loads. Atrium orientation also has an impact on daylighting, heating and cooling energy performance. Atrium size may also increase or limit these benefits. Shallow atriums are good for daylighting to reach the occupied areas at the floor level and adjacent spaces, but they may increase direct solar heat gains at the atrium floor and, therefore, increase the cooling energy requirements. However, high-storey atriums may limit daylighting to reach the floor level. Adjacent spaces interact with the atrium space through convection heat exchange and daylighting penetration through windows in the atrium interior walls. The atrium space may gain or loose heat by convection through corridors/doors that link the atrium space to the adjacent spaces. Daylighting contribution at the atrium floors may decrease as a large portion of daylight may be transmitted through internal windows. Consequently, the atrium indoor temperature and lighting, heating and cooling energy requirements may be affected accordingly. Atrium fenestration is an important element in atrium designs. Fenestration, which includes glazed walls and skylight, provides daylighting and solar heat gains to the indoor space and gives view to the outside. Skylight shape and fenestration glazing type and surface area are major design parameters to solve the trade-off between daylighting and solar heat gains, and to achieve high atrium amenities and significant energy savings. Finally, to further achieve significant energy savings, the mechanical (HVAC) and lighting systems should be controlled to respond to the variability of the outdoor conditions.

Atrium Shape

Three generic atrium shapes are selected, which are commonly used in buildings. These include: (1) An enclosed atrium, which occupies a central space of a building. (2) A three-sided atrium, which has three interior walls and one exterior, glazed wall. The glazed wall is oriented to the south for maximum daylight gathering. (3) A linear atrium, which has two long interior walls and two short exterior, glazed walls. The glazed walls are oriented towards east-west for maximum daylight penetration to the adjacent spaces.

Interaction of an Atrium with its Adjacent Spaces

The atrium space may have walkways (galleries) along internal walls at each floor level to facilitate circulation to the atrium adjacent spaces. Two options of adjacent spaces are selected. The first option assumes the atrium space is closed to the adjacent spaces. This is to simulate the conditions where the adjacent spaces are built to take advantage of atrium daylighting (in case the internal walls have windows). The atrium space communicates with its adjacent spaces via doors that remain closed most of the time. Convection heat gain/loss from/to the adjacent spaces is through cracks around doors and interior walls. The second option assumes the atrium is open to the adjacent spaces. This is to simulate the conditions where the adjacent spaces are not built to take advantage of daylighting. The adjacent spaces may communicate with the atrium space through open doors/corridors at each floor level. Convection heat gain/loss from/to the adjacent spaces is through open doors/corridors.

Skylight Shape

Three skylight shapes are selected as design alternatives: flat, square-pyramidal and pitched. Flat skylights are appropriate to any atrium shape. However, they are rarely practical due to structural and other related damage and snow built-up problems, particularly in cold climates. Pyramidal skylights are appropriate for enclosed and three-sided atriums. Pitched skylights are convenient for linear atriums.

Fenestration Glazing Types

The simulated fenestration glazing types include double and triple clear/tinted glazing with or without low-e coatings. Table 1 summarizes the optical and the thermal properties of the selected glazing assemblies.

Fenestration Surface Area Ratio

As a means to control solar heat gains in summer, a portion of the atrium roof and wall may be glazed. The atrium fenestration may occupy 100% or 50% of the total atrium roof and external wall surface areas (excluding the surface areas for walkways). It is assumed that the fenestration surface area is composed of 25% frame and 75% glass surface areas.

Mechanical System Control Strategy

The atrium space is supplied by a constant air volume system with variable air supply temperature. Each floor of the atrium may receive different amounts of air for heating and cooling. The air mass flow injected into each floor of the atrium is calculated based on the peak loads for heating and cooling. The maximum supply temperature for heating is assumed to be 43°C and the minimum supply temperature for cooling is assumed to be 13°C [16]. The indoor temperature is controlled to vary between 21°C and 24°C. Heating starts when the indoor temperature drops below 21°C and cooling starts when the indoor temperature rises above 24°C. Each atrium floor is fully-conditioned. However, the skylight zone (for non-flat skylights) just above the atrium top floor is free-floating.

Electric Lighting System Control Strategy

The lighting system is controlled using a continuous dimming control system. The principle of a continuous dimming control system is to supplement daylighting by allowing an electric lighting power reduction in direct relation to the amount of natural light entering the space. A dimming control system incorporates three basic components: photosensor, control unit and dimming unit. The photosensor measures the light level at the work plane and generates an electric signal proportional to the illumination striking it. The control unit processes the signal from the photosensor and converts it into a command signal to the dimming unit. The dimming unit varies the light output of the electric lighting by varying the amount of power flowing to the lamps. This allows the electrical lighting system to generate just the right amount of light needed to meet the target illuminance.

BASECASES

Basecase atriums are selected in order to compare different design options and select the optimum design that meets the user specified requirements for energy efficiency. Whether or not the basecases are representative of real atriums is not important at this point. What is important is to determine the relative change in performance due to a change in design with respect to the basecase. The notion of the basecase holds only for relative design performance outputs, such as energy use and peak loads. The characteristics of the basecases are as follows.

Atrium Shape

The shape of the basecase atrium is similar to that of the design alternative. The adjacent spaces are assumed closed to the atrium space.

System Control Strategy

The basecase has similar HVAC system control strategy as the design alternative. However, the lighting system control strategy is lights always on during occupancy hours.

Fenestration

The fenestration (wall and skylight) of the basecase is double-glazed with clear float glass and occupies 100% of the roof and wall surface areas. The shape of the skylight is flat.

Construction Materials

As required by the National Building Code of Canada [17], the ground floor of the atrium should have an overall U-value less than 0.88 W/m^2K and the atrium exterior walls and roof (non-glazed portion) a U-value less than 0.27 W/m^2K.

Occupancy Density and Schedule

Occupancy in an atrium space depends on the atrium building use (commercial/office building) and on the atrium space use: social gathering area, promenading area, or circulation area. In this study, the atrium space is used as a circulation area to different locations in an office building complex. Only the ground floor is occupied. Primary activities include walking and standing. Occupant density is $9m^2$/person [16], and occupancy schedule during the weekdays is shown in Table 2. The atrium space is not occupied during the weekends.

Air Leakage Characteristics

Air leakage characteristics of the atrium are specified in terms of the equivalent leakage area per component surface area. An equivalent leakage area of 2 cm^2/m^2 is assumed for cracks in interior and exterior walls and roof [16,18]. In case where the atrium is open to the adjacent spaces, the equivalent leakage area for the interior walls is assumed to be 125 cm^2/m^2, which is equivalent to about four standard door openings per floor level of an enclosed atrium.

Design Performance Outputs

The design performance outputs are presented in dimensionless ratios of a given design output to its counterpart of the basecase. The major advantage of this approach is that the impact of the design options on the design performance may be generalized for other similar designs in regions with similar climates. The performance outputs, which have been used to evaluate the atrium design alternatives are indicated below:

Seasonal Solar Heat Gain Ratio

Solar heat gain ratios in cooling and heating seasons are useful for passive solar design of atriums.

Cooling and Heating Peak Load Ratios

The cooling and heating peak load ratios are important in the pre-design stage of the mechanical system.

Annual Cooling, Heating and Total Energy Ratios

The annual cooling and heating energy ratios are important to estimate the annual energy cost and to select design options of an atrium under a prevailing climate (selection criteria may be based on cooling energy, heating energy, or total energy).

Modeling Air Flow within an Atrium and its Adjacent Spaces

A zonal model with mass-pressure coupling is employed in this study to predict inter-zonal flows between the atrium and its adjacent spaces and between the atrium and the outside. The atrium space is split into a number of vertically-stacked zones. The zone nodes are linked to each other by low flow resistance components, and to the inside and outside by some flow components, which represent cracks, or doors/openings in the atrium building structure. The airflow between the atrium and the adjacent spaces is de-coupled into two components. The first component represents the airflow that is due to the stack effect. The air mass, which enters the atrium space at the bottom/top from the adjacent spaces, has to leave the atrium space at the top/bottom to the adjacent spaces, depending on the temperature differences between the atrium zones and the adjacent spaces. The neutral height occurs around the atrium mid-height. The airflow between the atrium space and adjacent spaces occurs through cracks, doors, or open corridors that link the atrium to the adjacent spaces. The component of the stack effect is represented by one node with a constant temperature (21°C) and an unknown pressure. The second component represents the outside air that enters the adjacent spaces through cracks/openings in the adjacent building structure, where it gets warmed up to the temperature of the adjacent spaces (21°C), and then enters the atrium space at the bottom (first floor), and exits from the top (roof). This air mass flow is a function of the surface areas of the interior walls of the first floor. The outside air may also enter or exit the atrium space through cracks in the roof and exterior walls. Each atrium zone, which has exterior walls, is linked to an exterior node.

MODELLING TEMPERATURE STRATIFICATION WITHIN AN ATRIUM SPACE

A new method is developed to predict temperature stratification within an atrium space. The developed model is consistent with the use of airflow network models and the thermal zone concept in building thermal-simulation software. The atrium space is split into a number of vertically-stacked zones. Each zone is bounded by a set of real and fictitious surfaces. Fictitious surfaces, which separate thermal zones, are treated in a similar way as real surfaces, i.e., they are assigned an emissivity, solar transmittance, thermal capacity, thermal conductivity and convection film coefficient. The values of these characteristics are calculated so that the heat balance of each atrium real surface is conserved and does not depend on the number of the zones the atrium is split into. This needs to compare the heat balance of each real surface of the atrium as a whole (undivided) with the heat balance of each real surface of the divided atrium. The comparison criteria are as follows:

1. Solar radiation absorption by real surfaces;
2. Convection heat transfer between a real surface and the adjacent air; and
3. Radiation heat transfer among real surfaces.

To meet the first criterion, fictitious surfaces are assigned a solar transmittance of 99.9% (fully transparent). Using a ray-tracing/tracking method, solar radiation absorption by real surfaces of each thermal zone may be accurately predicted.

To meet the second criterion, fictitious surfaces have to be assigned a convection film coefficient. To calculate the film coefficient, the flow and temperature fields within the whole space have to be known. Alternatively, the film coefficient may be given by similar correlation as for walls/floors. Other simplified methods may be used to supply directly the value of the film coefficient as an input to simulation programs. In DOE-2 software, the film coefficient is set to 14.8 W/m^{2o}C (2.6 Btu/hr.ft^{2}F) [19]. Togari et al. [14] and Takemasa et al. [12] used a value of 2.3 W/m^{2o}C in their zonal model applied to an atrium to predict inter-zonal heat transfer with and without solar radiation. Chow [20] used a value of 10 W/m^{2o}C, taken from the study by Achterbosch et al. [21], in his three-zone temperature stratification model in an atrium space.

To meet the third criterion, radiation heat transfer between real and fictitious surfaces within a given zone should be maximized since the temperature of the fictitious surface will lay between the average temperatures of the real surfaces of the adjacent zones on both sides. Fictitious surfaces are, therefore, assigned a high emissivity (equal to 0.99), a low thermal capacity, and a high thermal conductivity (low conduction resistance). However, the high emissivity will not produce the right amount of radiation heat transfer between real surfaces on both sides of the fictitious surface. The convection film coefficient may, therefore, be boosted to complement the radiation heat transfer of the fictitious surface so that its total (convection plus radiation) heat transfer is equal to the radiation heat exchange between atrium real surfaces on both sides of the fictitious surface.

Determination of the Convection Film Coefficient for Fictitious Surfaces

In this study, the film coefficient is calculated based on thermal simulations of a typical atrium building. ESP-r software [23] is used for this purpose. ESP-r offers some flexibility to meet the aforementioned criteria, namely the prediction of solar radiation absorption using the built-in ray-tracking method. A set of values are given to the film coefficient, and the convection and radiation heat exchanges are calculated for the multi-zone space and then compared with those calculated for a single zone space. Solar radiation absorption, radiation and convection heat exchanges calculated for the single-zone space are considered as exact values. A reasonable value for the film coefficient may then be selected. Below is an example of this application.

The simulated building is a cubic atrium of 16mX16mX16m dimensions. The walls of the atrium are made of 10 cm concrete, the roof is double-glazed with 6 mm clear float glass, and the floor is 20 cm concrete. The boundary conditions are as follows. The south wall and the roof are in contact with the outside. The east, north and west walls are in contact with interior zones under 15°C, 21°C, and 5°C, respectively. The floor is in contact with the ground. These boundary conditions are chosen so that the radiation heat transfer among the internal surfaces may not be neglected compared to the convection heat transfer.

The building is divided into four vertically-stacked thermal zones. The simulation is carried out on a sunny day, June 24, for the city of Ottawa, Ontario. The solar radiation absorption, and convection and radiation heat transfer are calculated for the one and four zone models.

Solar radiation absorption

The ray-tracking algorithm in ESP-r is used to predict the solar radiation absorption by real surfaces of each thermal zone. The solar radiation is assumed to enter the thermal zone from its top surface (ceiling). However, the ray-tracking algorithm for insolation originating from internal transparent surfaces (surfaces that are not directly hit by solar radiation) looses accuracy as it does not correctly track the solar radiation incidence angle on that surface. This inaccuracy increases with the number of the thermal zones. As a result, the simulation time step has a significant impact on solar radiation absorption. To illustrate this effect, Figure 1 shows the profile of the solar radiation absorbed by the atrium floor surface for the one and four zone models. The results obtained for the four-zone model are de-phased by about two times the used time step as compared with those obtained for the one-zone model using a one-hour time step. A time step T = ¼ hour applied to the four-zone model yields approximately similar results as the one-hour time step applied to the one-zone model.

Figure 2 shows the profile of the absorbed solar radiation by the interior surfaces of the one-zone model using one-hour time step and of the four-zone model using ¼ hour time step. The predicted values for the four-zone model agree reasonably well with the predicted values for the one-zone space. The maximum error is about 31% for the west surface.

Radiation and convection heat transfer

A series of values are assigned to the film convection for the fictitious surfaces of the four-zone model, and the radiation and convection heat transfers are evaluated and then compared with those for the one-zone model. A value of 10 $W/m^{2o}C$ of the film coefficient is found to yield reasonable results.

Figures 3, 4 and 5 show the profile of the radiation, convection and total (radiation and convection) heat fluxes of the atrium interior surfaces, respectively. Overall, the radiation, convection and total fluxes calculated for the four-zone model are in reasonable agreement with those calculated for the one-zone model, although some surfaces of the four-zone model exhibit some differences with respect to those of the one-zone model. This difference may be attributed to multiple reasons. First, the film coefficient of fictitious surfaces may vary with temperature and from zone to zone. Second, the predicted surface temperatures for the one-zone model are different from the predicted surface temperatures of the four-zone model, which is due to different solar radiation absorption as depicted in figure 1. However, simulation results (not shown here) obtained for a two-zone model with an opaque roof show better agreement for the same value of the film coefficient. The figures also show that the radiation heat transfer is much higher than the convection heat transfer. Therefore, any method that does not take into account radiation heat transfer would result in poor accuracy in predicting building thermal loads.

VALIDATION

The foregoing models are implemented in ESP-r software to compare simulation predictions with field measurements conducted on a case study atrium. The case study is a three-storey atrium building located in the region of Ottawa (latitude 45.0° and longitude difference 0.7° east). The atrium has an octagonal shape with a pyramidal skylight and is surrounded by walkways that lead to the adjacent spaces. A linear corridor at each floor level connects the atrium to a larger eight-storey atrium. The first floor houses the main building entrance, conference or meeting rooms and the reception desk. The second and third floors are identical and are surrounded by offices and conference rooms.

The field measurements were conducted in two phases. The first phase took place from June 2 - 27, 1995 to address summer conditions, and the second phase from November 29 - December 15, 1995 to address winter conditions. Measured parameters included indoor temperatures in the atrium space and the adjoining spaces, outdoor temperature, outdoor solar radiation, indoor solar radiation below the skylight (global horizontal), supply air flow rate and air infiltration rate. Time-of-use of the electrical lighting fixtures in the atrium space was also measured using data loggers. In addition, separate tests were conducted in the summer and in the winter seasons to determine the contaminant migration pattern when released in the center of the atrium at ground level. Further details may be found in Laouadi and Atif [22].

Figures 6 and 7 show the profiles of the measured and predicted indoor temperatures of the atrium floors on the weekends of December 2-3 and 9-10, 1995, respectively. The atrium space was not occupied and the HVAC system was turned off. The predicted temperatures of the three floors were almost identical to the corresponding measured temperatures. The maximum difference between the measured and predicted temperatures was about ±2°C. The solar radiation did not significantly affect the indoor temperature of the atrium due to the low solar transmittance of the skylight (13%). However, convection heat gains from the adjacent spaces through the open corridors contributed to maintain the atrium indoor temperatures close to those of the adjacent spaces.

Figure 8 shows the profiles of the measured and predicted indoor temperatures of the atrium floors on June 10-11,1995. The atrium space was not occupied and the HVAC system was turned off. Temperature stratification in the space is significant and may reach up to 5°C between the top and bottom floors. The predicted and measured temperatures of the atrium floors followed the same trend, and they were in good agreement for clear/sunny and overcast days. The maximum difference between the measured and predicted temperatures was about ±1°C.

CONCLUSION

A methodology to develop, through computer simulation, skylight design tools for thermal and energy performance of atriums in cold climates was outlined. A series of design alternatives that included atrium and skylight variables and system control strategies were selected as input parameters for the simulation. A series of thermal and energy performance outputs were also identified, which may be used as criteria to assess an energy-efficient design. New prediction models were developed to overcome some limitations of computer simulation. An airflow network model was developed to handle the mutual interaction between an atrium and its adjacent spaces without requiring additional geometrical information on the rest of the building. A model to handle temperature stratification within an atrium space was also developed. The model takes into account radiation (overlooked in airflow network models) and convection heat transfer, and, therefore, is consistent with the airflow network models and with the zone concept used in building thermal-simulation computer programs. The atrium space may be split into a number of vertically-stacked thermal zones. Thermal zones are separated by fictitious surfaces. The latter are treated in a similar way as real surfaces, i.e., they are assigned a high emissivity, high solar transmittance, high thermal conductivity and film coefficient of 10 W/m^2 °C. These values were estimated to yield reasonable values for solar radiation absorption, radiation and convection heat balances for real surfaces irrespective of the number of thermal zones. These models were integrated into a simulation computer program and then validated against field measurements in a case study atrium. The case study is an enclosed atrium, open to the adjacent spaces through corridors at each floor level. The indoor temperatures of the atrium were monitored in the summer and winter days. Comparison studies on indoor temperatures showed good agreement between field measurements and computer predictions using the developed models for both winter and summer days. The predicted indoor temperatures of the atrium floors were within ±2°C difference from the measured temperatures. For the winter days, the convection heat gains from the adjacent space to the atrium through the open corridors contributed to maintain the atrium temperatures close to those of the adjacent spaces. In the summer days, the solar heat gains resulted in significant temperature stratification of about 5°C between the top and bottom floors.

Acknowledgement

This work was funded by the Institute for Research in Construction of the National Research Council Canada, and CANMET/Building Group of Natural Resources Canada. The authors are very thankful for their contribution.

References

1. American Architectural Manufacturers Association (AAMA), *Skylight Handbook, Design Guidelines*, Des Plaines (1987).

2. Architectural Aluminum Manufacturers Association (AAMA), *Design for energy conservation with skylights*, AAMA TIR-A6, Chicago, Illinois (1981).

3. IEA, *Annex 26: Energy-Efficient Ventilation of Large Enclosures. Ventilation of Large Spaces in Buildings, Part 3: Analysis and Predictions Techniques*, Editors: Heiselberg P., Murakami S., Roulet C.A (1997).

4. Kato S., Murakami S., Shoya S., Hanyu F., and Zeng J., CFD Analysis of Flow and Temperature Fields in Atrium with Ceiling Height of 130 m, *ASHRAE Trans*., **101, Pat 2**, pp. 1144-1157 (1995).

5. Moser A., Off F., Schalin A. and Yuan X., Numerical Modeling of Heat Transfer by Radiation and Convection in an Atrium with Thermal Inertia, *ASHRAE Trans*., **101, Pat 2**, pp. 1136-1143 (1995).

6. Sonda Y., Higuchi S., Ohgaki S. and Ozeki Y., Simulation of Temperature and Flow Field in an Atrium. Part 2: Comparison of Results from Experiments and Numerical Analysis, and Applications, *Proc. Room Air Convection and Ventilation Effectiveness*, Tokyo, Japan, pp. 491-500 (1992).

7. Kondo Y. and Niwa H., Numerical Study of an Atrium by Means of a Macroscopic Model and K-ε Turbulence Model. *Proc. Room Air Convection and Ventilation Effectiveness*, Tokyo, Japan. pp. 109-113 (1992).

8. Takahachi N., Iwata E. and Funatsu M., Simulation and Evaluation of the Environment of a Large-Scale Atrium, *Proc. Room Air Convection and Ventilation Effectiveness*, Tokyo, Japan. pp. 511-515 (1992).

9. Chikamoto T., Murakami S. and Kato S., Numerical Simulation of Velocity and Temperature Fields Within an Atrium Based on Modified K-ε Model Incorporating Damping Effect Due to Thermal Stratification*, Proc. Room Air Convection and Ventilation Effectiveness*, Tokyo, Japan, pp. 501-509 (1992).

10. Inard C., Meslem A. and Depecker P., Energy Consumption and Thermal Comfort in Dwelling-cells: A Zonal-Model Approach, *Building and Environment,* **33(5)**, pp. 279-291 (1998).

11. Inard C., Butty D., Simulation of Thermal Coupling Between a Radiator and a Room with Zonal Models, *12th AIVC Conference*, Ottawa, Canada, pp. 125-131 (1991).

12. Takemasa Y., Togari S. and Arai Y., Application of an Unsteady-State Model for Predicting Vertical Temperature Distribution to an Existing Atrium, *ASHRAE Trans*., **102, Pat 1**, pp. 239-247 (1996).

13. Arai Y., Togari S. and Miura K., Unsteady-State Thermal Analysis of a Large Space with Vertical Temperature Distribution, *ASHRAE Trans*., **100, Part 2,** pp. 396-411 (1994).

14. Togari S., Arai Y. and Miura K., A Simplified Model for Predicting Vertical Temperature Distribution in a Large Space, *ASHRAE Trans*., **99, Part 1,** pp. 88-99 (1993).

15. Murakami S., Kato S., and Yokoi M., Micro/Marco Analysis of Air Mass, Heat and Energy Transport within an Enclosure, *ROOMVENT'94,* Krakow, Poland (1994).

16. NRCC, Performance Compliance for Buildings, Specifications for Calculation Procedure for Demonstrating Compliance to the National Energy Code for Buildings Using Whole Building Performance, NRCC, Canada (1994).

17. NRCC, National Energy Code of Canada, Canadian Commission on Building and Fire Codes, NRCC, Canada (1995).

18. ASHRAE, *ASHRAE Handbook – 1997 Fundamentals*. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (1997).

19. Landsberg D.R., Misuriello H.P. and Moreno S., Design Strategies for Energy-Efficient Atrium Spaces. *ASHRAE Trans*, **92, Part 2A**, pp. 310-328 (1986).

20. Chow W.K., Assessment of Thermal Environment in an Atrium with Air-Conditioning, *J. environmental Systems*, **25(4),** pp. 409-420 (1997).

21. Achterbosch G.G.J., Jong P.P.G., Krist-Spit C.E., Van der Meulen S.K. and Verberne J., The Development of a Convenient Thermal Dynamic Building Model, *Energy and Buildings*, **8,** pp. 183-196 (1985).

22. Laouadi A., and Atif M.R., Comparison between Computed and Measured Thermal Parameters in an Atrium Building, *Building and Environment*, **34**, pp. 129-138 (1999).

23. ESRU, *ESP-r User's Manual*, Glasgow: Energy Systems Research Unit, University of Strathclyde (1998).

Table 1 Optical and thermal characteristics of the selected glazing assemblies (center-of-glass values)

Glazing type	Description	U-value ($W/m^2\ ^oC$)	SHGC	Solar Trans.	Visible Trans.
double clear	6 mm clear float glass (exterior) 13 mm air gap 6 mm clear float glass (interior)	3.15	0.72	0.61	0.76
double gray	6 mm gray float glass 13 mm air gap 6 mm clear float glass	3.24	0.45	0.33	0.36
double clear low-e	6 mm clear float glass 13 mm air gap 6 mm low-e clear float glass	1.81	0.56	0.47	0.74
triple clear	6 mm clear float glass 13 mm air gap 6 mm clear float glass 13 mm air gap 6 mm clear float glass	2.22	0.62	0.48	0.67
triple clear low-e	6mm clear float glass 13 mm air gap 6 mm low-e clear float glass 13 mm air gap 6 mm low-e clear float glass	1.12	0.45	0.30	0.63

Table 2 Occupancy density and schedule for an atrium space during weekdays

Time (hr.)	7	8	9	10	11-14	15	16	17	18	19
Occupancy	0.1	0.7	0.8	0.9	1.0	0.9	0.8	0.7	0.3	0.1

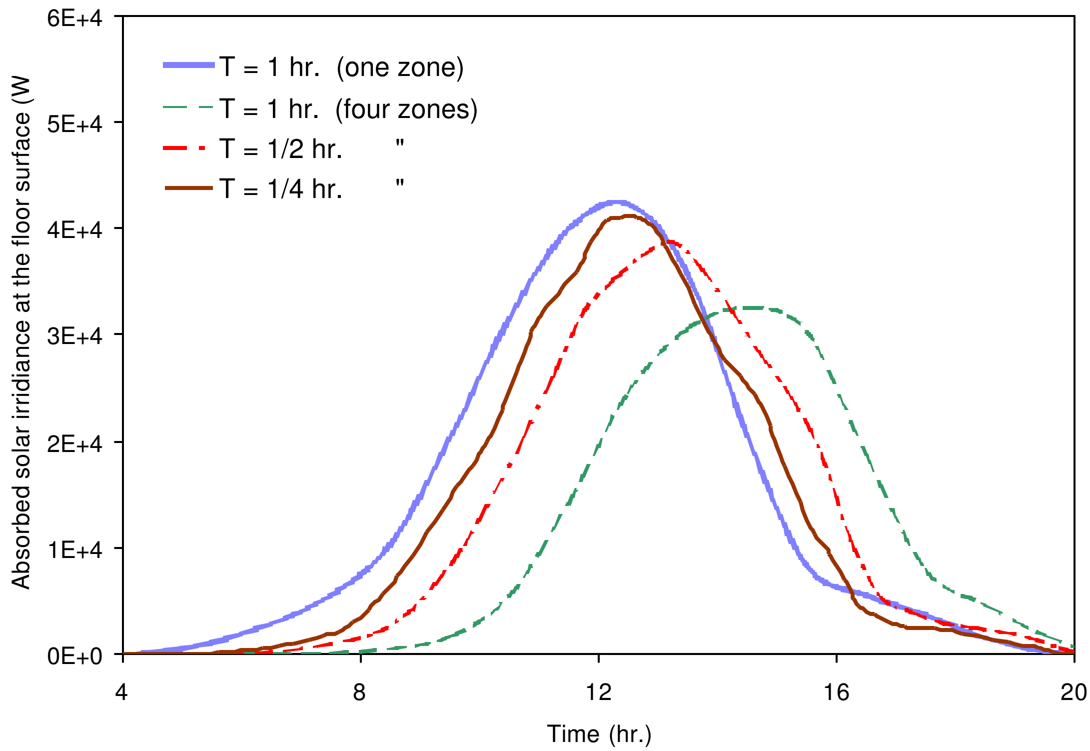

Figure 1 Effect of time step on surface solar radiation absorption

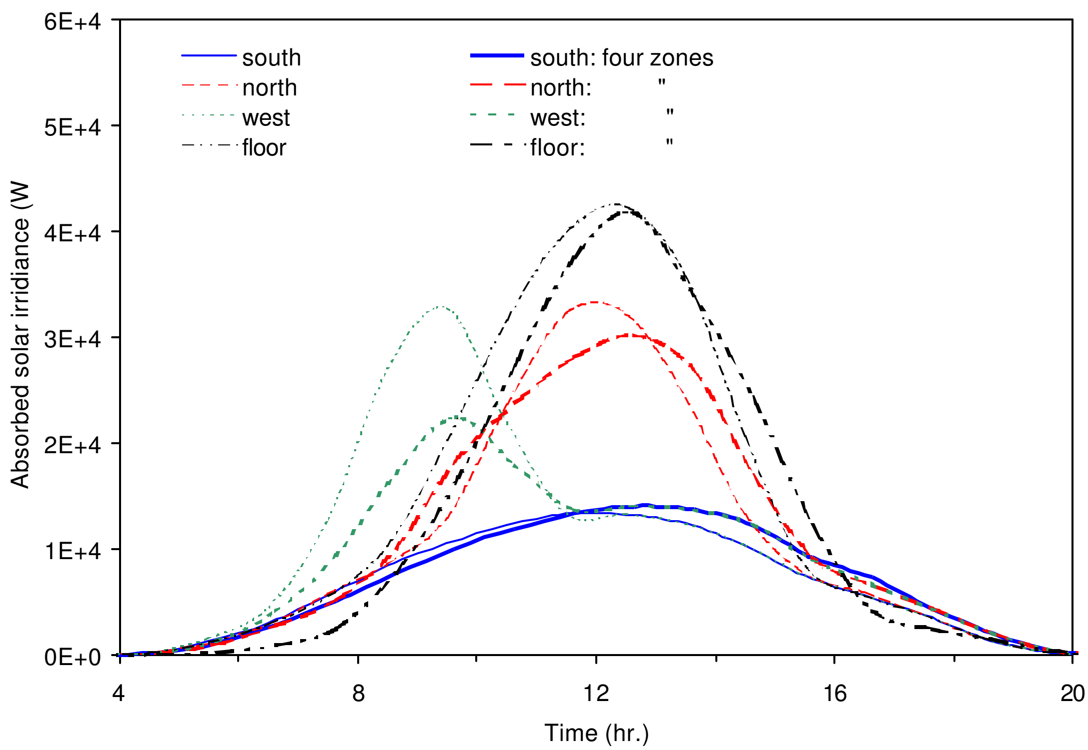

Figure 2 Solar radiation absorption by internal surfaces

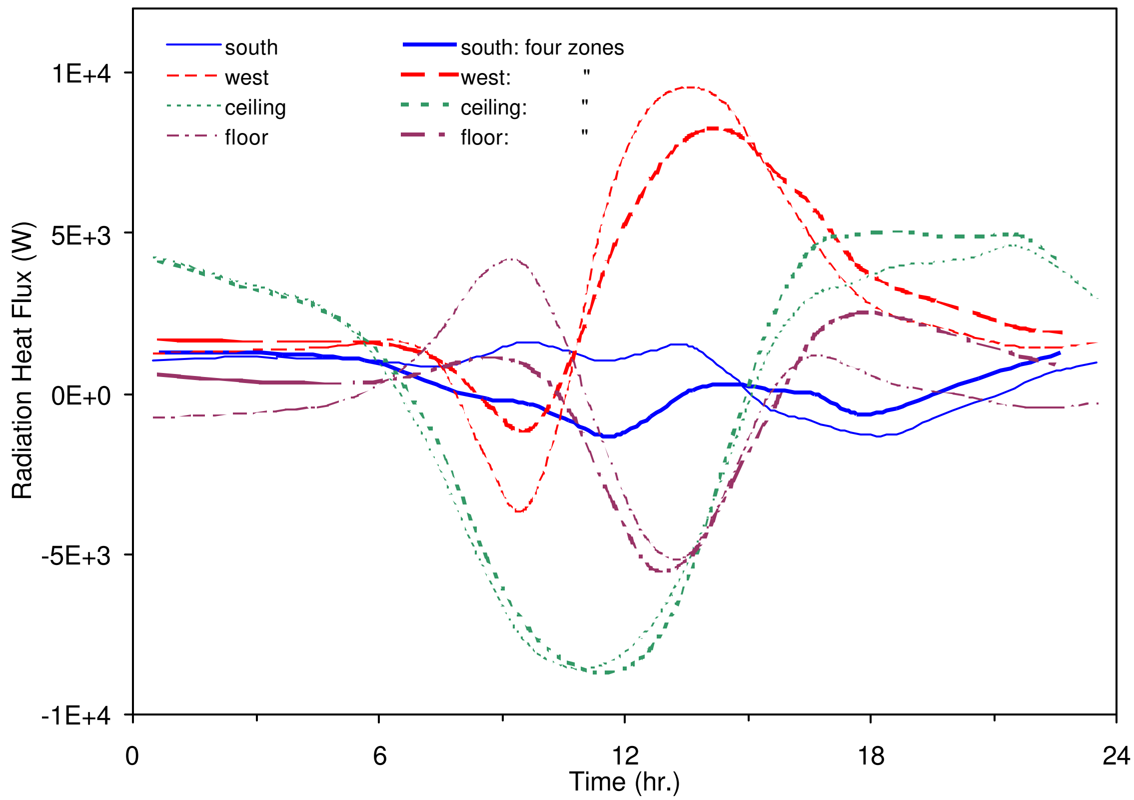

Figure 3 Radiation heat flux at internal surfaces

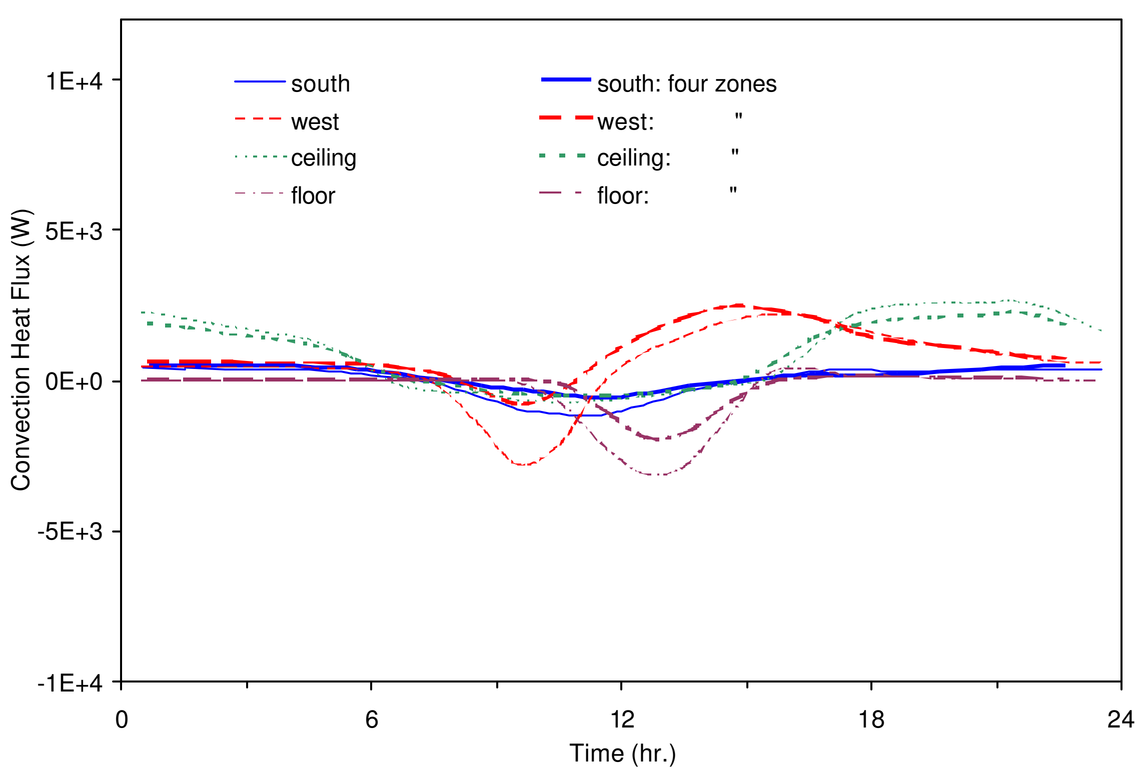

Figure 4 Convection heat flux at internal surfaces

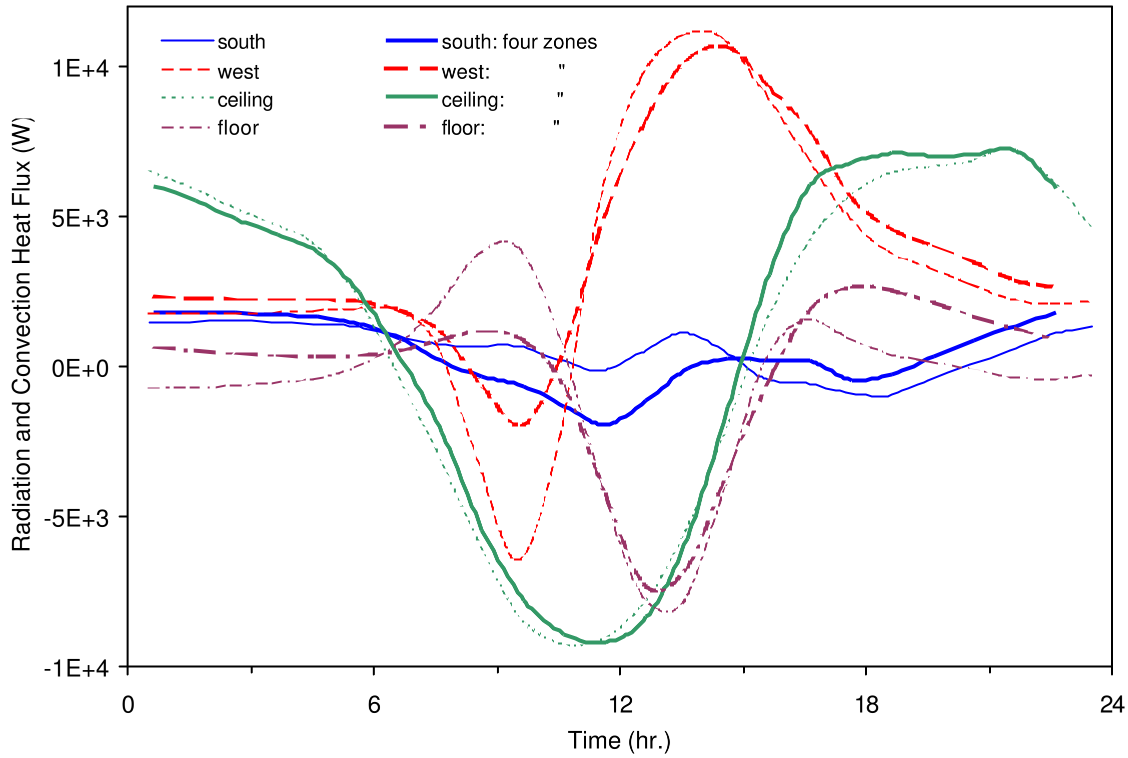

Figure 5 Combined radiation and convection heat flux at internal surfaces

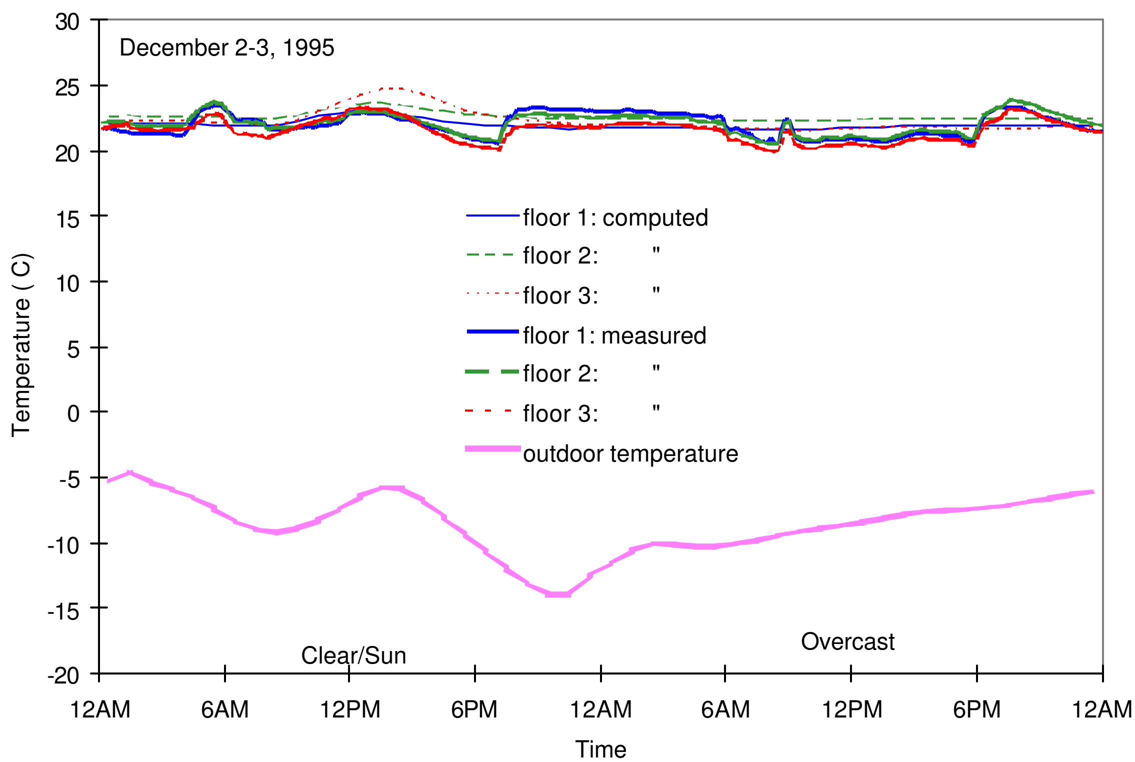

Figure 6 Comparison of measured and predicted indoor temperatures on December 2-3, 1995.

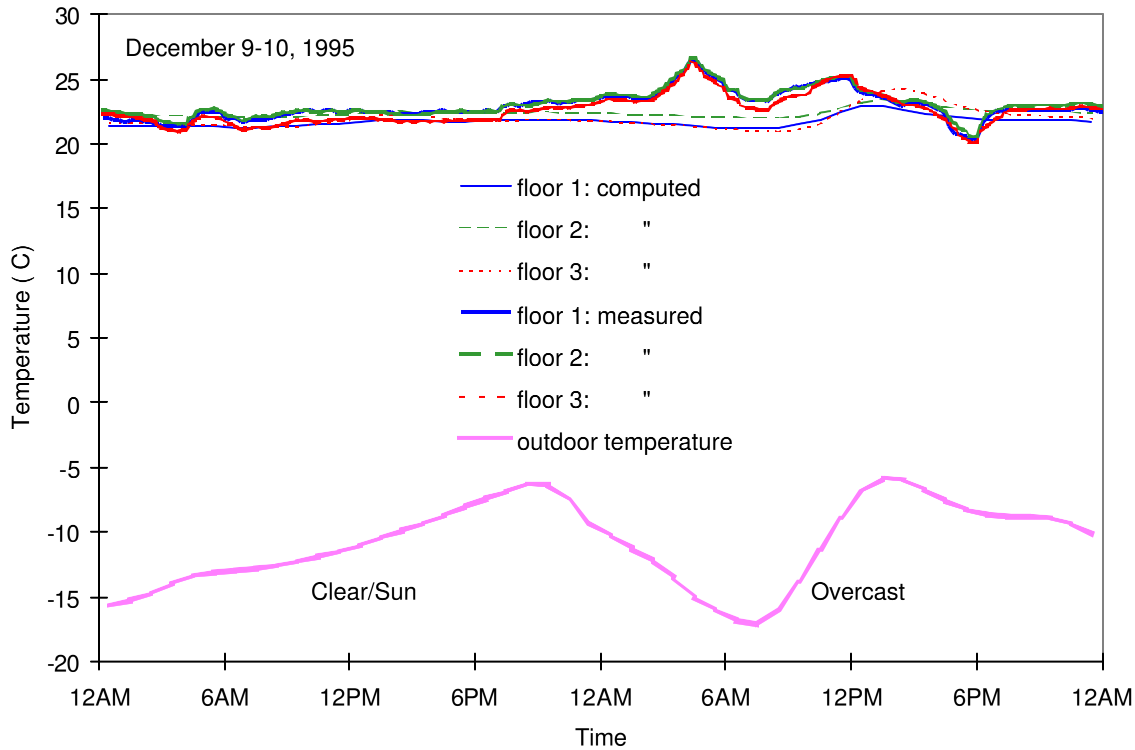

Figure 7 Comparison of measured and predicted indoor temperatures on December 9-10, 1995.

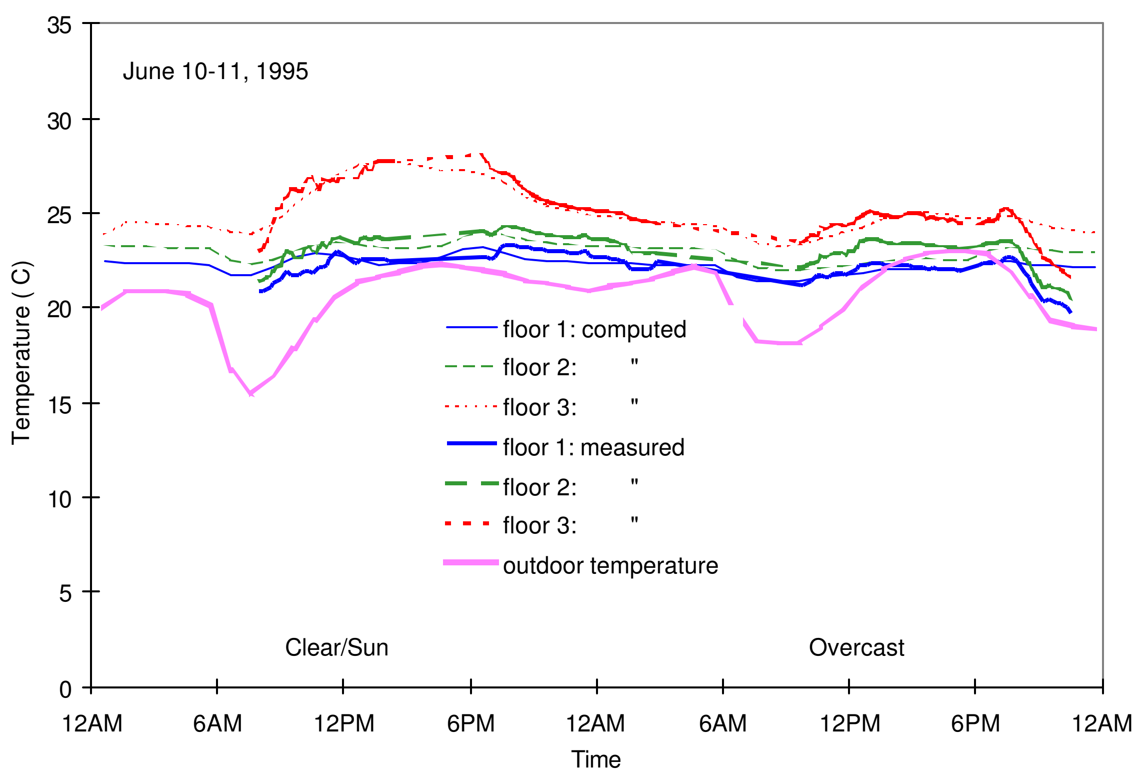

Figure 8 Comparison of measured and predicted indoor temperatures on June 10-11, 1995