The Design, Simulation, and Operation of a Comfortable Indoor Climate for a Standard Office

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ABSTRACT

Building operation strategies can greatly affect occupant comfort and energy use, and building simulation tools can provide the system designer with detailed information about the dynamic behavior of the building. With this information, the designer can then optimize the capacity and operating schedules of the HVAC system to take advantage of the thermal interactions of the building.

The prediction of human comfort is an area in which extensive research has been carried out and requires calculation of various factors in the occupied zone.

An analysis of the thermal environment requires a complete solution to the equations representing air movement and thermal response of the room under dynamic conditions.

Using a dynamic simulation computer program, various configurations were simulated that resulted in an optimum design being achieved based upon comfort conditions, not temperatures.

This paper shows how different fabric construction, glass types, sun shading, and air-conditioning systems were simulated, resulting in an optimal design and operating strategy for a comfortable indoor climate throughout a year.

INTRODUCTION

The most important function of a building is to provide a comfortable indoor climate that is achieved as economically as possible.

Extensive investigations and experiments involving numerous subjects have resulted in methods for predicting the degree of thermal discomfort of people exposed to an environment. The most well-known and widely accepted methods are Fanger's "comfort equation" and his "predicted mean vote" and "predicted percentage of dissatisfied" (Fanger 1972). With these methods, several thermal comfort standards (e.g., ASHRAE 1981; ISO 1984; Jokl 1987) have been established during the past decade. These standards specify environmental parameter ranges (i.e., comfort zones) in which a large percentage of occupants (generally at least 80%) regard the environment as acceptable. Most work related to thermal comfort has concentrated on steady-state conditions. Only one of the above standards (ASHRAE 1981) also specifies limits for changing environmental parameters.

Fanger (1972) deduced a "thermal index" that could express a subject's thermal sensation in a climate deviating from the optimum. Fanger assumed that thermal sensation is a function of the thermal load of the body. The predictive mean vote (PMV) index can be determined when the activity (metabolic rate) and clothing (thermal resistance) are estimated and the following environmental parameters are defined: air temperature, mean radiant temperature (MRT), relative air velocity, and partial water vapor pressure. The PMV index is based on a thermal load and is defined as the difference between internal heat production and heat loss to the actual environment for a person with (theoretical) mean skin temperature and sweat secretion at an actual activity level.

Fanger quantified the relationship from the results of experiments in which people were asked to cast a "thermal sensation" vote. The PMV scale is, perhaps, a little difficult to interpret. People are not identical, so in reality a group of people would report a varying range of thermal sensations. The PMV indicates the most probable sensation from the thermal load conditions. Thus, the PMV gives a general indication of the level of comfort (i.e., thermal sensation) but contains no indication of the range of comfort actually experienced.

The predicted percentage of dissatisfied (PPD) index establishes a quantitative prediction of the number of thermally dissatisfied persons who have voted on a seven-point comfort sensation scale, i.e., hot (+3), warm (+2), cool (-2), or cold (-3).

The PPD scale provides an indication of the range of comfort experienced in reality due to individual differences. The relationship between PPD and PMV was deduced by Fanger. The PPD indicates the percentage of people who, when asked the question, "How comfortable are you?" would say, "I feel too warm" or "I feel too cold."

It is impossible to satisfy all persons in a large group in the same climate. Even with a perfect environmental system, a PPD of less than 5% is rarely attainable (a point often overlooked in practice, where any complaints, however few, are taken as an indication that the system is defective or badly operated).

If the thermal field is uniform, the PMV will be the same for all of the occupied zone, and by changing the temperature level, a PMV of zero can be obtained. This is the only way the minimum PPD of 5% can be achieved for

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a whole zone. If the thermal field is not uniform in the occupied zone, changing the temperature level makes it still possible to achieve an average of zero PMV, but the PPD will be higher than its minimum value of 5%.

This research shows the results of replacing conventional control constraints with comfort constraints (PMV ± 0.5). The application of replacing dry-bulb, resultant, or environmental temperatures with the six variables included in the PMV calculation is shown. Also shown are the fluctuations of the PMV (within limits) and how this will be tolerated by the occupant or occupants and under which circumstances these fluctuations will take place. Simulation techniques are used to determine control strategies. These control strategies are then optimized to minimize the operating cost (i.e., energy and demand changes) while controlling the HVAC system to meet comfort criteria in the occupied zones.

BACKGROUND OF DESIGN METHODS

Because of an increasingly competitive and technologically advancing building industry serving ever more demanding clients, the design function is becoming more complex. Building environmental performance is now critically assessed, and the capital and running costs of the services necessary to provide the required environmental conditions come under careful scrutiny. The analytical tools in common use in the building industry have not kept abreast of the needs of today's design professional. Although more comprehensive and appropriate methods of analysis have been in existence for many years in the academic and research communities, they have been slow to emerge as commonly used design tools for commercial office space.

The purpose of most of today's calculations is to determine the correct heating and cooling capacities for a room so that a required room temperature can be realized at a given outdoor climate (design condition). The heat loss or gain through the room envelope and the losses by infiltration and ventilation are calculated by methods based on a steady-state model.

The optimum with respect to energy use depends on many variables, including economic and environmental impact issues. Because a building and its plant are an integrated dynamic system, it is difficult to establish an optimum for any objective function influenced by this dynamic behavior. Optimization of part of a system "never" yields the optimum for the system as a whole! So in order to establish optimum energy use, we first need to be able to approach the overall system integrally.

These problems have to do with insufficient capacity in certain circumstances. Two factors play a role. The first factor is the increased degree of insulation, used as a result of the energy crisis and subsequent higher prices, which also leads to increased airtightness of buildings. This results in a lower specific heat capacity of the installation, which considerably increases the need for accuracy in the calculation method and its correction factors. Typically, internal gains are on the order of 30 to 45 W/m^2. For an average working space of 10 m^2 per person, that is the equivalent of around 400 W. A large percentage of these internal gains (between 60% and 70%) is in the form of electromagnetic radiation and is absorbed directly by internal surfaces prior to being convected to the air space. Heating is not always necessary. With a well-insulated building envelope, the internal heat production is enough to heat the office even when the outside air temperature is -5°C. Heating will only be necessary when the outside air temperature is lower than -5°C and when the office is unoccupied. Dynamic phenomena, such as the warming up of the building after an interruption in the heating, are much more critical because of overcapacity. In an absolute sense, this necessitates an accurate simulation of the heat exchange process. All physical phenomena have to be calculated precisely to obtain the required accuracy. The main factor involved is the occupants' demand for a high-quality indoor climate. The thermal comfort in a room must be considered at all times.

A person's thermal sensation is related to the thermal balance of the body as a whole. This balance is influenced by physical activity and clothing, as well as by environmental parameters, such as air temperature, mean radiant temperature, air velocity, and air humidity. When these factors have been estimated, the thermal sensation for the body as a whole can be predicted by calculating the predicted mean vote.

ASSESSING THERMAL COMFORT

Thermal comfort is generally defined as that condition of mind which expresses satisfaction with the thermal environment. Dissatisfaction may be caused by the body as a whole being too warm or cold or by unwanted heating or cooling of a particular part of the body (local discomfort).

From earlier research (Fanger 1972; McIntyre 1980; Gagge 1986), we know that thermal comfort is strongly related to the thermal balance of the body. This balance is influenced by

- environmental parameters, such as air temperature (θ), mean radiant temperature (MRT), relative air velocity (v), and relative humidity (RH), and
- individual parameters, such as activity level or metabolic rate (M) and clothing thermal resistance (I clo).

Limitations of Comfort Predictions

Fanger's comfort equation is empirical and is based upon statistical data gathered in working environments. Consequently, care is necessary in interpreting comfort results in a space that is not essentially a workplace (for example, a shopping mall or leisure complex). The main characteristics of a work environment are as follows:

- Occupants are in the space for continuous long periods.
- People are at work, not at leisure.
- The minimum clothing level is generally higher in a working environment (i.e., on the hottest day, persons at leisure wearing shorts and a T-shirt would probably wear a light suit if they were at work). These characteristics mean that the level of comfort expected in a working environment is probably higher than the level of comfort expected in a leisure environment. So, when analyzing a space that is not a workspace, the comfort results will probably be pessimistic; that is, people will feel less satisfied with an environment if it is their workplace rather than a place of leisure because they will tend to judge the environment more severely.

For a global analysis, the model carries out an analysis of the radiant field at each point of analysis in the occupied zone. A person is assumed to exist at each point and a heat balance can be established at the surface of the person. Angle factors are used to evaluate the surface/subjects radiant exchange.

At this stage only, long-wave radiation from normal low-temperature surroundings has been considered (where radiant exchange is dependent on the temperature of the surroundings). However, short-wave solar radiation can have a significant effect upon the MRT (as radiant exchange with the surroundings is independent of the temperature of the surroundings due to the high radiant source temperature). The effects are considered using the theory developed by Fanger. The path of sunlight is tracked in the space and modifies the MRT (at each hour) to include the effect of direct solar radiation if the point of analysis is not shaded.

COMPLEXITIES OF DYNAMIC BUILDING LOAD CALCULATIONS

Dynamic thermal interactions—under the influence of occupant behavior and ambient conditions—between a building and its systems are still difficult to predict, and several causes influence the results. In practical terms, this often results in non-optimal building/system integration. Until recently it was often thought that ambient conditions and solar radiation largely influenced the calculation results. But this investigation will show that the internal loads are the primary influence on building/system interaction. However, the corresponding architectural design of a building can still influence building loads considerably. Temperature effects (swing) can be influenced by building constructional design.

The following sources act upon the indoor climate via various heat and mass transfer processes:

- Conduction through the building envelope and partition walls.
- Radiation in the form of solar transmission through transparent parts of the building envelope and in the form of long-wave radiative exchange between surfaces.
- Convection, causing heat exchange between surfaces and air.
- Air infiltration through the building envelope, inside the building, and within the installations.

The configuration of perimeter walls and the percentage and type of glazing in the external and internal walls are very important. Usually the glazing is a weak point for both heating and cooling loads, and special attention must be paid to its structural design. U-value, transparency, and reflectance features have considerable effects on dynamic building loads.

Architectural Design and Thermal Insulation

The heat losses or gains of a building generally take place at the borders between the indoor and outdoor climates, i.e., the building shell, which consists of the outside walls and glass areas, the roof, and the floor. To keep these resulting heat losses at a minimum, it is necessary to keep the borders to a minimum, which requires a unique building that has a low Ao/v relationship, which is the relationship between the heat-exchanging encasing area Ao (the shell) and the enclosed volume v (the gross volume). Next to minimizing the outside area and form of the building, thermal insulation is one of the most important factors for keeping energy use at a minimum. The thermal transmittance value is a function of the relationship between the encasing area and the gross volume (the Ao/v relationship) of the building and the thermal insulation index, the IT value, which is calculated as follows:

$$IT = \frac{80 \cdot (Ao/v) \cdot (1-u)+30}{4 \cdot (Ao/v)+1} \tag{1}$$

where

Ao = the encasing area of the building (the shell),
v = the enclosed volume (the gross volume),
u = the average thermal transmittance value of the building envelope ($W/m^2 \cdot K$).

In this manner, the defined IT index can be used to show the quality of a building's thermal insulation. The thermal insulation index for a well-insulated building must be at least 12. Energy-saving buildings must attain a value of at least 14. The minimum IT values for different countries are shown in Figure 1, and Table 1 shows the IT values for the different building configurations used for this comparison.

Climate windows are double-glass windows complemented by a third layer on the inside. Air is extracted from the room via the opening between the second and third layer of glass. Solar heat, which then enters the window, is

TABLE 1
Building Configurations Used for the Comparison

		CBM	FGDP	Schiphol P4	Chipshol
ROOM DIMENSIONS					
total floor area		25000 m2	2 x 8000 m2	65000 m2	10000 m2
length		5,4	5,4	5,4	5,4
width		3,6	3,6	3,6	3,6
height		3,6	3,6	3,6	3,6
lowered ceiling height		2,7	2,7	2,7	2,7
ORIENTATION					
window orientation		south	south	south	south
OCCUPATION					
occupants per room		2	2	2	2
occupancy period		8:00 to 18:00	8:00 to 18:00	8:00 to 18:00	8:00 to 18:00
INTERNAL LOADS					
lighting	[W/m2]	8	15	9	15
occupants	[W/m2]	8	10	8	10
equipment	[W/m2]	10	7	18	20
total	[W/m2]	26	32	35	45
CONSTRUCTION					
exterior wall	inside	concrete 200 mm	concrete 200 mm	concrete 200 mm	concrete 230 mm
		min. wool 50 mm	insulation 100 mm	min. wool 70 mm	min. wool 50 mm
		cavity 50 mm	concrete 100 mm	cavity 40 mm	cavity 250 mm
	outside	concrete 100 mm		steel plate 2 mm	concrete 150 mm
K-value	[W/m2.K]	0,51	0,35	0,44	0,5
roof		screed 20 mm	screed 20 mm	screed 20 mm	screed 20 mm
		insulation 80 mm	insulation 80 mm	insulation 80 mm	insulation 80 mm
		concrete 220 mm	concrete 250 mm	concrete 220 mm	concrete 200 mm
K-value	[W/m2.K]	0,4	0,4	0,4	0,4
floor/lowered ceiling		carpet 5 mm	carpet 5 mm	carpet 5 mm	carpet 5 mm
		concrete 220 mm	concrete 220 mm	concrete 220 mm	concrete 200 mm
		cavity 660 mm	cavity 660 mm	cavity 660 mm	cavity 700 mm
		tiles 10 mm	tiles 10 mm	tiles 10 mm	tiles 10 mm
K-value	[W/m2.K]	1,71	1,71	1,71	1,71
GLAZING					
glazing percentage		32%	28%	43%	36%
type		climate window	Reversol silver	climate window	IPN
K-value with vent.		1,54	-	1,85	-
K-value without vent.		2,02	3,3	1,9	1,7
solar transmission		19%	37%	15%	28%
light transmission		32%	27%	32%	25%
HEATING/VENTILATION					
infiltration [a.c./h]		0,5	0,5	0,5	0,5
mechanical vent. [a.c./h		2	2	2,5	2,5
supply air temp. summe		17	17	17	17
supply air temp. winter		20	20	20	20
type of heating		air	radiator	air	radiator
secondary cooling		VHV unit	VHV unit	VHV unit	VHV unit
IT value		17	16	18	17

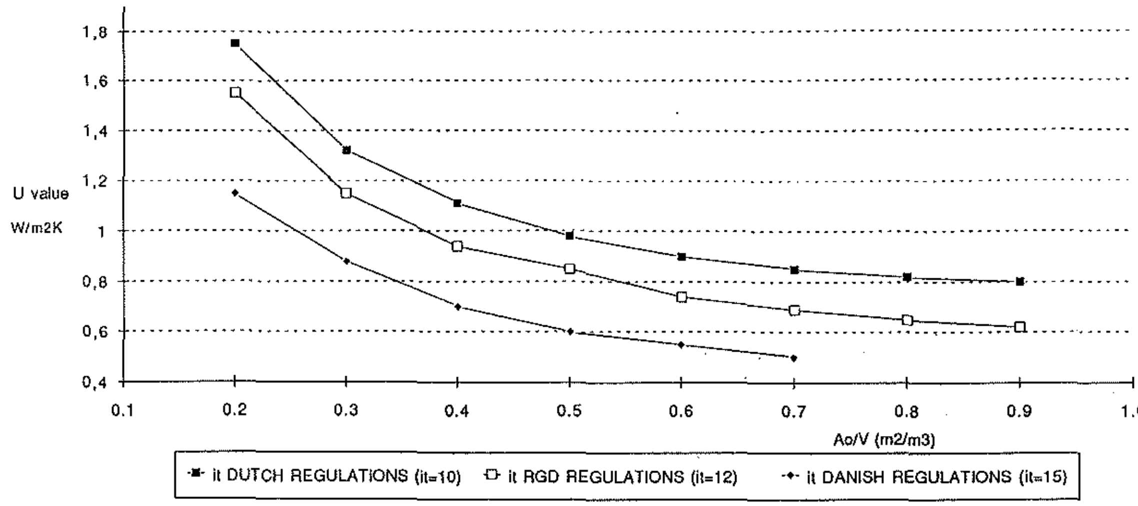

Figure 1 IT *Value in relation to* U *and* Ao/V.

directly absorbed by the extract air and does not enter the room. The advantage of this system is that the temperature of the inside glass has nearly the same temperature as the room summer and winter, which greatly improves the comfort levels in the room. As the solar heat is absorbed by this extract air, it provides energy for heat exchange equipment in the air-handling unit. During the summer, this air is directly extracted from the building.

SIMULATION TOOLS

The use of simulation tools is becoming common practice. Simplified peak load methods (such as UAΔT for heating and the CLTD/CLF method for cooling) are typically used for design (sizing) calculations. These methods, by their nature, limit the range of conditions that can be analyzed for optimum sizing. Simulation tools traditionally have been used for energy analyses, that is, for the determination of annual energy consumption for a typical year, but they can also be used for design calculations if properly applied.

The only differences between a peak-load sizing calculation and an annual energy analysis are the assumptions made concerning the outside environment and the internal operation of the building—the heat transfer principles are the same. A simulation that is valid for off-peak conditions will also be valid for peak conditions.

The benefit of using a dynamic simulation tool is that complex peak conditions can be modeled that would not be possible with traditional design methods. In order to give the designer a complete picture of a building's thermal characteristics, a simulation tool must sufficiently model the dynamic effects of the building and mechanical systems. An hour-by-hour simulation program that uses a heat balance method is a minimum requirement in order to simulate dynamic effects. The program must be capable of dealing with varying space temperatures and must handle the transient thermal mass effects properly. In addition, the tool must account for all the obvious environmental factors and internal loads.

The weather data required to estimate the performance of the plant and building are the ambient dry-bulb temperature, ambient humidity ratio, and the solar radiation. It is also necessary to evaluate the incident radiation on exterior building surfaces, which requires knowledge of components of both beam and diffuse radiation along with surface orientation and ground reflectance properties. In order to study the effect of weather on dynamic comfort control in a systematic manner, the approach utilized in this study was to generate diurnal variations with statistical correlations in terms of average daily weather variables. A weather generator was used to produce diurnal variations in ambient dry-bulb, wet-bulb, and solar radiation based upon daily statistics. The advantages of this approach over the use of a standard reference year is that it allows for systematic parametric studies of the effects of weather on dynamic comfort control in terms of simple statistical parameters. The variables that characterize the diurnal variations in ambient temperature, humidity, and solar radiation are the daily average temperature and solar turbidity.

MODELING

Plant

Various plant configurations could have been modeled. During the last few years, however, a specific plant configuration has emerged that can provide and optimally control a comfortable indoor climate.

This system, shown in Figure 2, consists of a central air-handling unit that provides two changes of ventilation air per hour (ach) at 16°C during the summer and 20°C during the winter. The humidification of the supply air varies between 30% and 70%. This air is supplied to the rooms by

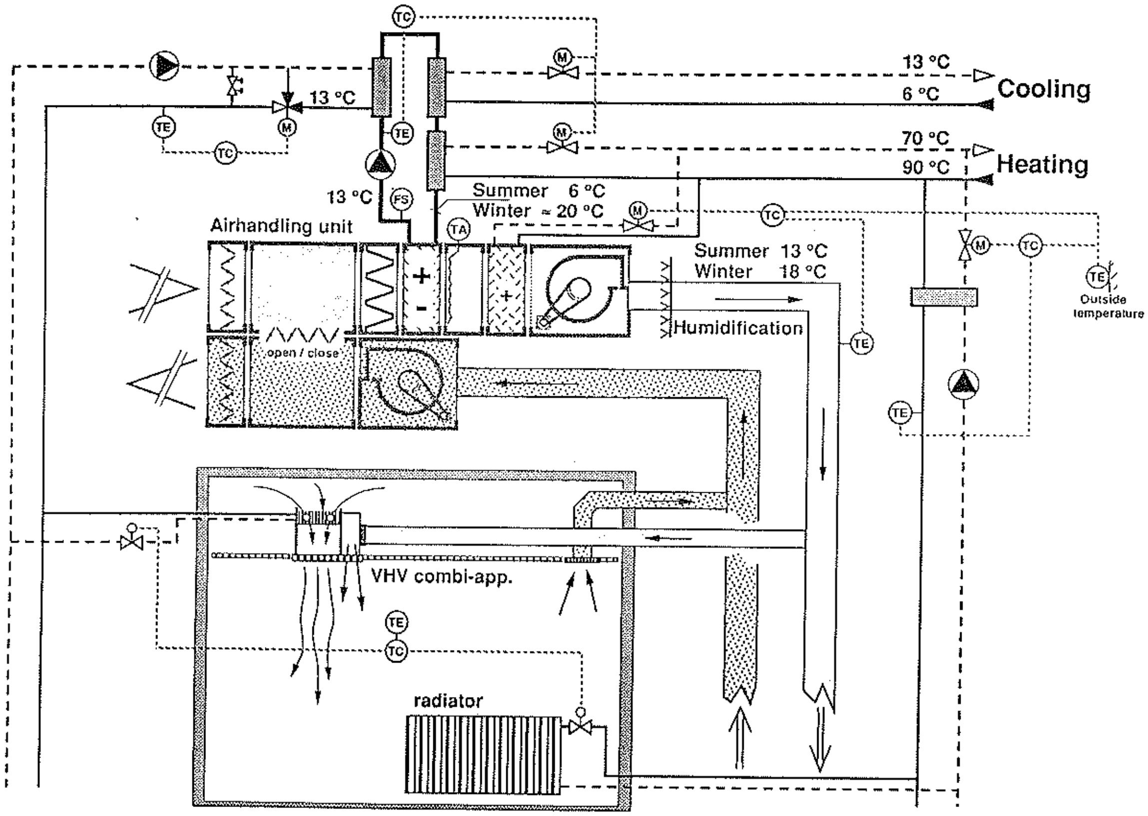

Figure 2 *Schematic free cooling.*

means of slot diffusers mounted in the lowered ceiling at a distance of about 1 meter from the outside wall. These slot diffusers can also be installed next to the VHV units as one complete unit in the lowered ceiling.

Secondary air circulation is driven by the VHV unit mounted in the lowered ceiling (see Figure 3). Warm air rises and is collected above the lowered ceiling. This air is then cooled by the VHV unit and enters into the room where its physical properties circulate the air further through the room.

The amount of secondary circulation is dependant upon the temperature differential between the air temperature in the lowered ceiling and the temperature of the VHV unit. A rule-based control strategy has been developed that provides an optimal control of the complete plant. The indoor climate may also be controlled by the occupants basically via two mechanisms:

- altering the building envelope or inner partition by, for example, opening doors, windows, or vents, or by closing curtains, lowering blinds, etc.;
- scheduling or adjusting the setpoint of some controller device that may act upon the building by automating tasks.

Thermal Comfort Simulation

The prediction of the comfort level requires calculation of the following factors at a required location in the occupied zone:

- dry-bulb air temperature,
- radiant temperature,
- air speed,
- vapor pressure.

Such analysis of the thermal environment requires a complete solution to the equations representing air movement and thermal response of the building fabric under non-steady-state conditions.

Heat is transferred by conduction, convection, and radiation, each of which must be considered separately. The calculation of radiation from factors is essential to the assessment of radiant heat flow; these are calculated for the space. Conduction through the enclosure surfaces is calculated dynamically, with time steps adjusted by the model.

The model takes account of the spatial arrangement of the surface and the way each surface affects others. This makes it possible for the sunlight falling on each surface to be treated separately. The model also takes into account the effects of humidity and room temperature on the heat given off by occupants as well as the level of activity.

DESIGN APPROACH

The system design approach presented here utilizes an hour-by-hour simulation tool as the basic calculation procedure. This approach has been applied repeatedly with much success and has proved its worth in practice. The

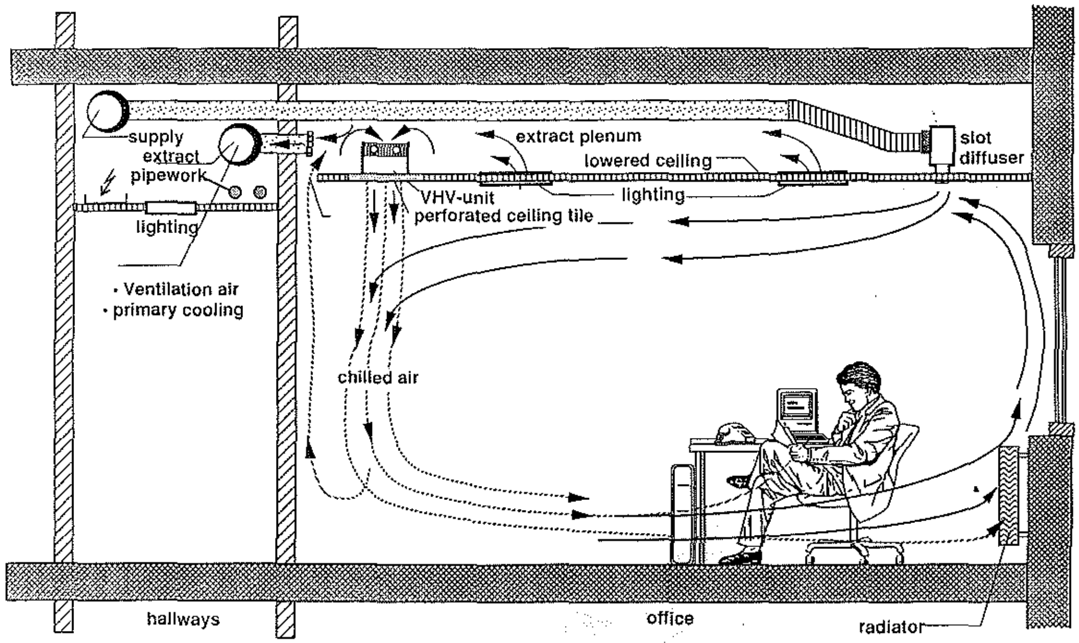

Figure 3 *Climate control for offices, VHV system.*

discussion here will concentrate on the determination and operation of the heating and cooling systems for comfort control of a space in a building.

The basic principle is to eliminate all load peaks as much as possible.

The ideal is a system that operates at a constant load near the peak capacity of the equipment, which will minimize the peak energy demand and the amount of less efficient part-load operation.

Naturally, this ideal goal will not be fully achieved, but for many applications, especially in high mass buildings, the design can approach the goal. The design procedure involves several passes in which various scenarios are simulated. This method of iteration allows all influences to be included.

The analyses start with simple calculations of fabric element performance (thermal properties, condensation), shading, and solar gain calculations for windows and then progress to thermal calculations of rooms and complete buildings. Further data can then added so that complete comfort simulations can be carried out under dynamic conditions.

Four different building configurations were investigated (Table 1). These are actual design studies, and, as the table shows, each building has a different configuration. All the buildings are situated in the Netherlands. The room or rooms being simulated had a standard floor dimension of 3.6 by 5.4 (19.4 m^2) and had a lowered ceiling 2.7 m above the floor. The variations in the building construction had little effect on the results; however, the type of glazing and internal loads did influence the results. To expand the results even more, it was decided to change the room dimensions and to investigate the influence of a roof on these rooms (see Table 2). One of the variations simulated was a 960 m^2 open plan office to investigate any differences between the results achieved for the 19.4 m^2 offices. The various configurations are shown in Tables 1 and 2.

RESULTS

Glazing

The following glazing and climate window configurations were analyzed and compared to each other:

1. double-blank glass with internal horizontal blinds,
2. double reflective glass with internal horizontal blinds,
3. climate windows with integrated horizontal blinds.

The analysis took place under the same solar and ambient conditions for two months:

January — minimum outside air temperature, -11°C;
— solar intensity on the vertical north-orientated surface, 54 W/m^2;
— solar intensity on the vertical south-orientated surface, 551 W/m^2.

July — maximum outside air temperature, 32°C;
— solar intensity on the vertical south-orientated surface, 650 W/m^2.

Figures 4 and 5 show the amount of solar intensities that are transmitted into the rooms for January and July.

Figures 6, 7, and 8 show the inside surface temperature of the glazing for January's south and north orientation and July's south orientation.

TABLE 2
Basic Assumptions for the Simulation

Variant		1	2	3	4	5	6	7
Computer code		KLM54	KLM54R	KLM72	KLM54D	KLMK	KLM72D	KLMVER
Dimensions								
width x length		3,5x5,25	3,5x5,25	3,5x7,05	3,5x5,25	14,1x7,05	3,5x7,05	14,1x68
Lowered ceiling height		2,7	2,7	2,7	2,7	2,7	2,7	2,7
Orientation	[º]	240	240	240	240	150	240	150
Occupants		2	2	2	2	10	2	100
Internal load								
lighting	[W/m2]	14	14	14	14	14	14	14
occupants	[W/m2]	8	8	8	8	8	8	8
equipment	[W/m2]	23	23	23	23	23	23	23
total	[W/m2]	45	45	45	45	45	45	45
Exterior wall construction								
concrete	[mm]	200	200	200	200	200	200	200
insulation	[mm]	80	80	80	80	80	80	80
cavity	[mm]	50	50	50	50	50	50	50
platework	[mm]	2	2	2	2	2	2	2
K-value	[W/m2.K]	0,44	0,44	0,44	0,44	0,44	0,44	0,44
Roof construction								
concrete/aerated concrete slab	[mm]				450		450	
insulation	[mm]				80		80	
felt/bitumen layer	[mm]				5		5	
K-value	[W/m2.K]				0,5		0,5	
Floor/ceiling construction								
carpet	[mm]	5	5	5	5	5	5	5
concrete/aerated concrete slab	[mm]	450	450	450	450	450	450	450
cavity	[mm]	660	660	660	660	660	660	660
tiles	[mm]	10	10	10	10	10	10	10
K-value	[W/m2.K]	1,71	1,71	1,71	1,71	1,71	1,71	1,71
Window construction								
height	[m]	1,8	2,4	1,8	1,8	1,8	1,8	1,8/2,4
type		climate window	climate window	climate window	climate window	climate window	climate window	climate window
K-value	[W/m2K]	1,05	1,05	1,05	1,05	1,05	1,05	1,05
Solar transmission	[%]	21	21	21	21	21	21	21
Ventilation								
outside air infiltration		0,5 ACH	0,5 ACH	0,5 ACH	0,5 ACH	0,5 ACH	0,5 ACH	0,5 ACH
mechanical ventilation		3,0 ACH	3,0 ACH	2,2 ACH	3,0 ACH	2,2 ACH	2,2 ACH	2,0 ACH
supply air temperature	[ºC]	16	16	16	16	16	16	16
secondary cooling		VHV-unit	VHV-unit	VHV-unit	VHV-unit	VHV-unit	VHV-unit	VHV-unit

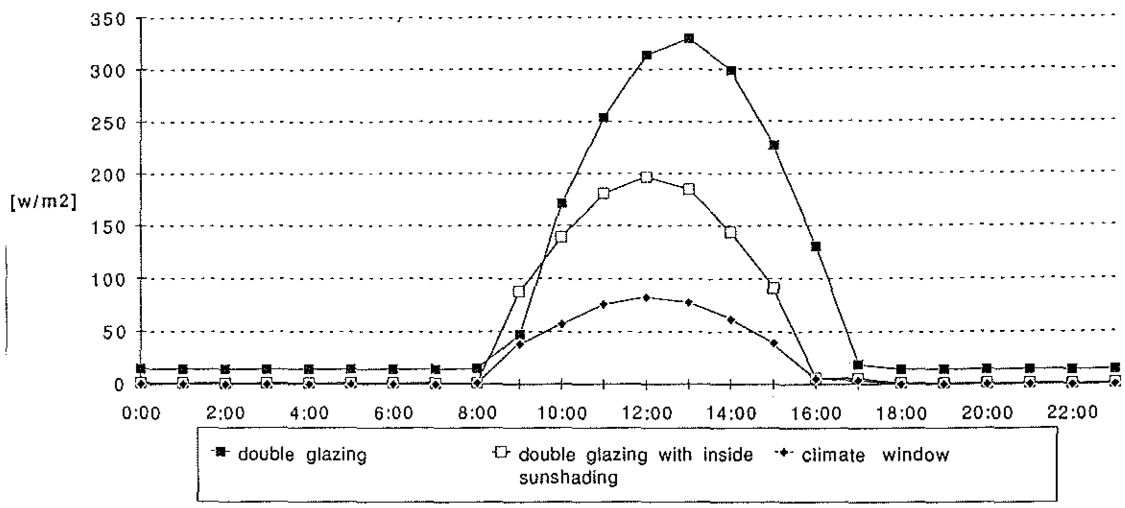

Figure 4 *Transmitted solar energy (January).*

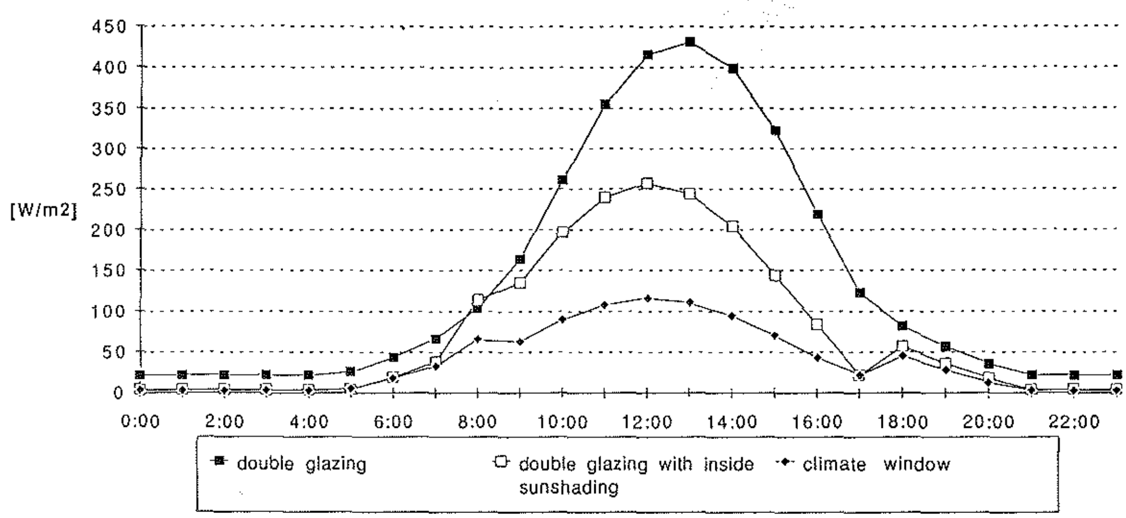

Figure 5 *Transmitted solar energy (July).*

The effect of the climate window can be clearly seen in Figures 4 and 5. In January the high loads of solar radiation transmitted through the double glazing would lower the heating load and decrease energy consumption. Figure 5 shows the results for July when the climate window lowers the level of solar radiation transmitted through the window, which decreases the cooling load and reduces energy consumption. From the results shown in Figure 4, it could be concluded that double glazing is advantageous during the winter. Figures 6 and 7 show the resulting inside surface temperatures of the glazing variations, and it is clear that the climate window construction increases the inside surface temperature of the glazing. This is important, as we were controlling and operating the space between comfort limits and therefore required a flatter curve to improve the resulting MRT in the space. Figure 8 shows the inside surface temperatures for July. The climate window has the smallest temperature swing, which results in a smaller deviation of the MRT within the space.

Comfort Conditions

Figure 9 shows both inside air temperatures and PMV values for winter conditions. During the winter periods, both CBM and Schiphol had lower inside air temperatures; these variations were heated by air as both had climate windows. The other two tended to overheat by about 1 to 2 K. This was due to the response time of the radiators because of the high internal gains and because the optimum start algorithm used could not cope with the pending internal load. The reason for this was that the simulation model targeted its heat requirement at 20°C ± 1 K at 08:00. At 08:00 the computer simulation model proceeded to "switch" on the internal load. The room thermostat then proceeded to switch the heating off, but the radiator supplied heat for some time after this signal. This phenomenon resulted in an activation of the VHV unit, which meant that the convective cooler was compensating for this overshoot.

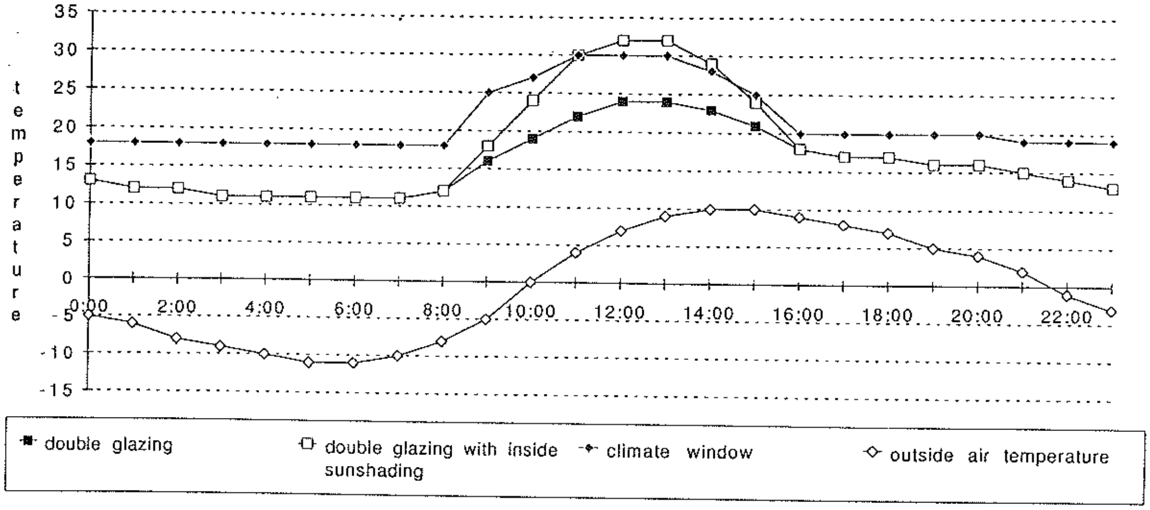

Figure 6 *Inside surface temperatures of south-oriented glazing (January).*

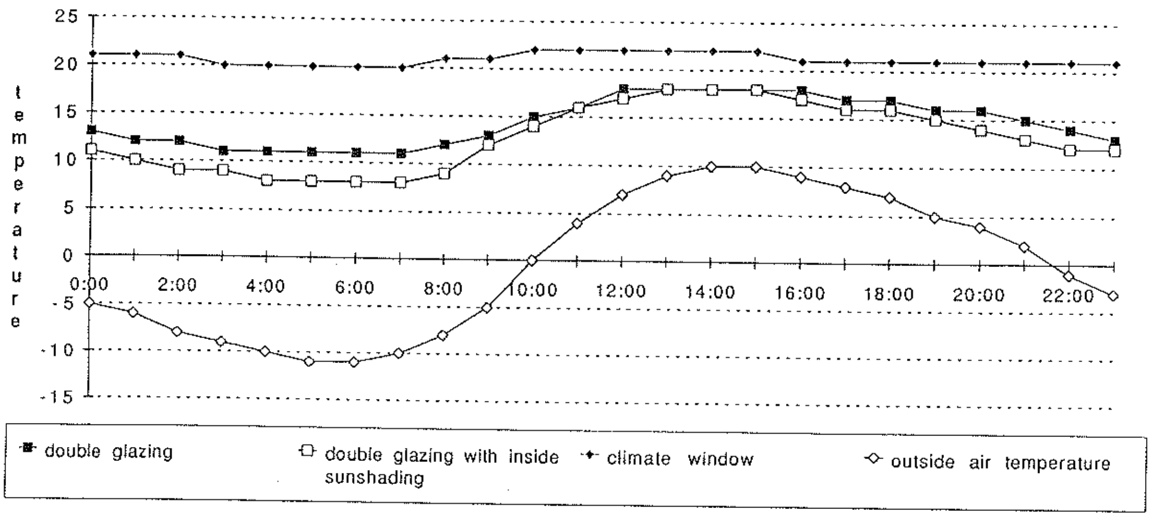

Figure 7 *Inside surface temperature of north-oriented glazing (January).*

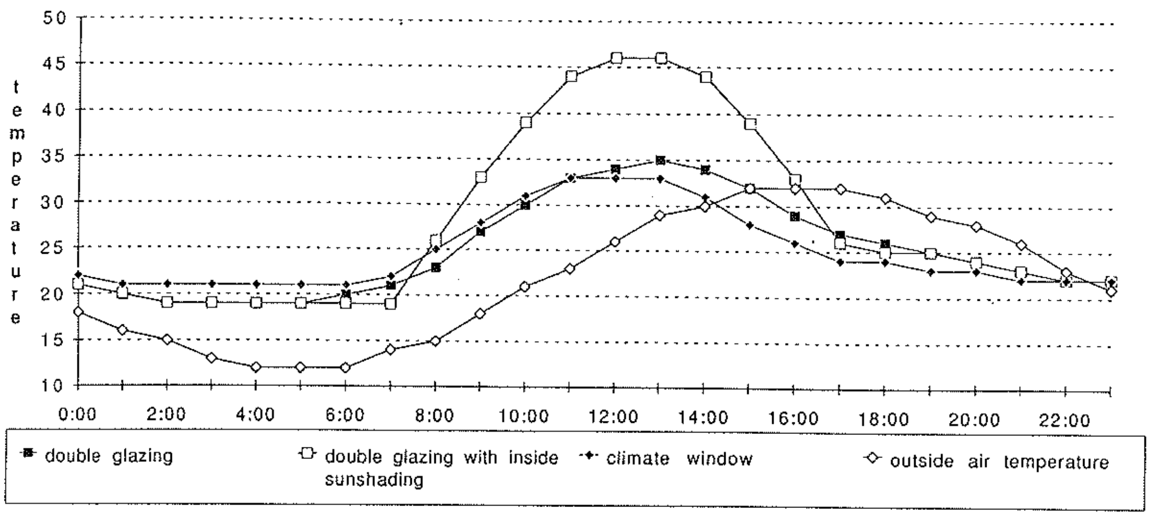

Figure 8 *Inside surface temperatures of south-facing glazing (July).*

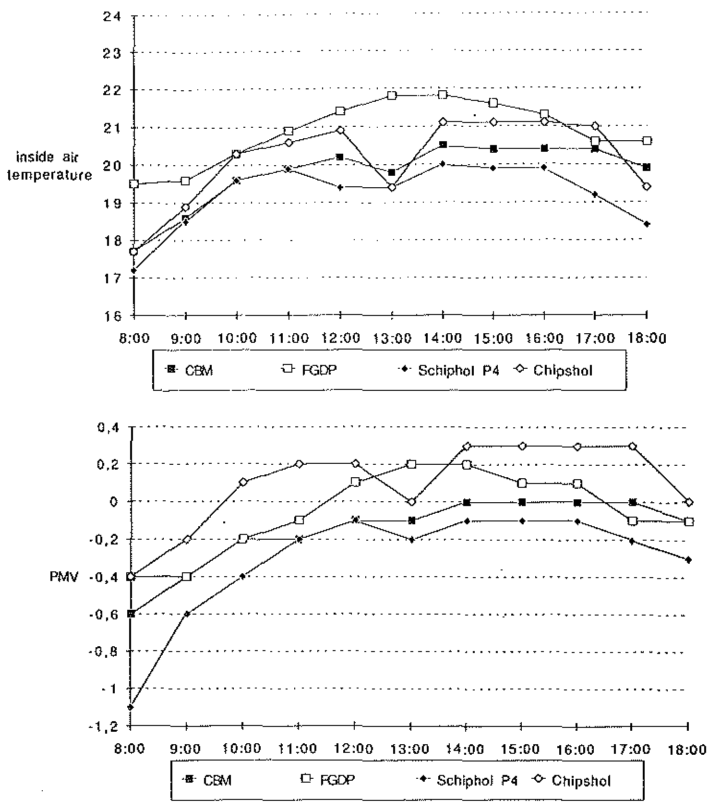

Figure 9 *Inside air temperatures and PMV values for a winter period (-11 °C).*

Experiments were carried out at optimal start times for the plant, but these proved to be unsatisfactory due to two primary reasons.

1. When the heating plant was switched on to provide an inside air temperature at approximately 07:00, the heating plant was then shut down and left to coast until 08:00 when the internal loads (lighting, occupants, and occupants' equipment) would provide internal heat. What happened then was that heat provided by the radiators was absorbed by the building fabrics, which, in turn, increased the mean radiant temperatures and the PMV, decreasing comfort conditions.
2. The second factor was the occupancy profile, bearing in mind that the office being simulated was only one of about two hundred in the actual building. In practical terms, this meant that everybody would have to begin work and switch their equipment on at the same time every day of the week, which, of course, is not the occupancy profile of an actual office building.

Because the heating was switched off, cooling during the winter was not viewed as optimal use. This did not really worry us because we were running in the free cooling mode so the costs were virtually zero. It did, however, prove that an individual room control could be provided in a very simple manner.

The rooms that were simulated with climate windows were cooler than the rooms with glazing and radiators due to the convective heating of the air. Because the resulting room temperatures were within design limits, no heating or cooling was required. Heating would be necessary if the internal loads were lower (if the offices were unoccupied for example). The PMV results for these two variants were lower than the models with radiators because there was no direct radiation compensation available.

The dip is caused by the reduction of the heating output of the radiators, which is replaced by the internal gains (equipment, lighting, etc). Figure 9 shows that the comfort condition have PMV values of about - 0.2, which indicates that the space will feel cold rather than warm. The cold effect is created by the negative radiation from the windows and because the internal heat sources are more convective than radiative (equipment, lighting, etc.).

When intermittant heating is used, a period of preheating is necessary before the building is occupied; this preheating period varies with the oversize ratio of the system, which varies from day to day based on ambient conditions. For example, a heating system designed to provide 20°C with a constant outside temperature of -12°C would be under half-load conditions at a constant 4°C outside temperature, or, alternatively, it would have an oversize capacity of 100%. The time when the heating system should start, therefore, varies from day to day if the building is always to achieve a disired temperature (within comfort limits) at 9 a.m. for example. If a heating system is oversized, the preheat period will be shorter and the system will operate for a reduced period of time, resulting in lower running costs. It follows, however, that if too large an oversize ratio margin is used, any saving would be more than offset by the reduced part load of the plant. In addition, a larger system will have more heating surface and increased boiler capacity, resulting in a higher capital cost.

Figure 9 shows that the temperatures at the beginning of the work period are lower than normally used in optimization strategies. Most buildings are targeted at 20°C or 21°C. When using comfort constraints to operate the building, the temperatures at the beginning of the occupation period are lower because a PMV of -0.5 can be tolerated, which lowers the heating energy necessary to maintain these comfort conditions.

Figure 10 shows the summer temperatures and PMV values of the four variants. Both variants simulated with climate windows had a better temperature profile. The PMV values were all within the limits of -0.5 to +0.5. All simulations were carried out with a maximal outside air temperature of 32°C (a very warm period) and a total solar intensity of 800 W/m^2. Direct solar intensity of 650 W/m^2 with zero cloud cover was used.

The VHV unit proved to be very successful; the self-regulating convective cooling capacity needed no optimal operation algorithm. As the convective heat gain increased,

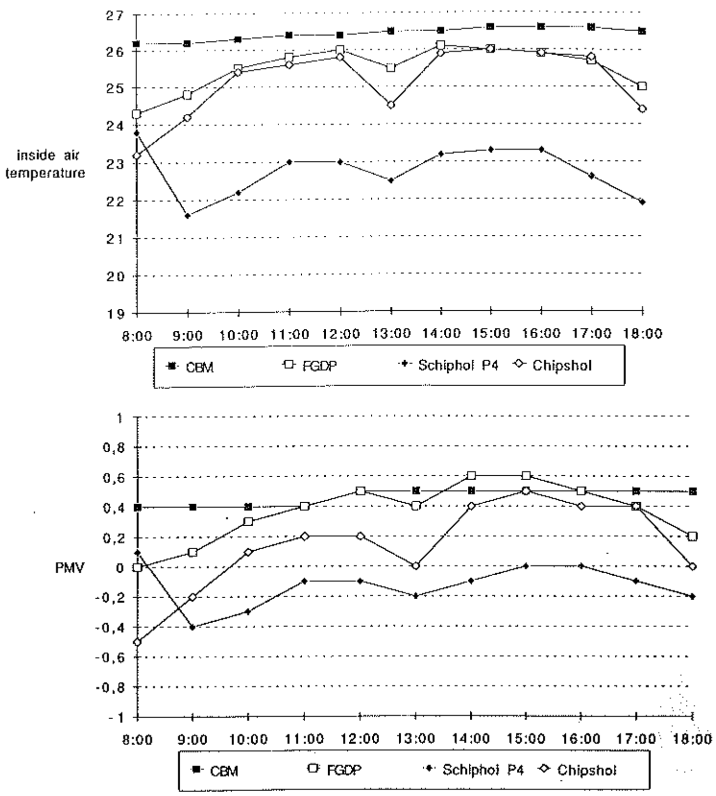

Figure 10 *Inside air temperatures and PMV values for a summer period (32°C).*

the amount of air moved by the cooling effect increased and subsequently decreased when the load decreased. The combination of variable load and circulation rate resulted in a comfortable inside environment throughout the day, with minimal temperature fluctuations. Because both occupancy and ambient conditions cannot be predicted, a certain amount of flexibility must be included in plant dimensions and control strategy.

Figure 10 shows that when operating the space within comfort limits, the inside air temperatures are higher than most present-day recomendations of maximum summer temperatures. Because the PMV are within limits, these higher temperatures can be accepted. The higher room temperatures during the summer period result in a smaller cooling load for the space and a decrease in energy consumption.

Figures 11 and 12 show further results obtained for different configurations for the same building. Various office configurations and a complete 1000 m^2 open plan office were simulated for a warm July day. Configurations 2 and 4 did exceed the PMV of +0.5, but this was due to the orientation and glazing areas of the rooms. Alternative 7, which was the 1000 m^2 open plan office, stayed within the required limits, even under the extreme conditions.

CONCLUSIONS

The object of this research was to investigate the simulation and operation of a comfortable indoor climate for a standard office. The results clearly show that this was achieved. A technique has been utilized for the design and operation of a building and its installations that is easily implemented on a computer, enabling an optimal strategy to be determined in advance from a knowledge of the various building interactions. This method affords a high degree of flexibility in the choice of constraints. It is a useful means of improving present design aids for the sizing and operation of a building and its plant under transient conditions. Several different facade constructions were simulated, but the differences between them were minimal. The test did show that significant results could be obtained with different glazing configurations.

The glazing areas varied from 28% to 43%, and the results showed the advantages of using climate windows.

These investigations show how the VHV units with low ach primary ventilation can be combined to produce an alternative to conventional forms of air conditioning, with the emphasis on obtaining the highest comfort levels in the workspace.

The investigations have concluded that supplying air at low velocity into a space will create a pool of fresh air that will circulate evenly through the space. When this air comes into contact with heat sources, such as equipment and people, it will rise up, ventilating and removing heat. This air is then collected at a high level, where it is cooled by the VHV unit and enters into the room where its physical properties circulate the air further through the room. The amount of secondary circulation is dependant upon the temperature differential between the air temperature in the lowered ceiling and the surface temperature of the VHV unit.

Another advantage of the VHV unit with low ach primary ventilation was the individual zone conditions it created. If a particular office or part of an office had a lower internal load than was simulated, then the room temperature would remain within the comfort conditions, the convective heat gain in the lowered ceiling would be minimal, and, therefore, the VHV unit would not be utilized, and, consequently, no ancilliary cooling energy would be required.

The system is a self-regulating system that does not have a complicated control strategy to carry out the simple tasks required. Operating an office under comfort conditions and not temperatures clearly shows that the energy necessary to maintain the required conditions is less than by conventional systems.

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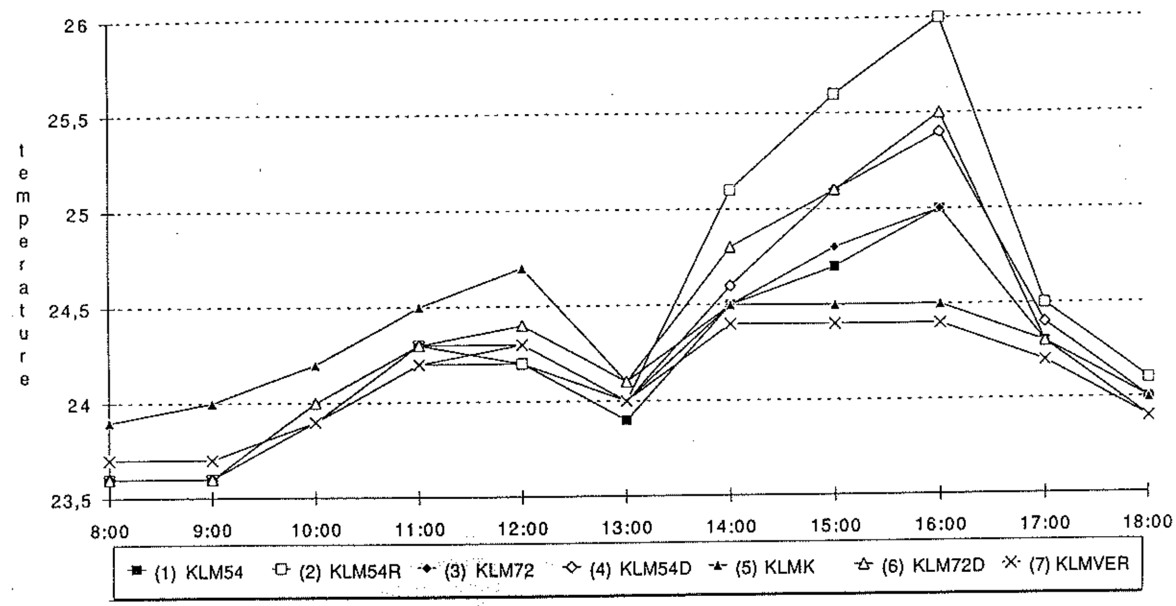

Figure 11 *Inside air temperature for different variations. Internal load: 45 W/m². Outside conditions: solar intensity on the vertical south-facing surface = 650 W/m² (no cloud cover), maximum outside temperature = 32°C.*

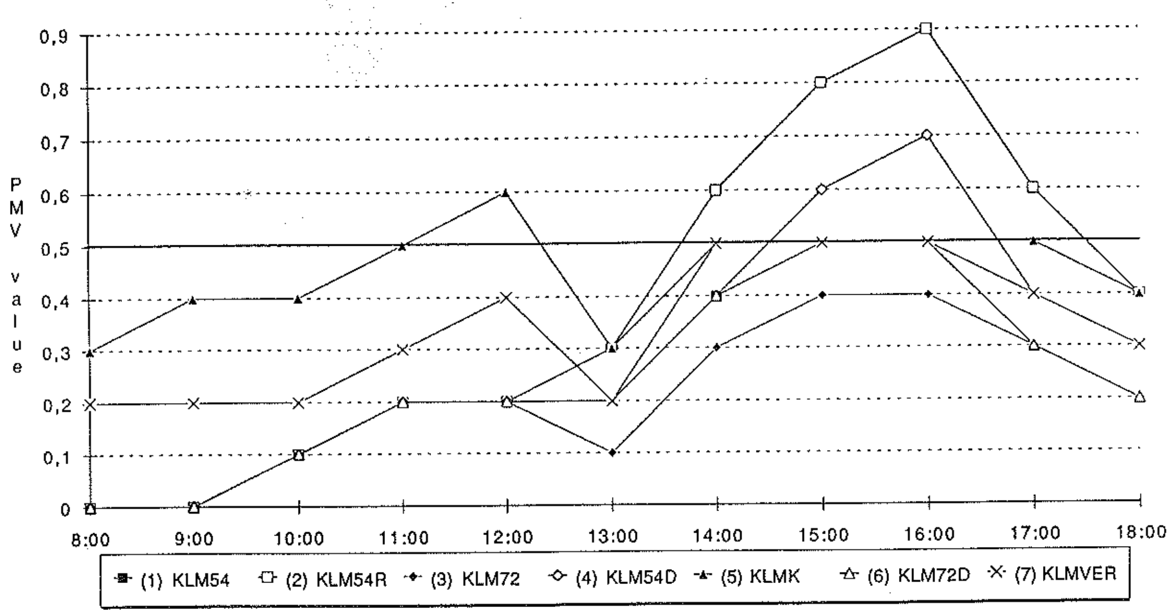

Figure 12 *PMV values for different variations. Internal load: 45 W/m². Outside conditions: solar intensity on the vertical south facing-surface = 650 W/m² (no cloud cover), maximum outside temperature = 32°C.*

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