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USING SOLAR ENERGY TO REDUCE HEAT STRESS IN HOT AND HUMID OFFICES - AN ALTERNATIVE TO CONVENTIONAL AIRCONDITIONING

Arturo Martin B. Santos
Assistant Professor
Department of Mechanical Engineering
College of Engineering
University of the Philippines
Diliman, Quezon City, Philippines

and

Lars Gunnarsen
Senior Researcher
Danish Building Research Institute

ABSTRACT

Among heat acclimatized people, sweating is often quite efficient. Supplying dried-only air to the immediate vicinity of office workers in hot and humid regions may be a promising low-cost alternative to traditional air conditioning. 123 heat-adapted subjects participated in six one-hour exposures in cubicles in a warm room without air conditioning. Each subject had individually-adjustable air outlets both above and below the desk. The temperature and humidity of the supply air was varied in a blinded and randomized design. One exposure had no air supply. At the end of each exposure the perceptions of subjects, water intake, skin temperatures, sweating and a simple performance measure were registered. The supply of dehumidified but not cooled air significantly increased acceptability and reduced most of the monitored indicators of heat stress. Solar energy was used in the air drying process and this may reduce the electricity consumption for drying considerably.

INTRODUCTION

Heat stress reduces human productivity (1). In hot and humid regions heat stress is expected to have a significant influence on the productivity of office workers. Air humidity becomes increasingly important for human thermoregulation at higher temperatures where sweating occurs. People living in hot and in particular hot and humid regions are often heat acclimatized. Their sweating is initiated faster and they have a greater number of active sweat glands. Optimal temperatures for comfort seem to be unaffected by heat acclimatization (2). Lowering the temperature indoors may not always be possible. The cost and availability of energy and air conditioning technology render this impossible in developing countries. A promising alternative to cooling offices may be to provide each workplace with a supply of dehumidified air.

By making it individually adjustable the cooling effect of the supply air on the subject can be maximized. The effect is achieved by sweeping the body with dry air, increasing the evaporation of sweat, but also by allowing elevated air velocities which increase the heat transfer coefficient.

A prototype for supplying dried-only air has been designed, fabricated, and tested. It uses solar energy, contains no ozone depleting chemicals, and may use less electricity compared to traditional air conditioning. In the prototype, the air was dried by passing it through one compartment of a desiccant dryer and then through a counter-current heat exchanger to remove the heat of absorption. The desiccant-dryer compartments were recovered using a solar air-heater. An auxiliary electric air heater maintained the recovery temperature during cloudy periods. The over-all system performance was compared with an equivalent conventional window-type air conditioner.

The purpose of this paper is to present an alternative to traditional air conditioning by absorption drying of the air supply based on solar energy.

METHOD

123 paid subjects performed simulated office work during one-hour exposures in cubicles. Data for the subjects are shown in Table 1. Each subject was exposed to six different thermal conditions in cubicles. During exposures the subjects could adjust the airflows from a personal diffuser in each cubicle. The temperature and humidity of the supply air were varied in a randomized design. The cubicles were placed in a normal room with windows and an air exchange rate of approximately 2 h^{-1}, with no mechanical ventilation or air conditioning. The humidity and temperature in the room varied somewhat according to the weather.

Table 1
Personal data for the 61 females and 62 males in the experiments

	Age Years	Height m	Weight kg	Clothing clo
Mean	19.5	1.62	55.3	0.49
Standard deviation	4.5	0.09	12.7	0.03

The design of the cubicles is shown in Figure 1. One cubicle functioning as a reference had no air supply. Six exposure cubicles A through F were treated as follows: A was supplied with dried air, B got dried and heated air, C got a mixture of room air and dried air, D had no supply air, E got only room air and F got heated room air. Temperatures and moisture contents may be seen in Table 2.

Human exposures were performed from September to December 1995. Subjects were exposed in two three-hour sessions, starting either mornings at 9.00 or afternoons at 13.00. Before the exposures, they were handed a written instruction on procedures and behavior during the experiments. They remained seated in the unconditioned room for a few minutes. They were then assigned to a cubicle and adjusted their diffuser according to their preferences. They were allowed to read or to do other activities simulating office work for approximately 45 minutes. Finally they were asked to complete a form containing questions twice during the last 15 minutes. Experimenters measured and observed reactions of the subjects twice during the last period. Temperatures and humidities were measured by an automated logging system every two minutes. After the exposures subjects returned briefly to chairs outside the cubicles before they were told to go to their new cubicles. Exposure parameters were not known to the subjects and the experimental plan was randomized and balanced between cubicles. In the statistical analyses only data logged during the last 20 minutes were used. Subjects' responses during the last 15 minutes were combined. This paper deals with some of the exposure parameters and the votes of subjects on the acceptability scale shown in Figure 3.

The mean exposure parameters are shown in Table 2. The mean values are not very different between the cubicles but the varying outside conditions increased the span of variation between single exposures. Because of the unconditioned room, it was not possible to avoid a significant covariation between room air temperature and room humidity.

Table 2
Mean exposure parameters

Cubicle	A	B	C	D	E	F
Humidity of supply air (g/kg)	16.0 (11 -19)	16.0 (11 -19)	17.2 (14 -19)	-	18.1 (16-20)	18.1 (16-20)
Temperature of supply air (°C)	31.7 (28 -35)	33.7 (30 -36)	31.4 (28 -34)	-	31.7 (28-34)	33.0 (29-35)
Air velocity averaged over the subjects centerline (cm/s)	25 (22 -27)	26 (22 -27)	24 (22 -27)	9 (6-12)	23 (22-27)	22 (22-27)
Operative temperature in room (°C)	29.6 (26-32)	Air flow of supply air Cubicle A, B, C, E, and F (l/s)				9.8
Humidity of room air (g/kg)	18.1 (16-20)					

The principle of the system is shown in Figure 2. Humid outside air passed through one compartment of a silica gel drum where it was dried. The heat of absorption was removed from the air flow by exchanging heat with outside air using a countercurrent heat exchanger. Heated air from a solar air heater was used to recover the absorber sectors. An auxiliary electrical heater was also used to ensure that air at a sufficiently high temperature entered the recovering sector of the absorber.

The drum was composed of separate sectors for alternate air-drying and silica gel recovery. Each sector held silica gel beads by two perforated plates. A simple air diffuser and the pressure drop through the perforated plate served to evenly distribute the air as it flowed through an absorber sector. Outside air left the absorber with less moisture and, due to the heat of absorption, hotter. An absorber sector was recovered by passing heated air through it.

The hot and dry air that came from an absorber sector entered a countercurrent heat exchanger where it exchanged heat with outside air and was cooled. The heat exchanger was made of 22 layers of galvanized iron sheets, which had a total area of 6.8 m^2, separated by 5 mm thick rubber. It had alternate passages for the dried air flow and the outside air flow.

An experiment was performed to determine the constant of the heat exchanger. During the experiment, the air entered the heat exchanger at 58 °C and was cooled to 31.2 °C when outside air was 30.1 °C. Temperature measurements before and after the countercurrent heat exchanger were made when the readings became steady within 1°C. The heat exchanger constant was determined using the equation for heat transfer:

$$Q = K\frac{(t_{17} - t_9) - (t_{13} - t_{10})}{\ln[(t_{17} - t_9)/(t_{13} - t_{10})]} \tag{1}$$

where Q is the heat transferred, K is the heat exchanger constant, and t are the temperatures with subscripts referring to Figure 2.

The solar air heater had a 2.3 m^2 dual glazed opening and a finned absorber panel. The five other sides were insulated by a 50 mm thick layer of mineral wool. The shell of the solar air heater was made of marine plywood. It was installed on the roof of the laboratory and a duct led the air into the laboratory where the rest of the system components were located. This 8 m long duct was insulated by 75 mm polystyrene foam which was wrapped by cloth and painted to give waterproofing.

All temperature measurements, relative humidity measurements and calibrations were logged automatically by a DATATAKER DT100 made by Data Electronics Pty. Ltd., Australia interfaced with a computer. The temperature probes were copper constant thermocouples and individually adjusted CRAFTEMP thermistors from Astra Tech AB of Sweden. The relative humidity transmitters were the OMEGA HX92 made by Omega Engineering Inc., USA. Air flows were measured using a pitot tube in a 100x100 mm^2 duct 2.5 m long. Flows were calculated as the average of nine equally spaced locations 1.2 m downstream.

Calibration of the temperature and relative humidity probes was done by subjecting them to two different conditions. The temperature probes were put in a box where the temperature was measured by a psychrometer with quick silver thermometers (± 0.2°C) and then in a pot of boiling water. The relative humidity sensors were put in a box in the laboratory and then in the hot and dry airstream leaving the absorber. The psychrometer was placed beside the relative humidity sensors in each case and the relative humidity was determined from a psychrometric chart. A linear relationship was assumed for all probes.

To determine the recovery characteristics of a drum compartment, an absorber sector was first fully wetted by passing outside air through it until the temperature and relative humidity, before and after the sector, were within 1°C and 2% respectively. The fully wetted sector was then dried using two different recovery temperatures. The drying was stopped when the moisture content reached steady state within 2 g/kg, at which point the sector was considered fully dry. The dehumidification characteristics of an absorber sector were determined by passing outside air through a fully dry sector until the sector was fully wetted. Temperatures and relative humidity readings were recorded automatically every 5 minutes during these experiments.

Temperatures before and after the solar air heater were automatically recorded every 2 minutes during approximately three months of daytime operation to determine its performance in recovering the absorber sectors. The hourly temperature averages were stored.

RESULTS

The mean acceptability vote for each cubicle is shown in Figure 3. The relation between acceptability and percent dissatisfied was calculated from (3) using acceptability votes on the same scale but used to express perception of air quality. The absence of a source of elevated air velocity and dry air in cubicle D results in a significantly less acceptable thermal environment ($P < 0.01$) than all other cubicles. Cubicle A with the driest supply air was more acceptable than the other cubicles at the $P < 0.05$ level.

Analyses of results showed that more information was obtainable from the data when they were analyzed exposure by exposure and not pooled. The four main exposure parameters are shown in relation to acceptability in Figure 4 for all exposures except cubicle D. The slopes are significantly ($P < 0.01$) less than zero with respect to the operative temperature and the temperature of supply air. The relation to the moisture content of the supply air was less significant ($P < 0.1$) and there was no significant effect of the moisture content of room air.

As mentioned earlier, the moisture content of the room air was significantly correlated with the operative temperature of the room. This correlation complicated the modeling of data. Regression was nevertheless attempted using the linear model:

$$\text{Acceptability} = K_1 + K_2 t_0 + K_3 X_r + K_4 t_s + K_5 X_s \qquad (2)$$

t_o : Operative temperature in the room (^{o}C)

X_r : Moisture of room air (g/kg)

t_s : Temperature of supply air (^{o}C)

X_s : Moisture of supply air (g/kg)

Because of the limited influence on acceptability of the supply air temperature and the correlation between t_o and X_r only K_1, K_2 and K_5 were significant. Constants were calculated using only the significant parameters. The resulting model is shown in Figure 5. From this model it may be seen that lowering the operative temperature 1 ^{o}C has the same influence on acceptability as lowering the moisture content of the supply air by 1.6 g/kg (standard error 0.9 g/kg).

Hourly average air temperatures that were achieved in the daytime from 9.00 to 17.00 using the solar heater are shown in Figure 6. These measurements were made during the period from September to December 1995 in the hot and humid tropical climate of Manila, the Philippines. This figure indicates the average percentage of the time that the indicated temperatures or higher are attained. It shows, for example, that an average air temperature of 65 °C or higher can be achieved by only solar heating 15% of the time.

The moisture gain of an absorber sector during air dehumidification and moisture loss during two different recovery temperatures is shown in Figure 7. Thus a fully recovered drum can be used for about seven hours if at least 2 g/kg is to be removed from the air stream or for about three hours if 6 g/kg is to be removed. Figure 8 shows the moisture performance of a silica gel compartment based on the information in Figure 7 and the air flow rates during dehumidification and recovery from Table 3. From these we can see that the average water transfer rates during recovery are relatively steady. During dehumidification, the average water transfer rates are faster than the recovery rates during the first four hours but slower than the recovery rates after the first eight hours.

Table 3
Data for silica gel drum

Number of equal absorber sectors	3	Heated air flow rate for recovery (L/s)	19
Area of an absorber sector (m^2)	0.212	Dehumidified air flow rate (L/s)	24
Weight of silica gel beads in an absorber sector (kg)	14.5	Thickness of silica gel bed in an absorber sector (mm)	70

Air flow rates through the counter current heat exchanger and the heat exchanger constant determined using Equation 1 are given in Table 4.

Table 4
Data for the counter current heat exchanger

Air flow rate of dried air (L/s)	24
Coolant outside air flow rate (L/s)	30
Heat exchanger constant (W/K)	197

DISCUSSION

Fangers comfort equation (2) gives a comfortable operative temperature of 26.0 °C for sedentary subjects with 0.5 clo at an air humidity of 20 g/kg and an air velocity of 0.25 m/s. Reducing the humidity to 10 g/kg increases the comfortable operative temperature to 28.0 °C. Present results indicate a greater influence of humidity. Moving from 20 g/kg to 10 g/kg will result in constant acceptability if the temperature at the same time is increased by 6.2 °C. The increased influence at warm as opposed to comfortable conditions is caused by the increased importance of the evaporation of sweat for heat loss at increased temperatures. Moisture is far more important for hot environments than for environments resulting in thermal comfort.

Using the heat-acclimatized peoples' ability to sweat by lowering the moisture content of the air and to reduce their heat stress has obvious environmental, economic and energy conservation benefits. The use of electricity may be reduced. Refrigerants are avoided and the process may as in the experiments be solar-powered. Since clothing requirements are not influenced very much by the facilitated evaporation of sweat, another benefit of the dry air system may be to avoid the hot and cold transients often experienced when entering a cooled space or when leaving an air-conditioned building.

Experiments were performed in a leaky room with a high air change rate to the outside. The room had no thermal insulation. A great deal of energy is required to cool such a room. The directed air flows from the personal diffusers pass close to the bodies of the users and the requirement for air tightness and thermal insulation is avoided. Thermal insulation of the ducts for distribution of dry air is not required.

The solar air heater contribution to recovery energy consumption can be determined from Figure 2. The area between 31°C, the average outside daytime temperature, and the curve is the increase in temperature that can be provided by the solar heater. Assuming an 86°C average recovery temperature, the solar heater contribution represents 30% of the required energy for recovery. Since the solar heater collection surface was only 2.3 m^2, it may be possible to reduce electricity consumption by increasing the surface area. Another is to make the system more compact and situating all components on the roof. This would reduce heat loss from of the ducts with warm air. The duct bringing dried air to workplaces need not be insulated.

The following example was made to compare electricity consumption of the set-up with a traditional airconditioner. Figure 5 shows that an equal increase in acceptability may be achieved either by reducing the operative temperature from 31 to 27°C at constant moisture content or by reducing the moisture content by 6 g/kg at constant temperature. The moisture reduction is possible with the experimental set-up.

An office building in a hot and humid tropical region would typically consist of single-glazed windows, plastered walls of concrete hollow blocks, an uninsulated tin roof, a drop ceiling made of plywood, and an uncarpeted concrete floor. A uniform transmission coefficient of 4.5 W/m^2 K was used for the entire building shell to simplify calculations. Since the current system has the capacity to supply three workplaces (maximum dried air flow rate was 30 L/s and each workplace received 10 L/s) with dried-only air, this would translate to an office space of about 30 m^2. A ceiling height of 3 m., three airchanges per hour, and outdoor temperature of 31 °C, outdoor moisture content of 20 g/kg (70%RH), no heat contribution from solar radiation, 240 W of fluorescent lighting and an air conditioner coefficient of performance of 2.8 with an evaporator surface temperature of 10 °C were assumed. From these, the power needed by a conventional air conditioner to achieve a room condition with an acceptability equivalent to a 6 g/kg moisture reduction of the outside conditions at constant temperature would be 0.83 kW. The resulting room temperature would be 30 °C and 15.5 g/kg (58%RH). Even the air conditioner did not reduce the temperature much compared to the moisture reduction.

Referring to Figure 2, and assuming that the absorber is recovered at 86 °C, the required increase in temperature that must be handled by the auxiliary heater can be determined. This is the area between the curve and 86°C and is 36.5°C. This translates to a 0.84 kW auxiliary heat requirement which is comparable to the 0.83 kW electricity consumption calculated for a conventional air conditioning system. Further improvements may reduce the electricity consumption of the prototype drier significantly.

An offshoot of this research may be the possibility of exploiting storage of the drying power of the sun. Storing the sun's heat for several months is impossible or very difficult to achieve at the moment. But dried silica gel may retain its drying capability if kept in simple airtight containers. It may be possible to dry the gel during periods of much sunshine for later use of the stored drying power during the rainy season. One potential application of this procedure would be in crop drying during the rainy season to prevent mold growth and other damages during storage. Rice, corn and some fruits like mangoes are examples of crops requiring post harvest drying.

CONCLUSION

Reduced heat stress among heat-adapted people in hot and humid offices may be achieved by drying the indoor air. This reduction is possible even in offices without airtight enclosures when the dried air is supplied to each workplace.

The combined effect of providing some individual control and elevated air velocities to each workplace significantly improved the acceptability of the thermal conditions. Acceptability was improved further when the supply air was dried.

A prototype solar-powered system for supplying dry air for workplaces has been designed, fabricated and tested. The system is a low-cost alternative to traditional air conditioning in workplaces in hot and humid regions. Further improvements on the prototype used for this study is recommended.

The drying power of the sun can be stored in recovered silica gel beads and used for other purposes. Future research on this is recommended to explore the possibility of desiccant drying of agricultural products during the rainy season.

ACKNOWLEDGMENT

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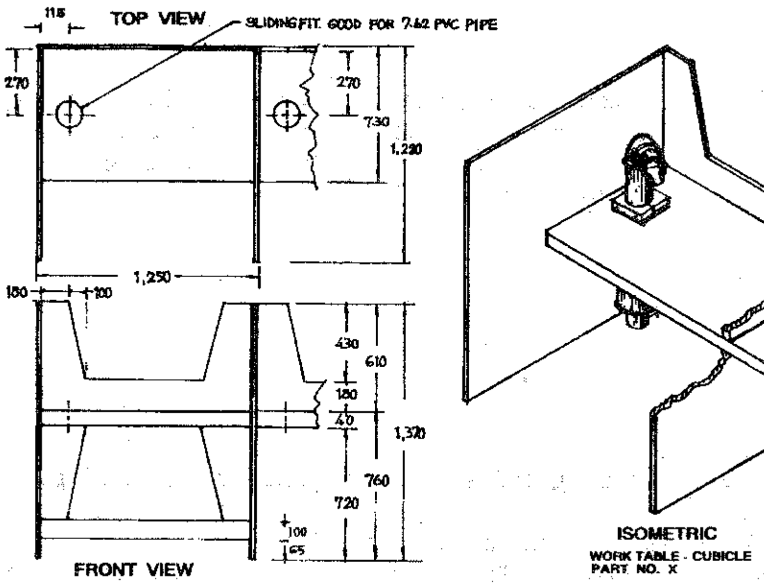

Figure 1. One of the six cubicles used for the experiments. All dimensions are in mm.

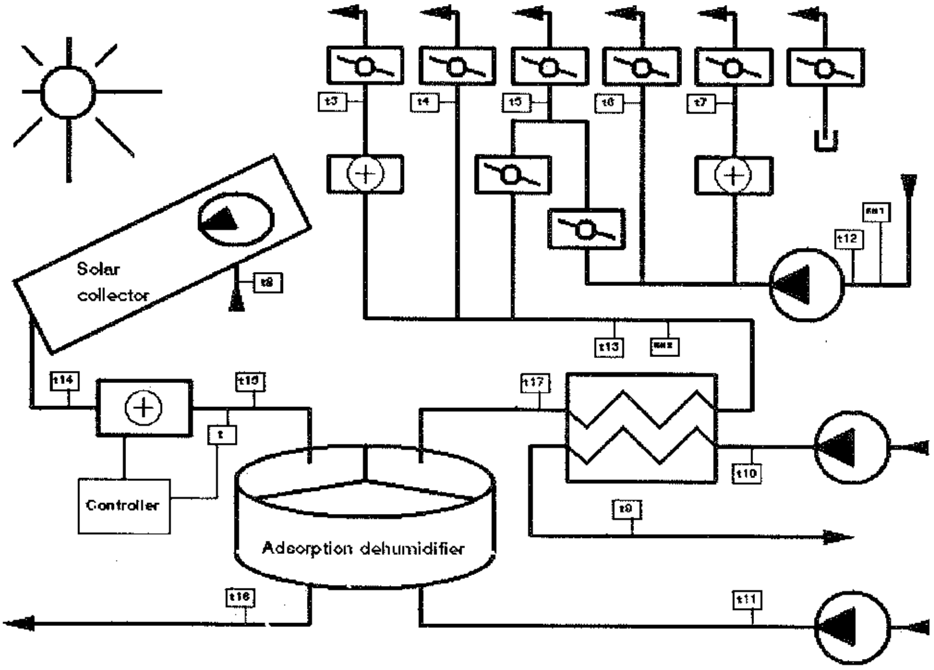

Figure 2. Schematic diagram showing how a dried air stream is produced continuously using the energy from the sun.

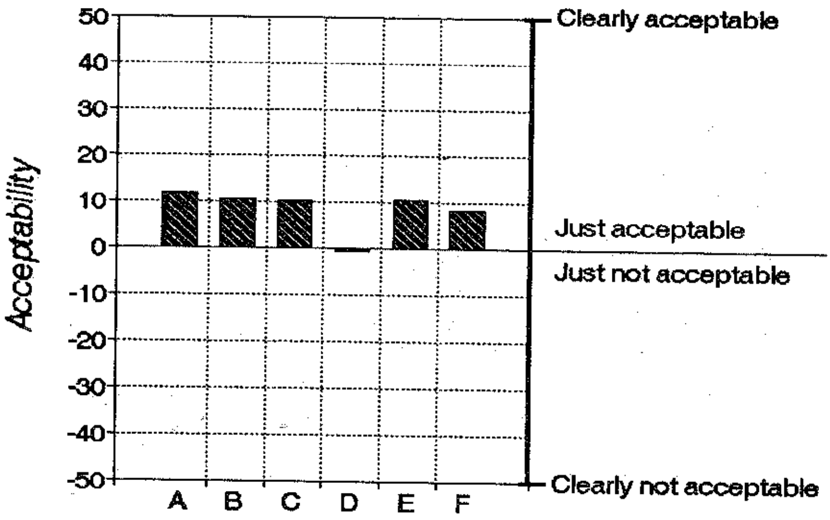

Figure 3. The voting scale and the acceptability level of the six cubicles. The subjects marked the scale in response to the following instruction. Please indicate your perception of general acceptability of your present thermal environment on this scale.

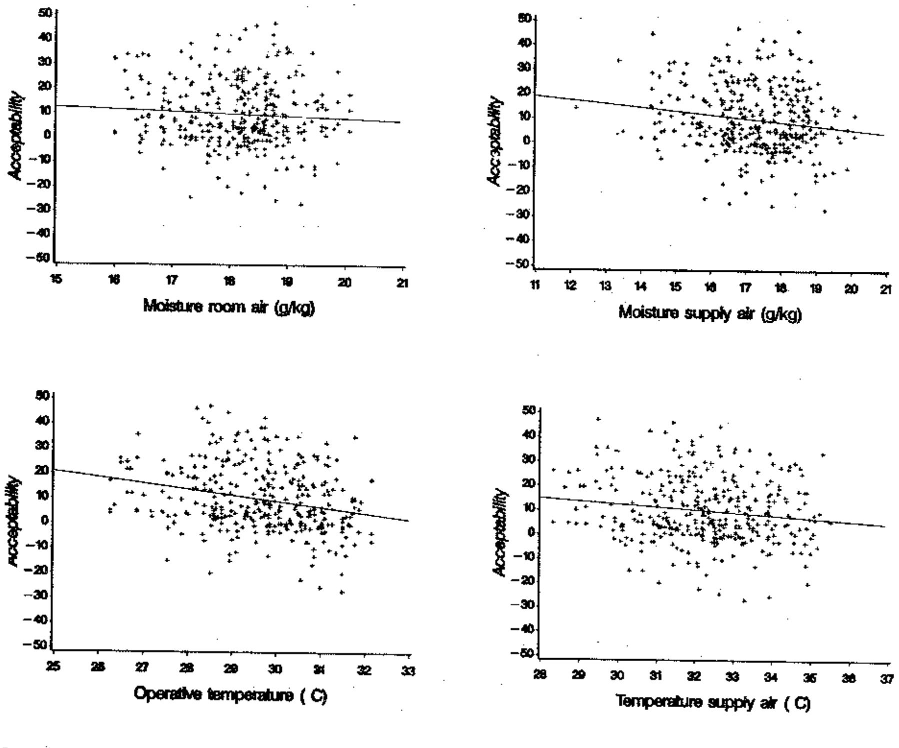

Figure 4. Acceptability versus the important exposure parameters. Moisture content of room air, moisture content of supply air, operative temperature of room air, and temperature of supply air.

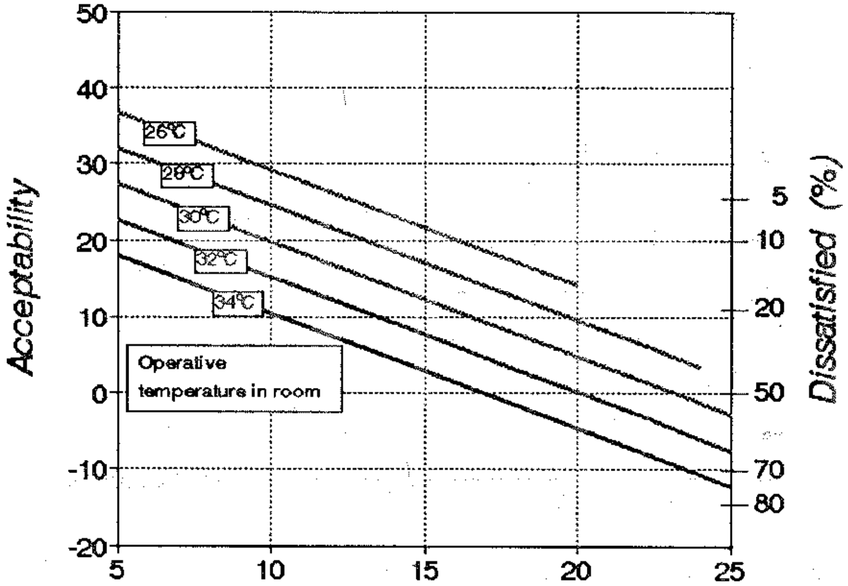

Figure 5. The model giving acceptability as a function of the operative temperature of the room and the humidity of supply air. A scale for the transformation to % dissatisfied is shown to facilitate comparisons.

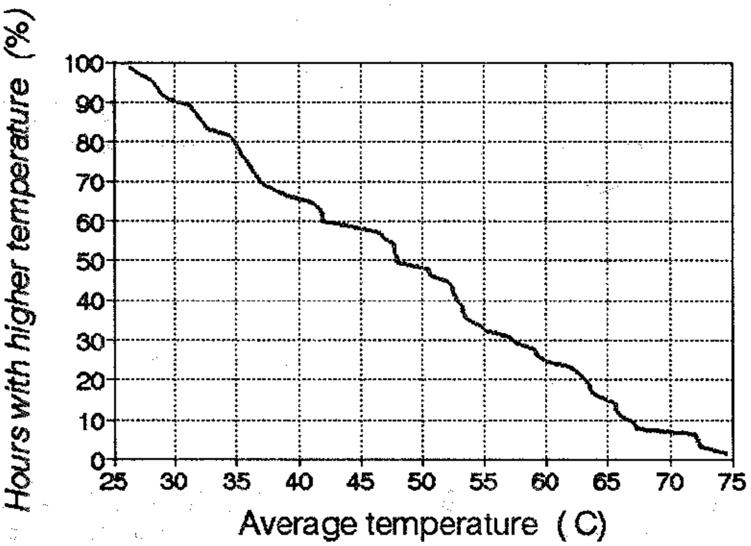

Figure 6. Hourly average heated air temperatures that could be achieved using the solar air heater for the duration of the experiments.

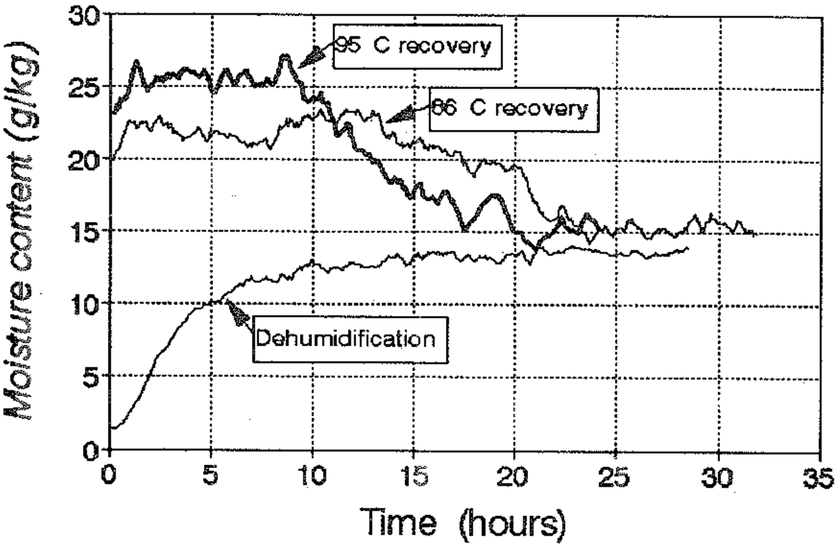

Figure 7. Time course of the moisture content after the absorber during two recovery periods and one dehumidification period.

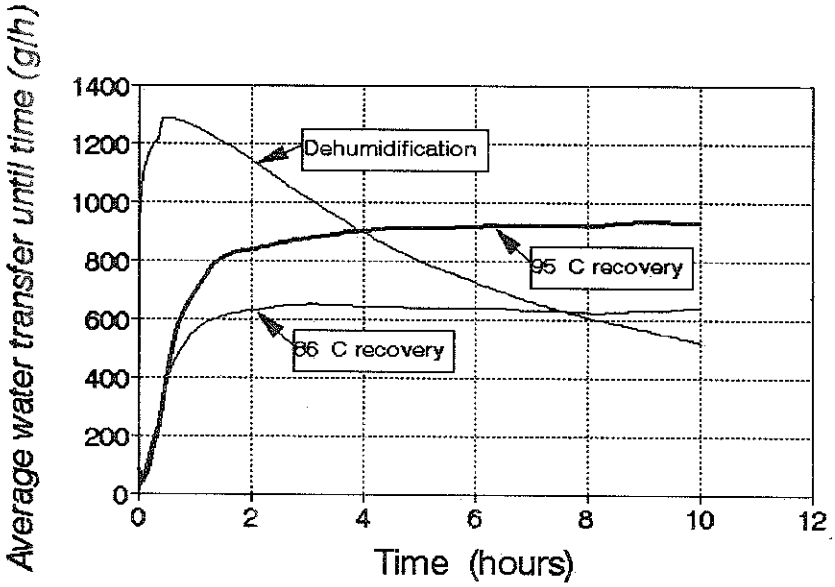

Figure 8. Moisture loss during recovery and gain during dehumidification of a silica gel compartment.