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EVALUATION OF BUILT ENVIRONMENT FROM THE THERMAL COMFORT VIEWPOINT

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ABSTRACT

The aim of this paper is to introduce a methodology to evaluate the thermal performance of the built environment, with respect to the relationship between the building parameters and the thermal sensations of building occupants. In this study, thermal sensations of occupants located at different points within an enclosed environment are described by the discomfort index and building parameters are analyzed for a room, since it is the representative unit of the built environment. The most important building parameters affecting comfort conditions in a room are location, orientation, and shape of the room and physical properties of the envelope surrounding the room, while the main comfort parameters are air temperature, thermal radiation, solar radiation, air movement, relative humidity, activity, clothing, and position and location of the body in the room. The thermal performance of various room configurations was evaluated by calculating discomfort indexes in terms of building and comfort parameters. The examples related to the application of the methodology are given in the paper.

INTRODUCTION

One of the most important requirements in a built environment is to satisfy the occupants' thermal comfort for human health and higher productivity in work. Therefore, a great deal of energy is consumed for heating and cooling the spaces in buildings. On the other hand, present conditions of energy sources in the world lead building designers to passive systems in order to reduce energy consumption. Therefore, building designers attempt to combine the optimum values of the building parameters providing thermal comfort conditions by means of minimum artificial energy. In order to determine such an optimum combination, it is necessary to establish the relationships between comfort and building parameters and then use these relationships in evaluating thermal performance of a range of cases in which these building parameters are systematically varied. The main building parameters affecting the occupants' comfort within a unit of the built environment, which is a room, are location, orientation, and shape of the room and physical properties of the envelope consisting of opaque and transparent components. The most important parameters of comfort are air temperature, thermal radiation between the body and surrounding surfaces, solar radiation entering the room, air motion and relative humidity, and the variables directly related to the person, such as activity level, clothing insulation, and position and location of the person in the room.

An enclosed built environment is judged by the occupants according to its ability to provide thermal comfort conditions in the enclosure. Therefore, thermal performance of a room should be evaluated by thermal response of the occupants to the thermal environment created in the room. Thermal response of the human body to its thermal environment in accordance with the abovementioned comfort parameters were studied extensively during the last two decades. But the studies dealing with the evaluation of thermal performance of the built environment are mostly based on air and surface temperatures achieved in the enclosure, not on thermal response of the building occupants.

The methodology introduced in this paper is based on the thermal sensations representing

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thermal response of the building occupants in order to evaluate the thermal performance of the enclosure from the thermal comfort viewpoint. In this study, the discomfort index was used for numerical expression of thermal sensations, since it is one of the commonly used thermal sensation scales. The J.B. Pierce Two-Node Comfort Model developed by Gagge (Gagge et al. 1970; Nishi and Gagge 1977) was modified in order to determine the discomfort indexes for standing and seated persons located at different points of the room. Moreover, direct and diffuse solar radiation received by the body in an enclosure were considered separately, since the direct solar radiation flux on the body varies with location and position of the person, as well as with the change of solar angles.

THERMAL COMFORT PARAMETERS AND THERMAL RESPONSE OF OCCUPANTS

In agreement with ASHRAE's Standard 55-81, thermal comfort is defined as that condition of mind that expresses satisfaction with the thermal environment (ASHRAE 1981). If a group of people is subjected to the same thermal conditions, due to the individual differences of people, it will not be possible to satisfy everyone at the same time. Therefore, the Standard specifies conditions in which 80% or more of occupants will find the environment thermally acceptable. Thermal acceptability is related to metabolic heat production of body, transfer of the produced heat to the environment, and the resulting physiological adjustments and body temperatures. Heat transfer between the body and its environment is affected by climatic variables, such as air temperature, thermal radiation, solar radiation, air movement, and relative humidity, and by personal variables of activity level, clothing, and position and location of the body in the enclosure. Position and location of the occupants are considered as one of the personal parameters, since direct solar radiation transmitted by window glass and received by the body and thermal radiation between the body and inner surfaces vary with the posture and location of the body in the room.

Certain values of the climatic variables are necessary for thermal comfort in accordance with the personal variables. Thermal comfort can be achieved by many different combinations of these comfort parameters. Thermal sensations that express thermal response of the human body to its thermal environment can be described by the feelings of hot, warm, slightly warm, neutral, slightly cool, cool, and cold. For the numerical evaluation of the thermal response of the human body, thermal sensations can be expressed by numerical scales. The most common thermal sensation scale used for describing the occupants' response to their thermal environment is given in Table 1 (Gagge et al. 1972). Quite extensive studies have been done during the past two decades to analyze the effect of comfort parameters on thermal sensations, and three main mathematical models were developed that are commonly used to predict the thermal sensations of human body.

1. Fanger comfort model (Fanger 1972)
2. Pierce two-node model(Gagge et al. 1970; Nishi and Gagge 1977)
3. Kansas State University two-node model (Azer and Hsu 1977)

These models are similar, and all of them are based on the energy balance equations between the body compartments and the environment. Detailed analysis and comparison of the models have been done by Berglund (1978) and are not given in this paper.

BUILDING PARAMETERS AFFECTING THERMAL COMFORT

The building parameters have an important role in determining the values of climatic variables of comfort and also the amount of consumed energy for maintaining thermal comfort conditions in buildings. In order to provide thermal comfort conditions in an enclosure while at the same time reducing energy consumption, it is necessary to analyze the effect of the building parameters on thermal sensations of occupants in an enclosure and then to combine the optimum values of these parameters. The building parameters for a room, which affect thermal comfort and energy consumption, are as the follows:

Location of Room. Location of room in a building determines the number of external elements surrounding the room. As is known, inner surface temperatures of external elements (walls, roof) vary with time due to the time-dependent heat flow through their components, even if the indoor air temperature is constant. If the room is located at the corner of the main floor, it has two external walls whose surface temperatures are usually different from the temperatures of other surfaces and indoor air due to the outdoor weather conditions. If the room is on the top floor, the temperature of the ceiling is one of the main factors affecting radiant heat exchange between the occupants and the surrounding surfaces. Therefore, location of the room, i.e., the number of external elements, affects the amount of radiant heat exchange between the occupants and the surrounding surfaces.

Orientation of Room. As is well known, orientation is one of the most important factors influencing indoor climate, as the solar radiation intensity on the outer surface of external elements varies with solar angles changing with orientation.

Shape of Room. The ratio of external wall length to room depth is called the shape factor of the room. The surface area of external walls, which has an important effect on thermal radiation between the occupants and inner surfaces, changes with the shape factor, even if the floor area and room height are constant. Therefore, shape factor of a room is one of the parameters affecting thermal sensations of occupants within the room.

Physical Properties of Envelope. External elements separating the indoor space from the external environment are called the building envelope and usually are composed of opaque and transparent materials. Even if the indoor air temperature has a constant value, inner surface temperatures of external elements and, accordingly, their radiant effects, vary with the rate of heat flow through the opaque and transparent components of these elements and the solar radiation transmitted by glazing, due to the thermal and solar radiation properties of the envelope. Therefore, these properties of the envelope are the basic determinants of indoor climate and, accordingly, thermal comfort and energy consumption. The main thermal properties of the envelope are overall heat transfer coefficient for opaque and transparent components, transparency ratio (ratio of the surface area of transparent parts to the surface area of the envelope), decrement factor, and time lag, while the solar radiation properties are transmissivity, absorptivity, emissivity, and reflectivity. For the opaque components, transmissivity is not valid.

In order to evaluate thermal performance of an enclosure, it is necessary to predict the sensitivity of thermal comfort to the abovementioned building parameters. In this study, the discomfort index was used to predict how thermal comfort is influenced by the building parameters.

EVALUATING THERMAL PERFORMANCE OF THE BUILT ENVIRONMENT

Thermal performance of an enclosure can be evaluated by the degree of satisfaction of occupants with the thermal conditions achieved in the enclosure. As mentioned above, the discomfort index is one of the most common scales to define the degree of thermal satisfaction. In the methodology introduced in this paper, discomfort indexes, which are calculated for different points of an enclosure in relation to the comfort and building parameters, were used for evaluating thermal performance of the enclosure. The methodology includes the following main steps:

1. Selecting the design days and determining the outdoor weather conditions for temperature calculations.

In order to determine indoor climatic conditions, it is essential to know the values of outdoor climatic variables such as air temperature,solar radiation, wind speed, and humidity. It is usually recommended to select the design days for which the temperature calculations will be done instead of repeating the calculations for all the days of the year. The year can be divided into two main periods, which are called "underheated" and "overheated" periods, according to the bioclimatic requirements of the human body, and January 21 and July 21 are the representative days of the underheated and overheated periods respectively (Olgyay 1963). Hourly variations of outdoor air temperature and solar radiation intensity for the design days are required, in order to determine the time-dependent heat flow through the building envelope.

2. Determining the values of building parameters affecting indoor climate.

In order to calculate the time-dependent values of the temperatures for predicting thermal conditions in an enclosure, the values of the abovementioned building parameters for the built environment under consideration should be known.

3. Determination of the variables related to the heat sources in the enclosure.

Total energy contribution of the auxiliary energy systems and the occupants to the environment should be known in order to determine thermal conditions in the enclosure. The amount of energy supplied by the heating or cooling system can be predicted according to the capacity and on/off periods of these systems. In order to determine the heat gain from the occupants and lighting system, it is necessary to know the number of occupants and occupation time, total wattage of the lamps, and on/off periods of the lighting system. Then the heat gain from the occupants and lighting system can be calculated hour-by-hour by means of the method suggested by ASHRAE (1981).

4. Determining the values of personal parameters of thermal comfort.

Thermal comfort requirements of the occupants depend on the activity level and clothing. Activity levels for typical tasks are given for a standard person in Met units, and clothing insulation values for typical seasonal clothing are given in Clo units (ASHRAE 1981). The occupants may change their position and location in the room. Therefore, these parameters are not considered as constant. Thermal sensations of the seated and standing occupants located at different points in the room will be calculated in order to evaluate thermal performance of the room.

5. Calculating hourly variation of thermal environmental variables that are the climatic parameters of comfort.

The hourly variation of indoor air temperature, thermal radiation from the inner surfaces, solar radiation transmitted by glazing and received by the occupants, relative humidity, and indoor air velocity should be calculated for the chosen design days in order to determine the thermal response of the occupants to the thermal conditions achieved in the room under consideration.

Air temperature in the enclosure is one of the most important factors affecting thermal comfort, since it is the main determinant of convective heat exchange between the body and its environment. Acceptable temperature range for a given activity level and clothing can be determined by means of bioclimatic charts (Arens et al. 1980). The bioclimatic chart for a sedentary activity and typical winter clothing is given in Figure 1. Indoor air temperature should float in this range during the occupied hours, otherwise an auxiliary system is needed to keep the air temperature in this range. If the heating or cooling system is not turned on, hourly variation of indoor air temperature should be calculated in terms of time-dependent heat flow through the envelope, solar radiation penetrating through glazing, and the rate of ventilation and infiltration through the openings and cracks. In this study, time-dependent heat flow calculations to determine indoor air temperature and inner surface temperatures are based on the finite difference method. Thus, the indoor air temperature at any particular time can be calculated by means of the following equation.

$$T_a = T'_a + \frac{\Delta t}{m.c} (Q_o + Q_w + Q_s + Q_v + Q_k) \qquad (1)$$

Thermal radiation between the human body and the surrounding surfaces is as important as convective heat exchange. Radiant heat exchange between the body and its environment can be expressed by the concept of "effective radiant field (ERF)" (Gagge et al. 1967). This concept is used to describe the additional long-wave radiation energy received by the body, when surrounding surface temperatures are different from the air temperature. The surface temperatures in an enclosure are usually represented by the concept of "mean radiant temperature (MRT)". In order to calculate MRT related to a person, the posture, orientation, and location of the person must be known, since MRT varies from point to point and for the same point also with the azimuthal orientation and posture of the body. Then, MRT for a person in an enclosure surrounded by "n" surfaces can be calculated by following formula (Fanger 1972):

$$MRT = T_1 \cdot F_{P-1} + T_2 \cdot F_{P-2} + \ldots + T_N \cdot F_{P-N} \qquad (2)$$

Angle factors (F_{P-N}) between body and surrounding surfaces are calculated by means of the following figure and equation (Fanger 1972):

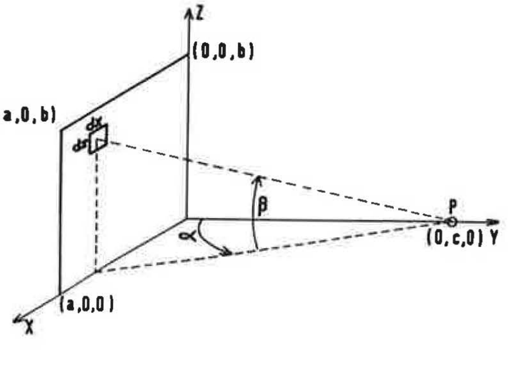


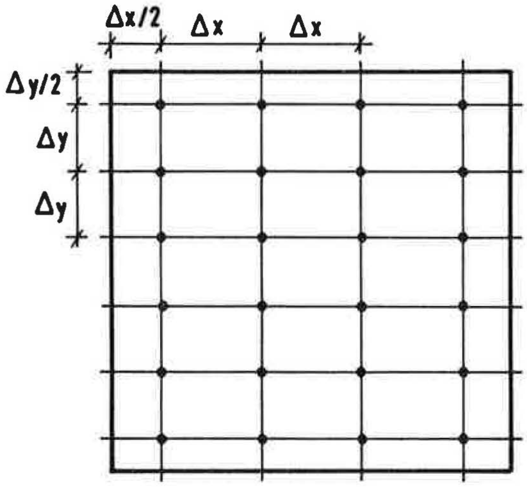
Diagram for angle factors between a person (centre in P) and a rectangle (a x b) (α; azimuth angle, β; altitude angle).

$$F_{P-A} = \frac{1}{\pi} \int_{\frac{x}{y}=0}^{\frac{x}{y}=\frac{a}{c}} \int_{\frac{z}{y}=0}^{\frac{z}{y}=\frac{b}{c}} \frac{f_p}{\left[1+\left(\frac{x}{y}\right)^2+\left(\frac{z}{y}\right)^2\right]^{3/2}} \, d\left(\frac{x}{y}\right) d\left(\frac{z}{y}\right) \qquad (3)$$

If location of the person is known, but azimuthal orientation is unknown, the angle factor is the mean value of the angle factors for $0<\text{azimuth}<360$. Projected area factors (f_p) for different altitude and azimuth angles and for seated and standing persons have been determined by Fanger (1972) as the results of an experimental work.

Hourly variation of inner surface temperatures of the thermally massive components ($T_1,\ldots,T_N$ for opaque components) can be calculated by using a simulation model based on the finite difference method, in accordance with outdoor climatic elements and physical properties of the envelope (Yılmaz 1985). As is well known, heat storage capacity is negligible for transparent components of the envelope. Therefore, inner surface temperatures of windows can be calculated for each hour under steady-state heat transfer conditions (Yılmaz 1985). Detailed information about the numerical method simulating time-dependent heat flow through the building envelope for determining hourly values of inner surface temperatures is previously published (Yılmaz 1985) and not given in this paper. For the calculations covered by the method, a Fortran program was developed (Yılmaz 1984). This energy-analysis program can provide the user with the hourly values of indoor air temperature (T_a) and the inner surface temperatures ($T_1,\ldots,T_N$) of the given enclosure for the day under consideration. The validity of the program was proved by comparing its results with the results of BLAST, which is a well-known and validated building energy analysis program. The tedious time-dependent temperature calculations can also be done by using one of the energy-analysis programs such as BLAST, DOE 2, etc.

Afterwards, mean radiant temperatures for seated and standing persons located at different points in the room can be calculated by solving Equation 2 in accordance with the calculated surface temperatures and angle factors. A subroutine, which was developed to calculate mean radiant temperatures in a rectangular room for standing and seated persons located at different points with the chosen interval between each other, was inserted into the abovementioned energy-analysis program.* The distance between the first point and the wall is equal to half of the chosen interval for both directions, as is shown in the following figure.



These points are on the horizontal plane passing through the body center. The distance between this plane and the floor is 0.60 and 1.00 m for seated and standing persons, respectively (Fanger 1972). In order to calculate the angle factors for each point, the subroutine requires information relevant to room geometry (i.e., room dimensions and location of windows) and Δx, Δy intervals. It is assumed that azimuthal orientation of the body is not known. The subroutine is called by the main program for each hour after the calculation of inner surface temperatures and then the mean radiant temperatures are calculated in the subroutine for seated and standing persons at each point.

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*The subroutine was also installed to the comfort version of the program BLAST.

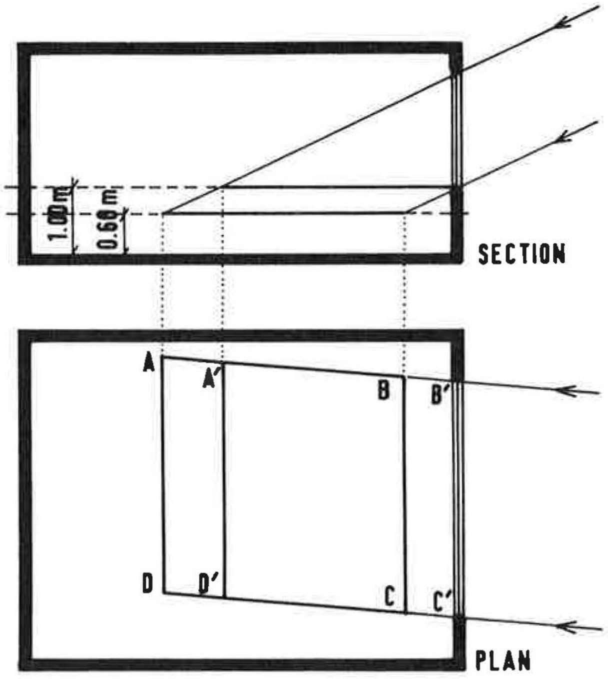
In addition to solar heat gain through opaque components, solar radiation transmitted by window glass has an important influence on thermal comfort in the enclosure by causing a significant amount of heat gain to the body and indoor environment. The heating effect of solar radiation may be pleasant for winter, while it is usually undesirable for summer, since it may cause the thermal sensation of being very hot, expecially when the body is exposed to the direct solar radiation in the enclosure. The effect of direct and diffuse solar radiation should be considered separately, since direct radiation is directional to the contrary of diffuse radiation.

The total diffuse radiation entering the room is received by the occupants and the other surfaces in the room. It can be assumed that the fraction of diffuse radiation received by each surface is proportional to its surface area. Due to irregularity of body contours, there is interradiation between the body parts. Therefore, the area exposed to the radiation is less than the actual surface area of the body. The area of the body that actually receives the radiation is the effective radiation area. The ratio of effective radiation area to actual surface area is called effective radiation area factor (f_{eff}). Effective radiation area factor is equal to 0.72 for standing and to 0.69 for seated persons in a standard clothing ensemble representing the most typical indoor clothing (Fanger 1972). Diffuse solar radiation intensity received by the body surface can be calculated as follows:

$$S_d = \left[(I_d \cdot \tau_d \cdot A_w)/A_T\right] f_{eff} \cdot \alpha \tag{4}$$

The rest of the total diffuse radiation is assumed as being received by the other surfaces, such as walls, floor, ceiling, and furnitures proportional to their surface area.

In case of the person in a sunlit area, he receives the direct solar radiation transmitted by the windowglass in addition to diffuse solar radiation and thermal radiation from the inner surfaces whose temperatures are different from the air temperature. In order to predict if the person is in a sunlit area, it is necessary first of all to determine the contours of the sunlit area, which vary with solar angle and room-window geometry. Since the angle factor calculations are based on the horizontal plane passing through the center of the person, the contours of the sunlit area should be determined on the same plane, as shown in the following figure.



Direct solar radiation received by the person located at a point in the sunlit area is the function of posture and azimuthal orientation of the person and altitude angle of solar beam. Hence, the solar radiation intensity on the body surface is

$$S_D = I_{DN} \cdot \tau_D \cdot f_P \cdot \alpha \tag{5}$$

Projected area factor (f_p), which is the ratio of body area projected on a plane perpendicular to the sun beam to effective radiation area, can be determined by using Fanger's graphics for relevant solar altitute and azimuthal orientation of the body (Fanger 1972). The absorptance of clothing and human skin for solar radiation has been measured over the wavelength 0.3 to 9 μ (Rapp and Gagge 1967, 1970). From these data, the skin-clothing mean absorptance (α) can be determined. In this study, it is assumed that the rest of direct solar radiation entering the room is received by the floor surface homogeneously. The direct heat gains from the diffuse and direct solar radiation is calculated in a subroutine inserted in the main energy-analysis program. Since it is assumed that the azimuthal orientation of the occupants is not known, projected area factors have been determined for the azimuth angles between 0. and 360. in order to solve Equation 5 in this subroutine.

The other climatic factors of thermal comfort, which are air movement and relative humidity, are considered as secondary factors for the moderate temperatures normally aimed at indoors. Therefore, it may be assumed that the values of these factors are constant during the day. Within the temperature range of thermal comfort, there is no minimum limit for air velocity. The maximum allowed air velocity in an enclosure shall not exceed 0.15 and 0.25 m/s for winter and summer respectively (ASHRAE 1981). Humidification may need to be limited to prevent condensation on inner surfaces of the enclosure in winter.

6. Calculating discomfort indexes for the chosen points in the room.

Thermal response of seated and standing persons located at the chosen points in the enclosure is determined by calculating discomfort indexes with respect to the calculated climatic and the selected personal variables. In order to calculate discomfort indexes, the Pierce Two-Node Model can be used. This mathematical model considers the body as two concentric thermal compartments representing the skin and core of the body, in order to simulate the human thermoregulatory system. Thermal sensations are determined for any particular time with respect to core and skin temperatures for cold environments and skin wettedness for hot environments. The model also predicts the level of discomfort ranging from comfortable to very uncomfortable (see Table 1). Skin temperature and wettedness are calculated by numerical integration in the model. The net radiation flux (Flux) reaching the body is represented by the concept ERF and calculated in the model with respect to the difference between indoor air temperature and mean radiant temperature (i.e., Flux = ERF). A computer program was developed by Gagge (1973) for these tedious calculations included in the comfort model. This program was inserted into the main energy-analysis program in order to calculate discomfort indexes for the chosen points in the room.* In addition to the long-wave thermal radiation, which is represented by ERF in the current comfort model, direct and diffuse solar radiation flux on the body surface were taken into account in this study. Thus, if the person is not in a sunlit area, the net radiation flux on the body surface for the daylight hours (from sunrise to sunset) is calculated as follows in the comfort routine:

$$\text{Flux} = \text{ERF} + S_d \tag{6}$$

If the person is in a sunlit area, radiation flux on the body surface is

$$\text{Flux} = \text{ERF} + S_d + S_D \tag{7}$$

The comfort routine is called by the main program for each hour and for the chosen points after the air temperature and mean radiant temperatures at each point were calculated. Then the discomfort indexes for the persons located at the chosen points are calculated in this routine in terms of the environmental factors, such as air temperature,mean radiant temperature, air velocity, relative humidity, activity level, and clothing.

7. Evaluating the room under consideration.

Consequently, thermally acceptable zones can be determined by plotting calculated discomfort indexes and joining their equal values on the plan of the room. The coincidence between occupied zone and thermally acceptable zone is the indicator of thermal performance of the room under consideration.

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*Comfort program was previously added to a version of the program BLAST (see the Technical Note 38: Description and Utilization of the Thermal Comfort Analysis Routine in BLAST, LBL, Passive Research and Development Group, May 10, 1984).

APPLICATION AND RESULTS

In this paper, application of the methodology is given for only a few cases as an example, not for all possible cases to produce general results. The applications for these examples are based on the following assumptions.

Living rooms, which are placed in a multistory residential building located in Ankara (Turkey), were chosen as the examples for this paper. Discomfort indexes were calculated for January 21 and July 21, which are the representative days of underheated and overheated periods. Outdoor air temperature and solar radiation data, which are based on hourly measurements, were obtained by the Turkish State Meteorology Service. The equation for daily variation curve of outdoor air temperature was derived in the energy-analysis program by means of harmonic analysis of the given hourly values. The calculations relevant to solar radiation are based on daily measurements of total solar radiation on horizontal surface. Direct and diffuse components of the total radiation were determined using the formula suggested by Page (1964) and then the hourly values of direct and diffuse radiation intensities on the building surfaces were calculated.

Calculations have been done for different orientations of the chosen enclosures located in different parts of the ground floor, main floor under the top floor, and top floor. Floor area of the rooms was considered constant, as being equal to 18 m^2, in order to be able to compare the sensitivity of thermal comfort to the other building parameters. Room height is equal to 3 m. The chosen rooms have two external walls oriented to the south and to the west if they are located at the corner of the building. Otherwise they have one external wall oriented to the south. The shape factors of the rooms are changed as being equal to 2/1, 1/1, and 1/2. If the rooms has two external walls, the shape factor is the ratio of the south wall length to the west wall length. Building elements, including the envelope and partitions, consist of the following main materials, from outside to inside:

External wall: Cement plaster, 0.02 m, common brick, 0.20 m, heat insulation, 0.02 m, cement plaster, 0.02 m.

Roof: Gravel, 0.06 m, heat insulation, 0.04 m, concrete, 0.10 m, cement plaster, 0.02 m.

Floor (on the ground): Concrete, 0.10 m, heat insulation, 0.04 m, wood, 0.04 m.

Vertical partition: Cement plaster, 0.02 m, common brick, 0.10 m, cement plaster, 0.02 m.

Horizontal partition: Wood, 0.04 m, concrete, 0.10 m, cement plaster, 0.02 m.

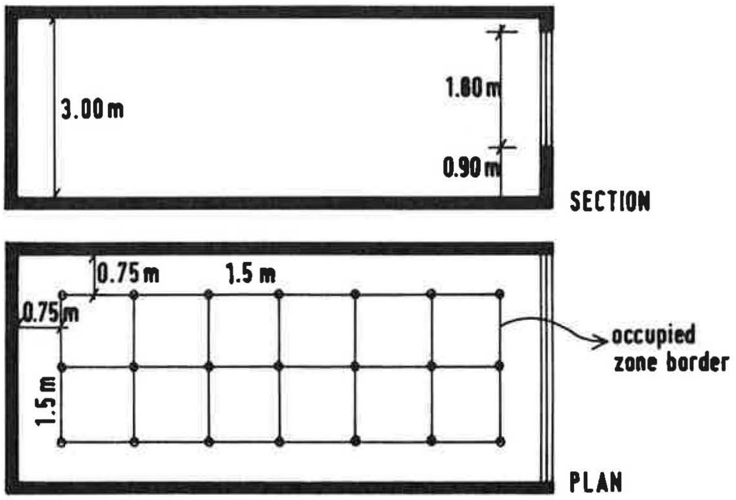
Materials and order of layers of the above listed building elements surrounding the rooms are identical for all rooms under consideration. Time-dependent heat flow through these elements was calculated, due to the physical properties of the materials constituting the elements.

Windows are made of double sheets of clear glass with metal frames, and U value of the window is equal to 3.0 $W/m^2 \cdot K$. Transparency ratio is 60% for the external wall or walls. Window height is 1.8 m and the window parapet is 0.9 m from the floor surface. There is not shading device on the windows.

The heating or cooling system is turned on between 18:00 and 24:00 to keep the air temperature at 21°C in winter if it is less than this value and at 27°C in summer if it is more than 27°C. For the unoccupied hours, if the air temperature is less than 18°C in winter, it is set at this value by the heating system, and it is allowed to float in summer. There are two lamps (75 W/lamp and 30% of the total wattage is radiant energy) in the rooms and they are turned on between 18:00 and 24:00. There are two persons between 18:00 and 24:00 in the rooms. They wear typical winter and summer clothing with insulation values of 0.9 and 0.5 Clo, respectively, and the activity level of typical sedentary tasks in a living room is 1.2 Met (ASHRAE 1981).

Hourly variations of inner surface temperatures and indoor air temperature have been calculated using the energy-analysis program developed by the author. Distance increment within the opaque components and time increment (Δt), which are required by the finite difference method for time-dependent temperature calculations, were chosen as 0.01 m and 72 s, respectively. Solar heat gain was calculated in the same program in accordance with solar angles and solar radiation intensity on the outer side of the envelope. Shading effect of the surrounding buildings and trees was not calculated. It was assumed that the façade of the room under consideration is completely shaded if the room is on the ground floor (i.e., it does not receive direct solar radiation). For the other cases (for the rooms on the main floor or on the top floor), the room façade is not shaded by the other buildings and trees.

Hourly variation of mean radiant temperatures for seated and standing postures of the occupants located at the chosen points in the room have been calculated by calling the relevant subroutine for each hour after the calculations of indoor air and inner surface temperatures. The interval between the points is equal to 1.5 m in both directions.



The contours of the sunlit area were determined in the program hour-by-hour, in terms of sun angles and room-window geometry, and thus the points in the sunlit area were determined. The surface area of the furniture in the room has been considered as being equal to half the floor area, in order to determine the fraction of diffuse solar radiation received by each surface in the room. Diffuse and direct solar radiation received by the occupants were calculated by means of Equation 4 and 5. It was assumed that the clothing-skin mean absorptivity of the human body is equal to 0.73.

It was assumed that air velocity in the enclosure is equal to 0.08 m/s and to 0.15 m/s for winter and summer, respectively, and relative humidity is 40% in winter and summer.

Then the discomfort indexes were calculated for the chosen points and for each hour, in terms of climatic conditions achieved in the room and the selected personal variables. For these calculations, the comfort routine was called for each hour and each point.

Finally, the calculated discomfort indexes were plotted on the room plans. Figure 2-12 are given as the examples for the seated persons in the living rooms; in order to express the sensitivity of thermal comfort to the building parameters. Some preliminary results of these examples may be summarized as follows:

Figures 2, 3, 4, 5, 6, and 7 show the sensitivity of discomfort indexes to the shape factor of the room. These rooms are placed on the main floor, which is under the top floor. Therefore, they receive both direct and diffuse radiation, as explained above. If the room has one external wall facing to the south and the shape factor is equal to 2/1; discomfort indexes are between 0.30 and 0.29 for 9% of the occupied area and range between 0.30 and 0.34 for the rest of this area in January at 14:00 (Figure 2).

If the room shape factor is equal to 1/2, discomfort indexes are between 0.00 and -0.03 for 4% of the occupied area, and for the rest of this area they change between 0.00 and 0.30 (Figure 3). In other words, for the room that has a shape factor of 2/1, the discomfort category is between neutral and slightly warm in 100% of occupied area; while for the other room, which has a narrower façade, the comfort category changes between neutral and slightly cool in some parts of the occupied area, during the sunny hours. For the rest of the day in winter, if there is no solar heat gain in the room, the percentage of the area in which thermal sensation is cool is higher for the room that has a bigger external wall than for the room with a smaller façade (Figure 4 and 5). Then we can say that the rooms that have a bigger façade area are more comfortable only during the sunny hours in winter and for the orientations exposed to the direct solar radiation. Otherwise, a smaller shape factor is more convenient for occupants' comfort in winter.

For summer, the room shape becomes a more important parameter for thermal comfort, because of the importance of solar radiation (Figure 6 and 7). At noontime, in the room that is located on the main floor and has a shape factor of 2/1, discomfort indexes change between 1.80 and 2.60, which express the thermal sensations of warm and hot, for most of the occupied area, while the thermal sensations are mostly neutral and slightly warm in the occupied area of the room that has a narrower façade. This means the smaller façade is more convenient for thermal comfort in summer conditions for the rooms oriented to the south.

Comparison of Figures 6 and 8 show us the sensitivity of discomfort indexes to the location of the room which is placed on the main floor at noontime. If the room is in the corner and one wall faces south and the other west (Figure 8), during sunny hours in summer most of the occupied area is uncomfortable or very uncomfortable, which is caused by hot and very hot thermal sensations. But if the room has only one external wall facing south (Figure 6), thermal sensations of the occupants change between warm and hot, which cause slightly uncomfortable and uncomfortable conditions. For the hours late in the afternoon, the differences are greater between two rooms that have the same shape factors, since one of them has a west wall.

Figures 9, 10, 11, and 12 are for the rooms that have south and west walls and are located on different floors of the building. The top floor is more comfortable than the ground floor only for sunny hours in winter, since the ground floor does not receive direct solar radiation for these examples. For the rest of the day, the difference in discomfort indexes between the two floors is not very significant. But in July, especially during the sunny hours, most of the occupied area is uncomfortable and very uncomfortable on the top floor, while the whole area is comfortable on the ground floor.

CONCLUSIONS

The methodology introduced in this paper is capable of evaluating the thermal performance of a room by calculating the discomfort indexes that vary with climatic conditions in the room and personal variables related to the occupants. Accordingly, it is useful to analyze the sensitivity of thermal comfort to the building parameters, which may be important for passive strategies in building design. Since the discomfort indexes are calculated in accordance with room geometry, the methodology can also be used to predict the asymmetric radiant effect of warm or cold surfaces in the room, such as a heating panel or a cold window surface.

It is obvious that inner surface temperatures of external elements and, accordingly, MRT and discomfort indexes, would be different for the different types of building envelope, due to the physical properties of the building materials constituting the envelope (Yılmaz 1985). The comparison of the building envelopes consisting of different materials is not given in this paper, since the effect of building materials on indoor thermal conditions were studied more extensively than the effects of the other building parameters.

Shape and location of the room are important as well the other building parameters. Therefore, the values of the other parameters affecting thermal comfort in the enclosure, such as the thickness of the heat insulation in the envelope or the dimensions of the shading devices, should not be determined independently from the room shape and location.

Thermal response of the human body receiving direct solar radiation in the room is significantly different from the other persons who receive only diffuse solar radiation. Therefore it is necessary to take the direct and diffuse solar radiation effect into account separately, especially for summer conditions, in order to predict the thermally comfortable areas in the room.

NOMENCLATURE

A_T = total area of the surfaces in the enclosure that receive radiation, m^2

A_W = surface area of the windows, m^2

c = specific heat of the air, $J/kg \cdot {}^oC$

ERF = effective radiant field, W/m^2

f_{eff} = effective radiation area factor for human body

f_p = projected radiation area factor for human body

Flux = net radiation flux reaching the human body in an enclosure, W/m^2
$F_{P-1}...F_{P-N}$ = angle factors between the person and surrounding surfaces
I_d = diffuse solar radiation intensity on the outer surface of the window, W/m^2
I_{DN} = direct solar radiation intensity on a plane perpendicular to the sun beam, on the outer side of the window, W/m^2
m = mass of the air in the room, kg
MRT = mean radiant temperature for a person in the enclosure, K
Q_k = amount of heat gain to the indoor air from the heat sources in the room within the time increment Δt, W
Q_o = amount of heat transfer between the indoor air and the inner surfaces of opaque components of the envelope, within the time increment Δt, W
Q_s = amount of heat gain to the indoor air from the solar radiation transmitted by glazing within the time increment Δt, W
Q_v = amount of heat gain/loss to/from the indoor air by means of ventilation and infiltration within the time increment Δt, W
Q_w = amount of heat transfer between the indoor air and the inner surfaces of transparent components of the envelope within the time incremenet Δt, W
S_d = diffuse solar radiation intensity on the body surface in an enclosure, W/m^2
S_D = direct solar radiation intensity on the body surface in an enclosure, W/m^2
T_a = ambient air temperature at any particular time, ^oC
T'_a = ambient air temperature before a time increment Δt, ^oC
$T_1...T_N$ = temperature of surrounding surfaces, K
α = the skin-clothing mean absorptance of the human body for solar radiation
Δt = time increment chosen for the finite difference method, s
τ_d = diffuse solar radiation transmissivity of the window glass
τ_D = direct solar radiation transmissivity of the window glass

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TABLE 1

Thermal Sensation Scale*

Numerical Code	Thermal Sensation	Comfort Category
+4	very hot	very uncomfortable
+3	hot	uncomfortable
+2	warm	slightly uncomfortable
+1	slightly warm	slightly uncomfortable
0	neutral	comfortable
-1	slightly cool	slightly uncomfortable
-2	cool	slightly uncomfortable
-3	cold	uncomfortable
-4	very cold	very uncomfortable

*Gagge et al. 1972.

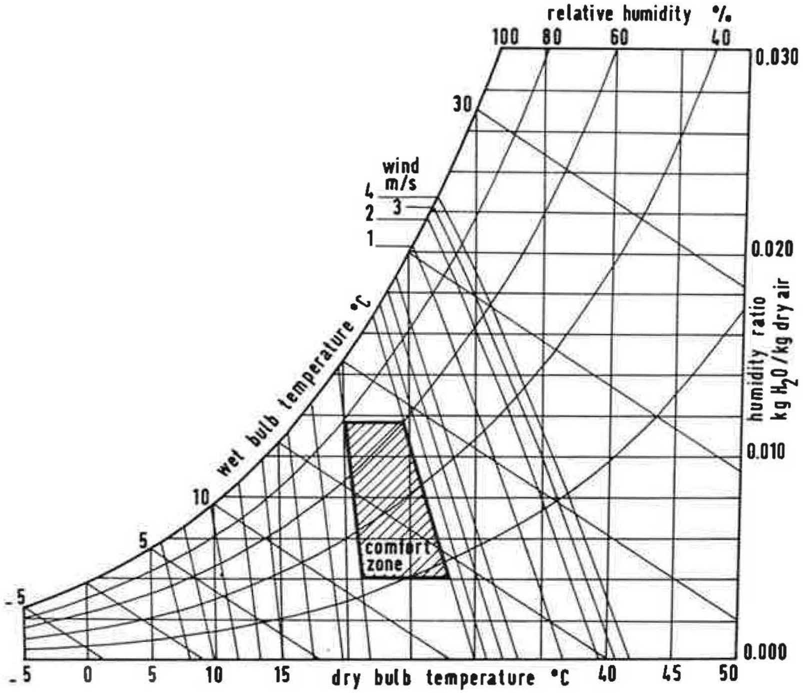

Figure 1. Bioclimatic chart - phychrometric format (1.3 Met, 0.8 Clo)

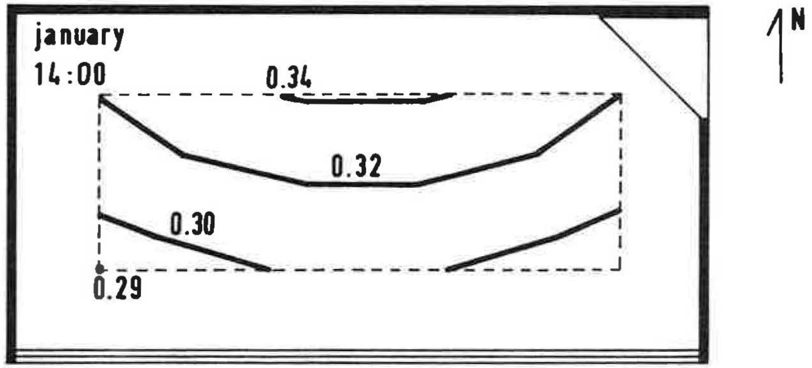

Figure 2. Discomfort indexes for seated person in the room located on the main floor and oriented to South. Shape factor of the room is 2/1

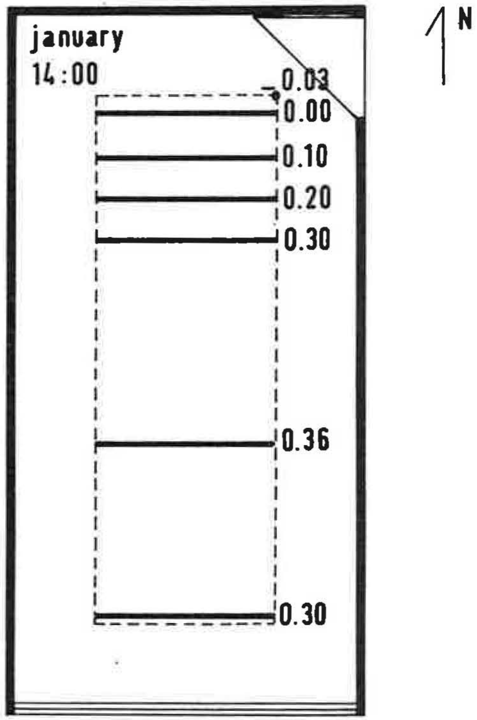

Figure 3. Discomfort indexes for a seated person in the room located on the main floor and oriented to South. Shape factor of the room is 1/2

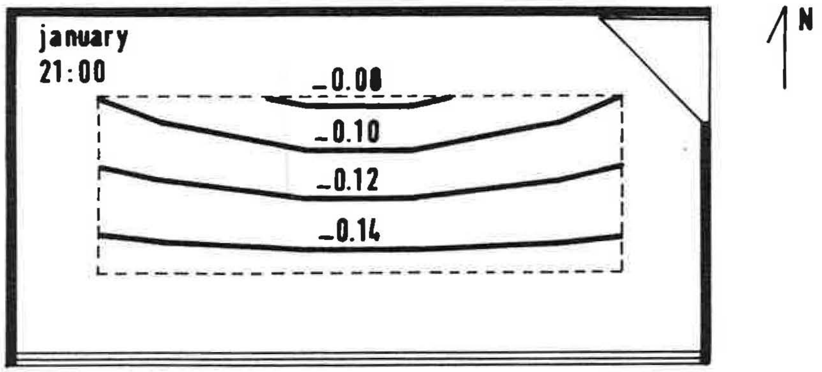

Figure 4. Discomfort indexes for seated person in the room located on the main floor and oriented to South. Shape factor of the room is 2/1

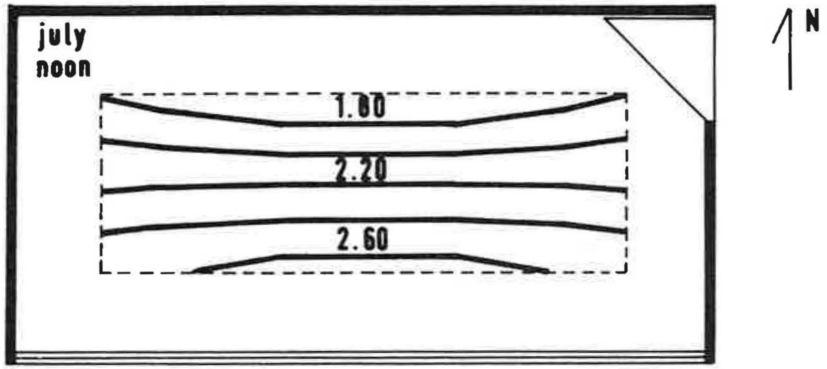

Figure 6. Discomfort indexes for seated person in the room located on the main floor and oriented to South. Shape factor of the room is 2/1

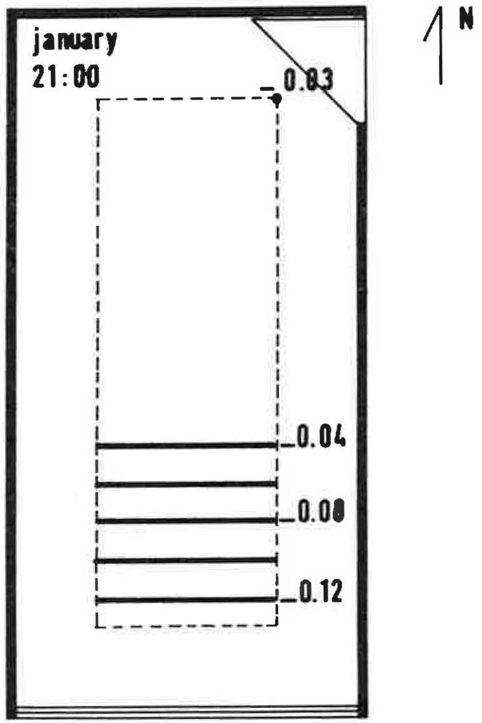

Figure 5. Discomfort indexes for a seated person in the room located on the main floor and oriented to South. Shape factor of the room is 1/2

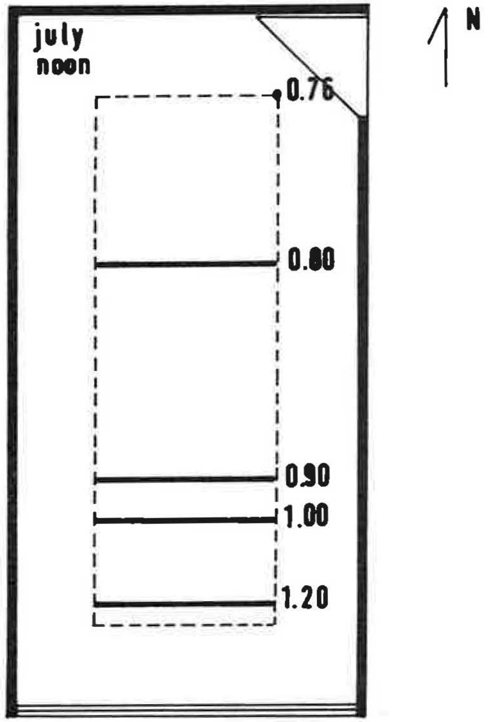

Figure 7. Discomfort indexes for a seated person in the room located on the main floor and oriented to South. Shape factor of the room is 1/2

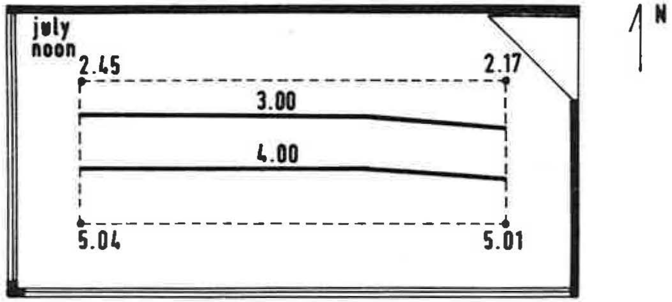

Figure 8. Discomfort indexes for seated person in the room located on the main floor and oriented to South and West, shape factor of the room is 2/1

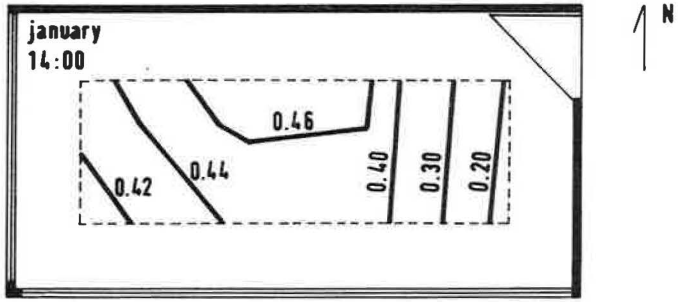

Figure 9. Discomfort indexes for seated person in the room located on top floor and oriented to South and West. Shape factor of the room is 2/1

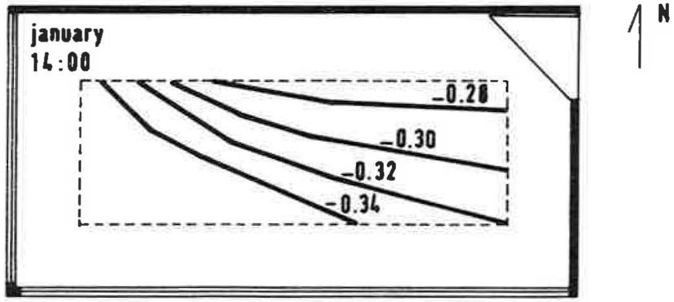

Figure 10. Discomfort indexes for seated person in the room located on ground floor and oriented to South and West. Shape factor of the room is 2/1

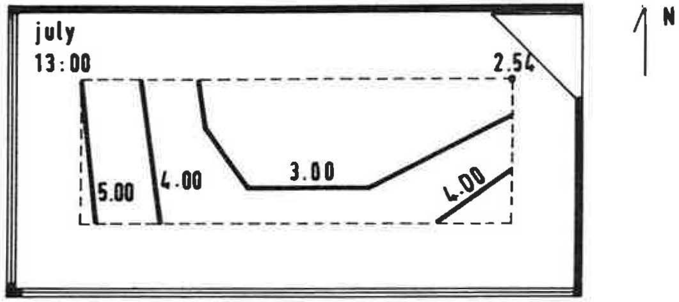

Figure 11. Discomfort indexes for seated person in the room located on top floor and oriented to South and West. Shape factor of the room

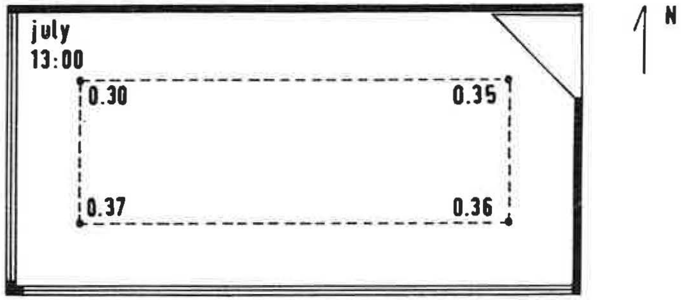

Figure 12. Discomfort indexes for seated person in the room located on ground floor and oriented to South and West. Shape factor of the room is 2/1