Envelope and Internal Space Performance of Office Buildings in a Hot Climate

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ABSTRACT

Throughout the Kingdom of Saudi Arabia, many buildings have their envelopes constructed with little regard for the hot summer temperatures, and this causes occupant discomfort. Temperatures in offices are normally controlled using a single-zone thermostat, and this type of control limits comfort to the sun-side of the space. There also tends to be problems associated with asymmetrical radiation.

A pilot study was carried out. A room in a building was selected in which airflows and temperatures were measured. The space was then simulated using computational fluid dynamics (CFD). Once the CFD model had been validated, it was used for further analysis.

Results from the pilot study highlighted several factors contributing to the problem. Airflow and temperature measurements defined the discomfort levels, and simulations obtained from the CFD showed that modifications made to the envelope specification could improve thermal comfort over a larger area of the occupied zone.

INTRODUCTION

During recent years, a significant amount of building development has taken place throughout the Kingdom of Saudi Arabia. Unfortunately, many of the buildings have been constructed with little or no concern for their thermal response or energy conservation. The thermal response of a building is a function of a number of parameters that in physical terms may be grouped into three broad classes—climate, enclosure, and occupancy. The main climatic factors are air temperature, solar radiation, wind speed, and direction. Enclosure factors include size, orientation, geographical location, and the physical properties of the building materials (Gupta 1970). Occupancy factors include the number of occupants, duration of occupancy, and the heat emitted by their activities.

The climate in the Eastern Province of Saudi Arabia is extreme with air temperatures ranging from average values of 16ºC in winter up to a maximum value of 47ºC in summer. Typical monthly air temperatures are shown in Figure 1. Total solar radiation values are shown in Figure 2 and are shown to range from just over 500 W/m^2 in winter and up to 930 W/m^2 in summer. Variations between monthly values are often associated with local wind patterns that suspend sand and dust particles in the atmosphere and these reduce the solar radiation.

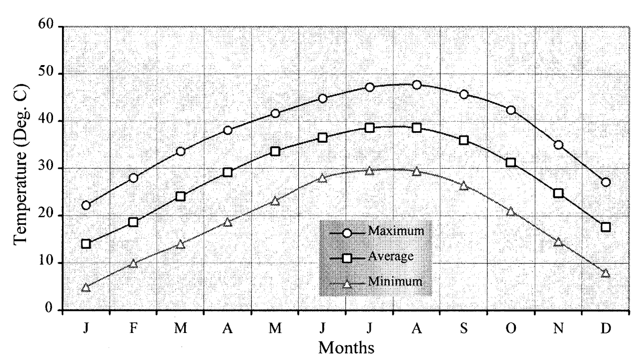

Figure 1 *Typical monthly air temperatures for the Eastern Province.*

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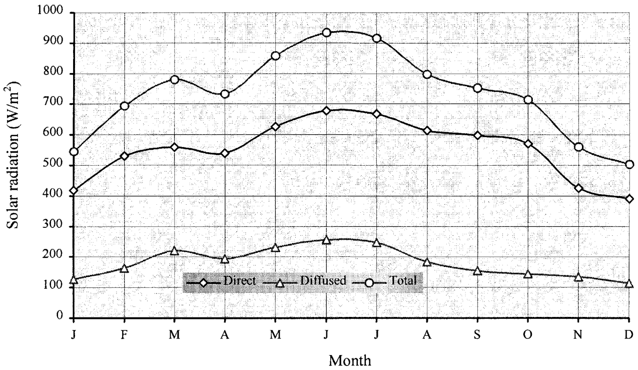

Figure 2 *Monthly total solar radiation for the Eastern Province.*

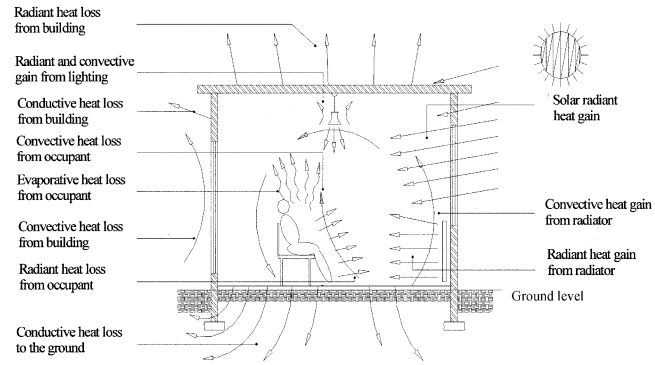

Figure 3 *Main mechanisms of heat gains and losses from a building.*

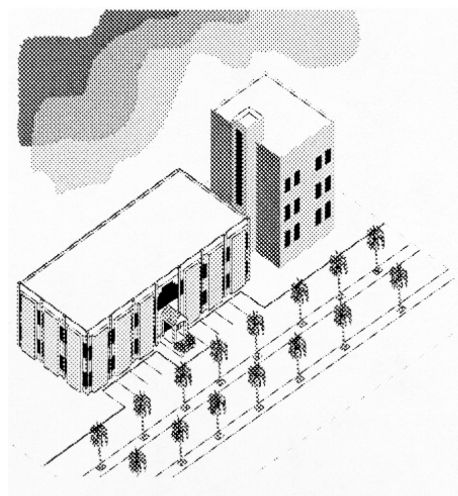

Figure 4 *Axonometric view of the building.*

Under such extreme summer temperatures and solar intensities, the ability of the building envelope to control the climate is extremely important. Many factors affect the degree of control, such as the thermo-physical properties of the envelope materials, geographical location, building dimensions, orientation, position of any insulation, window size and position, shading devices, air temperature, direct and diffuse solar radiation, and wind speed and direction. Interaction of these diverse factors causes different heat transfer processes to act on the envelope that in turn influence the internal environment of the building. The possible ways that a building can gain or loose heat under these conditions is illustrated simplistically in Figure 3, which shows the main mechanisms of heat transfer.

One of the main problems with most buildings in Saudi Arabia, is that the envelope is not designed to cope with the extreme summer climate. The hot summer outside air infiltrates into the building and increases the cooling load. The external walls also readily conduct solar gains to the inner wall surface, which then warm and radiate into the room. Most of the office buildings are also designed as open plan with the installed HVAC system controlled by a single-zone thermostat. The thermostat is generally adjusted by the room occupants to provide a comfort cooling temperature on the sun-side of the building. Under this type of zone control regime, during the hot summer months, offices tend to develop a thermal gradient across their space. The space on the sun-side of the building is mechanically cooled to provide an acceptable level of comfort, but this often tends to overcool the space on the shade-side. The comfort problem therefore appears to be twofold: thermal discomfort is caused by radiation asymmetry across a space and also by the inappropriate distribution of the mechanically cooled air to counteract solar gains on the sun-side. The problem is acute and many new office buildings remain unoccupied because they fail to provide even basic levels of thermal comfort. Thermal transfer through the roof of the building also occurs, but the shading offered by the vast array of roof-mounted cooling equipment often reduces this.

The purpose of this research was to help define some of the discomfort problems associated with the wall constructions used and to simulate other external wall constructions that might improve comfort inside the building. To do this, a typical space in an office building in the Eastern Province of Saudi Arabia was monitored over a late-summer period and the thermal performance of its envelope evaluated.

FIELD STUDY

The field trials were carried out in the Eastern Province of Saudi Arabia where a building in the city of Dammam was selected and one of its office spaces monitored. Dammam is located to the southwest of Al-Khobar and east of Dhahran at a latitude of 26.10° north and longitude 50.15° east. The office space was located in a two-story building and the longer western elevation is shown schematically in Figure 4. The first (or ground) floor was divided into small office spaces, while the second floor, shown in Figure 5, was divided into two large open spaces, typical of those found in the province.

The test room was an open space measuring 15 m by 15 m by 3 m high. It had external walls to the north, east, and west that were constructed using solid 150-mm-thick, pre-cast concrete panels rendered internally. The south wall

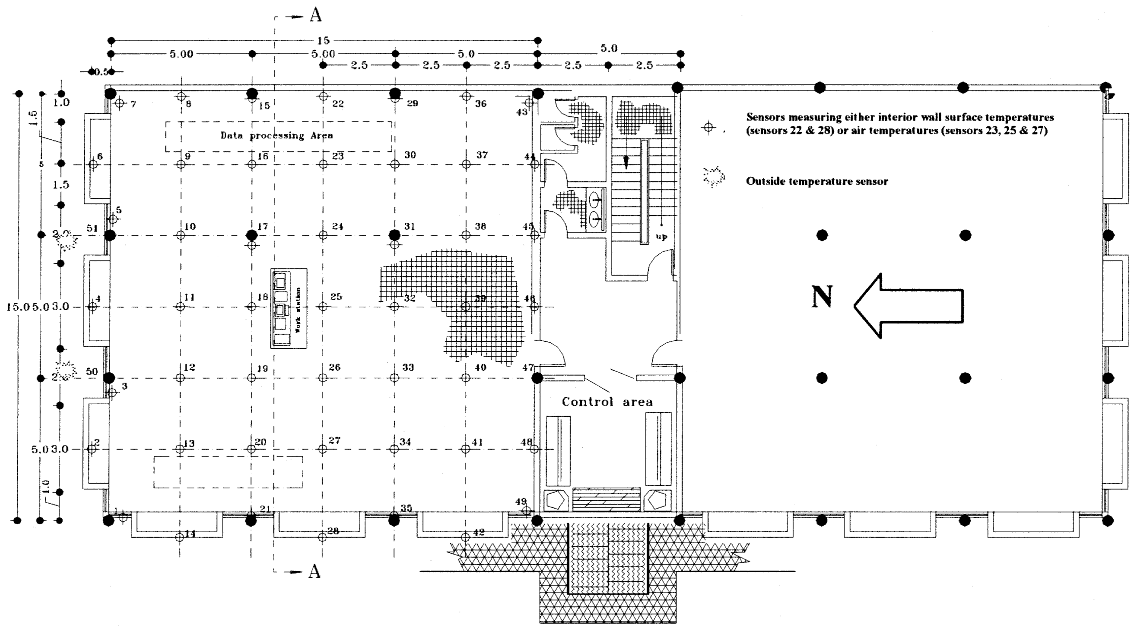

Figure 5 *Plan of test room.*

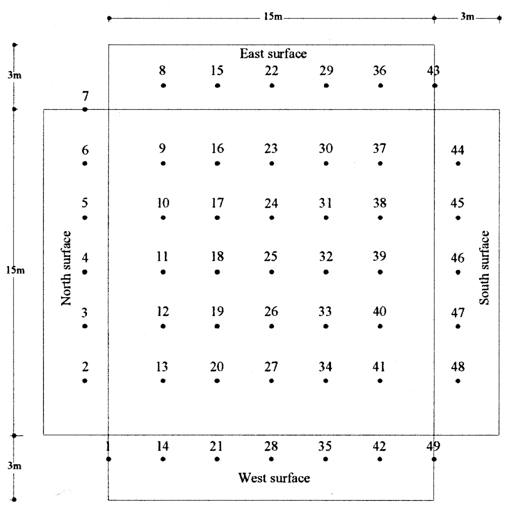

Figure 6 *Schematic showing layout of node points in the room.*

was internal and separated the space from a stairwell; it was constructed from 150 mm concrete blocks, rendered on both sides. Single-glazed windows were positioned in the west and north wall of the test room. The roof was constructed using steel girders on the underside, supporting a 150-mm-thick reinforced concrete slab topped by 100 mm of foamed concrete, 50 mm of polystyrene insulation, and a 20 mm waterproof (PVC) membrane.

The layout of the monitoring equipment is fully detailed by Al-Garny (1999) and composed of a network of 49 thermocouples at locations shown in Figure 6. The thermocouples were positioned at mid-height throughout the test room to measure either wall or air temperatures. Three globe thermometers were also installed inside the room at node points 23, 25, and 27 (see Figure 5) to measure mean radiant temperatures. Solarimeters were placed outside the building on the east, north, and west walls and orientated to measure the direct and diffuse radiation incident on the outer surface of the walls.

Installation and calibration of the equipment took place during the latter part of September and the thermal performance of the space was monitored over the following two months. The purpose was to measure the effectiveness of the envelope as a climate modifier and to compare the conditions measured in the space against those required for comfort.

FIELD STUDY RESULTS

A typical set of external air and corresponding wall surface temperature results obtained over a 24-hour monitoring period are shown in Figure 7. The outside air temperature would normally peak in early afternoon (as shown later in Figure 9) but hazy sky conditions during the monitoring period caused the rising external temperature to peak in late morning. The room data were obtained by monitoring internal wall surface temperatures on the east and west walls of the space at node points 22 and 28, respectively. During the monitoring period, normal room cooling was operational from 6 a.m. until 6 p.m. The results clearly show the rapid increase of the wall surface temperatures on both sides of the space from when the sun strikes the building in morning on the eastern wall to the delayed increase in temperatures on the western wall when the sun strikes in the afternoon.

It can be seen that wall surface temperatures on the east and west walls differ by more than 5ºC during the morning (between 9:00 and 12:00 hours) and late afternoon (between 15:00 and 17:00 hours). During these periods, uncomfortable conditions are typically experienced due to the asymmetrical radiation across the room.

A selection of corresponding room air temperatures, recorded at node points 23, 25, and 27 are shown in Figure 8. For comparison with thermal comfort, the lower and upper comfort temperatures appropriate to the region are superimposed on the figure at 25ºC and 27ºC respectively (Olgyay 1973). The data show that most parts of the room are uncomfortable most of the working day despite room cooling being operational. The increasing room temperatures toward the end of the day indicate when the room cooling was switched off.

CFD MODELING

After completing the experimental work, a model of the office space, using its actual wall, roof, and floor constructions, was generated in a commercially available CFD code (Al-Garny 1999). Before the code was used for any simulation work it was initially validated against a mathematical benchmark solution by De Vahl Davies (1983). Results from the code and mathematical solution were very close. The code was then subjected to a physical validation, and data from this showed a 2.2% mean error between measured and predicted air/surface temperature data and a 7.4% mean error between measured and predicted air velocities (Al-Garny 1999).

Once a degree of confidence had been gained in the CFD code, an additional check was made on its accuracy. Simulation modeling was performed under the climatic conditions prevailing during the collection of the experimental data. A comparison between measured and simulated data was made across all the east-west orientated grid lines shown in Figures 5 or 6. Presentation of these data has been limited to node points 8 to 14 and has been selected so that it extends the amount of data presented within the paper. Some of the data can be directly compared with data given in Figure 8, which were obtained along another grid line (node points 22 to 28). An example of the wall surface and air temperature results obtained from measurement at node points 8 to 14 is presented in Table 1 and compared against values simulated. The measured and simulated values show very close agreement as can be seen by the percentage errors given in the right-hand column of the table. A full set of results for the space is presented by Al-Garny (1999).

Once confidence had been gained in the CFD modeling, the technique was then used to simulate modifications to the envelope specification in an attempt to improve comfort conditions inside the office space.

ENVELOPE SPECIFICATION

In Saudi Arabia, the thermal performance of external walls is most critical during the morning and late afternoon when large amounts of solar radiation impinge upon them. Most commercial buildings in the country use concrete panels, concrete blocks, or clay bricks as the main wall construction. These constructions typically have a U-factor of about 1.8 W/m^2K and a time lag of between one to four hours. Wall insulation in any form is rarely used. Hollow clay bricks have recently been introduced as an external walling system and these have a better insulating capacity but lower thermal mass. Roofing systems are typically a 20 mm external waterproofing layer on top of 100 mm foamed concrete, supported by a 150 mm in-situ reinforced concrete slab. Depending upon the spans involved, the slab is often supported at intervals on steel beams that are concealed by a suspended ceiling. The construction typically has a U-factor of around 2.0 W/m^2K and a time lag of between one to two hours. Irrespective of the walling and roofing system used, mechanical cooling is always required, and while this provides a comfort temperature in some parts of the space according to the sun's location, it fails to control the problems caused by asymmetrical radiation due to internal wall temperatures.

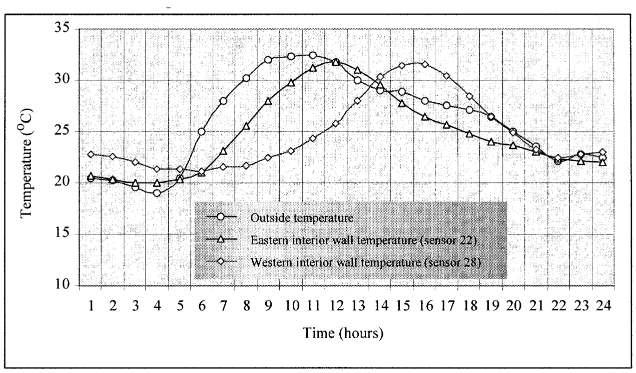

Figure 7 *Outside air temperature, east and west wall room surface temperatures.*

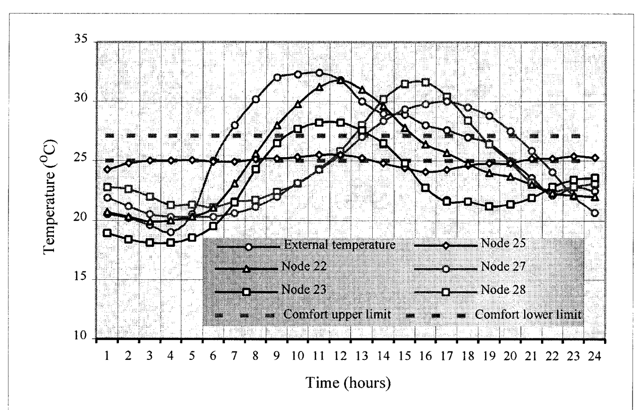

Figure 8 *Hourly variation in air temperatures across the space.*

TABLE 1
Measured and Simulated Air Temperatures

Node No.	Measured air temperature (^oC)	Simulated air temperature (^oC)	Difference (^oC)	Error (%)
8	29.2	30.1	+0.9	3.1
9	21.1	20.9	- 0.2	1.0
10	23.3	23.2	- 0.1	0.4
11	26.1	25.8	- 0.3	1.2
12	27.0	27.7	+0.7	2.6
13	29.0	29.2	+0.2	0.7
14	32.0	31.9	- 0.1	0.3

The problems caused by unsuitable external wall specifications are so acute that several investigations have been completed and reports are available by Al-Rowaished (1990), Stazi and D'orazio (1994), and Tinker and Al-Buijan (1998). Examination of the suggestions for improved external wall performance resulted in four composites being selected for use in further CFD simulations. The range of wall systems available for use in Saudi Arabia is limited. Many materials are not available locally and at present only a few wall systems are adopted for use. The systems selected are specified below, and interestingly, they all use expanded bead polystyrene insulation in some part of their thickness.

Wall 1 - 20 mm external render, 150 mm concrete blockwork with 50 mm expanded bead polystyrene protected by 10 mm internal plaster. The composite has a U-factor around 0.74 W/m^2K.

Wall 2 - 20 mm external render, 105 mm hollow clay brick with 50 mm expanded bead polystyrene and 10 mm lightweight internal plaster. The composite has a U-factor around 0.71 W/m^2K.

Wall 3 - 20 mm external render, 100 mm concrete blockwork, 50 mm expanded bead polystyrene and 100 mm concrete blockwork inner layer, 10 mm plaster internally. The composite has a U-factor around 0.64 W/m^2K.

Wall 4 - 20 mm external render protecting 50 mm expanded bead polystyrene, 100 mm concrete blockwork, 30 mm air cavity, 100 mm concrete blockwork inner layer with 10 mm internal plaster. The composite has a U-factor around 0.56 W/m^2K.

Having considered the importance of controlling thermal transfer through the walls of office buildings in Saudi Arabia, the following roof systems have been suggested by several authorities due to their simplicity and good thermal mass performance. Unfortunately, no law makes their use obligatory and they are presented for information only. Their U-factors depend upon the density of the materials actually used but typically range from 0.80 to 2.00 W/m^2K. Time lags are in the order of one to three hours.

Roof 1 - 20 mm waterproof membrane externally, 50 mm expanded bead polystyrene, 70 mm screed, 200 mm structural concrete slab, and 10 mm plaster to the ceiling internally.

Roof 2 - 20 mm waterproof membrane externally, 50 mm expanded bead polystyrene, 70 mm screed, 250 mm lightweight concrete structural slab, and 10 mm plaster to the ceiling internally.

Roof 3 - 20 mm waterproof membrane externally, 50 mm expanded bead polystyrene, 70 mm screed, 250 mm hollow-core concrete blocks supported between structural concrete beams, and 10 mm plaster to the ceiling internally.

WALL SYSTEM SIMULATION

On-site monitoring in the office space highlighted the problem of high wall surface temperatures and consequent radiant transfer from the inner surfaces of exterior walls. CFD simulations were completed using the original roof specification with each of the above four wall types to predict the internal wall surface temperatures each system would reach under the same climatic conditions. The external thermal climatic loads used in all the simulations were those of the hottest period (August) where external air temperatures can reach a maximum of 47°C and direct radiation intensities reach 620 W/m^2 (total radiation values of 800 W/m^2).

The simulated data are given in Figure 9 and have been limited to the eastern wall due to space restrictions in the paper. The temperatures presented are the spatial average of those simulated and show that some of the wall constructions have an improved thermal performance over that obtained from the walls of the test room even though a more extreme external load was applied in the simulation. Improved U-factors and slightly improved time lags reduced surface wall temperatures, and it can be seen that Wall 4 gave the best results, having a maximum surface temperature of 29ºC. This is close to the upper comfort limit temperature of 27ºC.

The results from the pilot study confirmed that any external wall should be constructed from materials that have adequate thermal resistance to reduce external heat transfer. The contribution that any increased thermal capacity may have had on the results needs to be investigated. The system designated as Wall 4 was shown to keep the internal-surface wall temperatures reasonable and was composed of a layer of protected external insulation and two layers of concrete blockwork separated by an air cavity and plastered internally. This configuration gave the least heat transfer under the local climatic conditions. Although the wall temperatures were reduced to minimize asymmetrical radiation problems, the room air temperatures remained above comfort levels in some areas despite the room cooling being operational during the simulation. Air temperature contour maps are given in Figures 10a and 10b where the darker shaded central areas define parts of the room where comfort temperatures are provided. Figure 10a shows areas of comfort provision provided in the original test room under mechanical cooling, and Figure 10b shows the slightly extended area of comfort provision when using Wall 4. In both figures, the top of the contour map represents the north wall of the simulated space.

The glazing system installed in the building used for the pilot study was composed of 6 mm single-sheet clear glass. Clearly such a system transfers significant amounts of solar energy through the window areas. This has been reported separately by Tinker and Al-Buijan (1998).

The CFD analysis clearly shows that under existing air distribution techniques, areas of discomfort still exist even though wall surface temperatures and consequently asymmetrical radiation has been reduced. The next stage of the research is to investigate different ways of distributing cooled air into the space to maximize the comfort area.

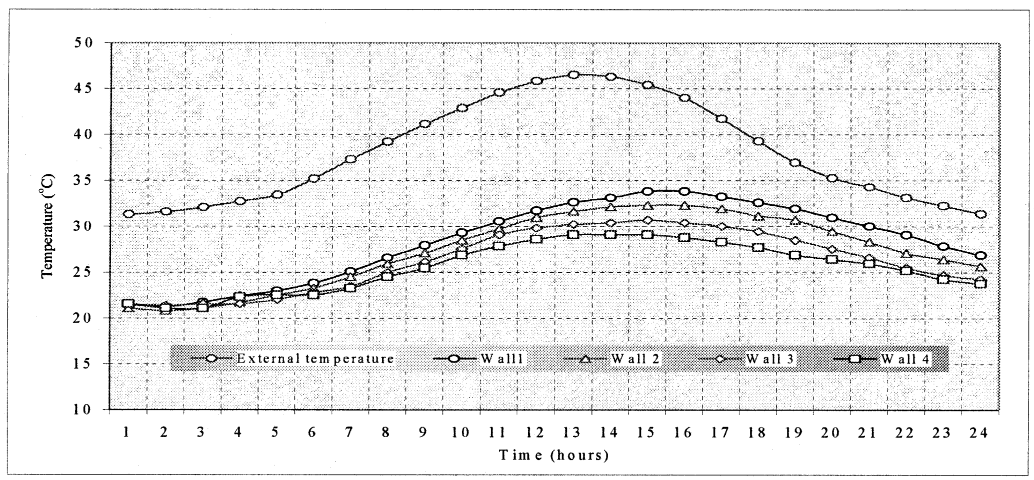

Figure 9 *Simulated temperatures on the inner surface of the east wall.*

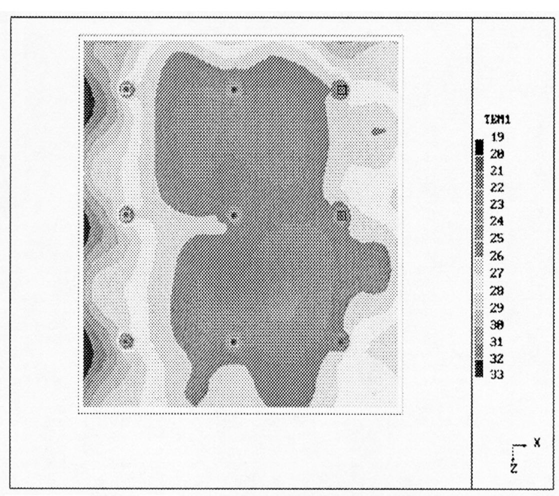

Figure 10a *Air temperature contours at mid-height in the test room.*

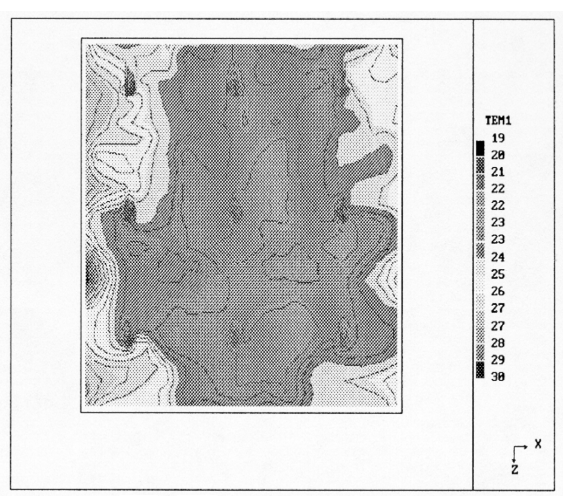

Figure 10b *Air temperature at mid-height using wall.*

CONCLUSIONS

- Measurements showed that existing envelope designs do not adequately control inner wall surface temperatures in office spaces in the Kingdom of Saudi Arabia and that this can result in discomfort by radiation.
- A CFD code was used to simulate wall surface temperatures and air temperatures in an office space. The results simulated by the code showed close agreement with those measured experimentally.
- Results from CFD analysis showed that interior wall surface temperatures could be reduced by using wall systems that included insulation in their thickness. Best results were obtained when the insulation was placed toward the outside of the construction as specified under the Wall 4 configuration. Reduced wall temperatures also helped to reduce asymmetrical radiation problems. Results further showed that despite using insulation in the walls, air temperatures in the office space would remain above comfort levels.
- The work also showed that existing single-zone thermostatic control for distributing cooled air into such spaces does not provide adequate thermal comfort across the space.

REFERENCES

Al-Garny, A. 1999. Using CFD to investigate air flow distribution to improve thermal comfort. Ph.D. thesis, School of civil Engineering, University of Leeds, U.K.

Al-Rowaished, A. 1990. Climatic influences on educational buildings in hot dry climate of Saudi Arabia. Ph.D. thesis, Department of Architecture, University of Queensland, Australia.

De Vahl Davis, 1983. Natural convection of air in a square cavity. A benchmark solution. *Int.Jnl. for Numerical Methods in Fluids* 3:249-264. Kensington: University of New South Wales.

Gupta, C.L. 1970. Heat transfer in buildings, A review. *Architectural Science Review*, Vol 1.

Olgyay, A. 1973. *Design with climatic, bio-climatic approach to regional architecture*. New York: Princeton University Press.

Stazi, A., and M. D'orazio. 1994. Hygrotermic quality evaluation of different types of building external walls. *International Conference on Building Envelope Systems and Technology*, Proceedings, pp. 420-424, Singapore.

Tinker, J.A., and K. Buijan. 1998. Thermal performance of fenestration systems in the hot climate of Saudi Arabia. *Thermal performance of the exterior envelopes of buildings VII*, pp. 311-318. American Society of Heating, Refrigerating and Air-Conditioning Engineers.