Variation in Indoor Thermal Environmental Parameters in an Open Space Office

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Abstract. Building energy modelling is an indispensable component of today's design method. However, as per research findings, real-life buildings could utilize almost twice the amount of their ideal energy performance. Thus, it is important to understand the variation in the thermal environmental and thermal sensation parameters in the office buildings during real-life operation. Currently, the design of the indoor environment in buildings is performed based on the appropriate national and international standards. Based on thermal comfort requirements for mechanically conditioned buildings, the temperatures are held within narrow limits, and it is expected that the new and existing buildings adhere to them very strictly. Naturally, the question arises, instead of keeping indoor thermal conditions constant, could it be healthier to make it dynamic. A more dynamic thermal environment that goes beyond the boundaries of comfort zones may be able to provide occupants with thermal comfort, along with instances of thermal delight and positive stimulation.

To this objective, physical measurements were carried out in open office space in Lausanne, Switzerland. Data showing the overall variation of the thermal comfort parameters in space and in time have been presented. The ranges of thermal environment parameters, i.e., operative temperature, relative humidity, air speed, and local discomfort factors consisting of horizontal and vertical radiant temperature asymmetries, vertical temperature differences are discussed. Also, thermal sensation indicators, i.e., PMV and PPD are calculated from the measured values. These values are then compared with the limits specified in the standard ISO 17772. The thermal environmental parameters, particularly operative temperature, mostly lay in the Category II and III. Local discomfort factors did not exceed the limits of Category I. Thermal sensation calculation showed that the conditions were more on the cooler side since PMV was in the range of -0.2 to -1 and, the PPD was between 10-20%.

Keywords. building energy modelling, thermal comfort, energy savings, dynamic thermal environment
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1. Introduction

The indoor thermal environment is largely influenced by the activities of the occupants, their metabolic rate and their thermal adaptability. Outdoor temperature also has a significant influence on the indoor thermal environment, even in the mechanically conditioned buildings. In winter, people resort to adaptive behaviours such as consuming hot food and beverages, putting clothing layers, etc. This can widen the range of the comfortable temperatures. The low outdoor temperature helps people to adapt to a cold environment. In studies, it has been found that lower the outdoor temperature and longer the cold climate was, the higher the usage rate of the district heating system in winter, and the longer the heating season was. The outdoor temperature affects the adaptive behaviour, even in heated buildings [1][2][3]. Maintaining a high indoor temperature during the winter is not only a waste of energy; but also nullifies people's adaptation to the environment [4].

The change in the thermal sensation of occupants with space is found to be an important factor determining thermal comfort. Under dynamic conditions, the change of thermal sensation of people with time has significant effect on the perception of thermal comfort [5]. Dynamic thermal environments, complete with certain natural features, may be more suitable for the human body [6]. Indeed, thermal environments that are beneficial to the human ability of thermal adaptation should be regarded as the healthier. Dynamic thermal environment can be established by allowing more variability of air temperature and/or air velocity. Studies of human responses showed that airflow similar to natural air movement has highest preference. Variation of indoor environmental parameters can result in substantial energy saving while an acceptable indoor climate could be maintained [7].

In rural areas in Northwest China the acceptable temperature ranges for the classrooms in Shaanxi, Gansu and Qinghai Provinces were 12.7-16.9 °C, 11.9-17.1 °C and 15.8-18.7 °C, respectively. Occupants have the ability to adapt to a wide range of temperature [8]. Studies suggest that people originally from cold climates even prefer a little bit lower temperature rather than a neutral temperature [9]. The indoor design temperature should consider the local climate and the clothing thermal resistance, the physiological characteristics, and the psychological adaptability of occupants. Maintaining a high indoor temperature consumes more energy, which is wasteful [10][11]. Results show that often buildings have discomfort due to high temperatures in the wintertime, which is indicative of over-heating [12][2][3].

Feeling of thermal comfort come from dynamic contrast [13]. If the poor thermal environment improves a little, people will feel significantly better [13]. The changes of temperature provide cold or hot stimulation on the human body, which can increase the pleasure of thermal sensation. Average operative temperature value of Europe is much higher than Asia (China). North America holds a narrower operative temperature range [14] thus in North America the indoor conditions have the highest meeting rate (93.5% of data points) of ASHRAE comfort zone. Most of outside-comfort-zone points of Europe are due to overheating, while the outside-comfort-zone points of China are mainly caused by overcooling [14]. The neutral indoor operative temperature during the summer in Beijing was 26.8 °C, while in the winter, it was 20.7 °C [4].

The above studies reveal that cooling and heating setpoints, as specified by the standards, are held within narrow limits. In Table 1, the categorization of the various environmental parameters as per ISO 17772 is tabulated [15][16]. The standard categorizes environmental parameters to "high" or "category I", "medium" or "Category II", "moderate" or "category III" and "low" or "category IV". The definition of each category are as follows:

I. High (Category I) should be selected for occupants with special needs (children, elderly, handicapped)

II. Medium (Category II) are the normal level used for the design and operation (typically used)

III. Moderate (Category III) can still provide an acceptable environment with some risk of reduced performance of the occupants.

IV. Low (Category IV) should only be used for a short time of the year or in the spaces with a very short time of occupancy.

The narrow limits of temperature could lead to the problem of high energy expenditure through overheating and overcooling. Also, it leads to the elimination of the innate thermal ability of the human body to adapt to the mild cold and mild hot conditions and unnecessary waste of energy. There are studies highlighting that exposure to mild cold conditions lead to the activation of Brown fat adipose tissues (BAT) which has been seen to increase the energy expenditure of the human body. Thus, speaking in the long term this can mean a healthier environment to have a mild cold dynamic indoor working condition [17][18].

To this objective, physical measurements are carried out in an open office space in Switzerland. Data showing the overall variation of the thermal comfort parameters in space and in time have been presented. The ranges of thermal environment parameters, i.e., operative temperature, relative humidity, air speed, and local discomfort factors consisting of horizontal and vertical radiant temperature asymmetries, vertical air temperature differences are discussed. Also, thermal sensation indicators, i.e. PMV and PPD, are calculated from the measured values and has been presented in this study. These values are then compared with the limits specified in the standard ISO 17772. The main purpose of the study is to illustrate the thermal environmental parameters during the real operation in an office building in Switzerland and assess their variability.

2. Methodology

The following section is devoted to describing the case study building and the measurement protocols.

2.1 Case Study

The case study building is an office building. The office space is located on the second floor and presents a dominant exposure to north. One smaller part of the open space offices faces east and single offices are exposed to the west. The floor plan (Figure 1) of the studied space consists of open space office (259.1 m2), 2 single offices (21.6 m^2/each), kitchen area (37.9 m2) and separated

Tab. 1 - Categorization of environmental parameters as per ISO 17772

Parameter	Category I	Category II	Category III	Category IV

Operative Temp (T_{op})	21-23 °C	20-24 °C	19-25 °C	17-26 °C
Relative Humidity (RH)	30-50 %	25-60 %	20-70 %	<20, >70 %
Air Speed (V_{air})	<0.1 m/s	<0.16 m/s	<0.21 m/s	>0.21 m/s
Hor. Radiant Asymmetry Temperature (ΔH^*)	<23 °C	-	<35 °C	>35 °C
Ver. Radiant Asymmetry Temperature ($\Delta V^\#$)	<5 °C	-	<7 °C	>7 °C
Vertical Temperature Difference (ΔT_v)	<2 °C	<3 °C	<4 °C	>4 °C
PMV	-0.2–0.2	-0.5–0.5	-0.7–0.7	-1.0–1.0
PPD	<6 %	<10 %	<25 %	>25 %

*For cold wall, #For warm ceiling

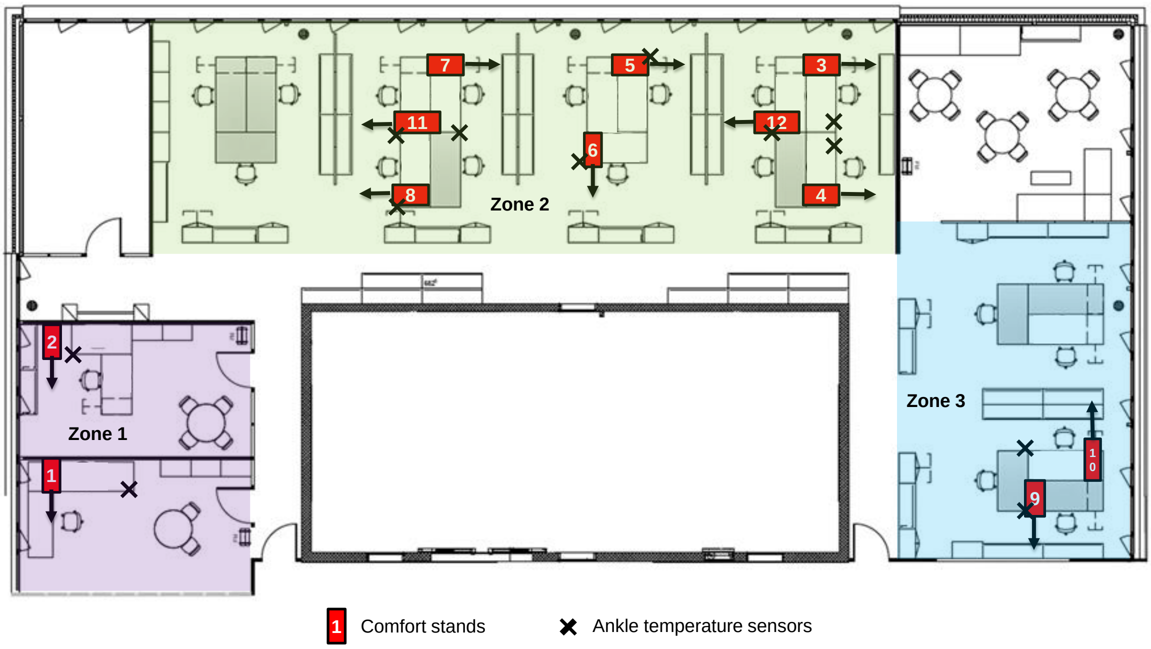

Fig. 1 - Case study plan with the location of the sensors

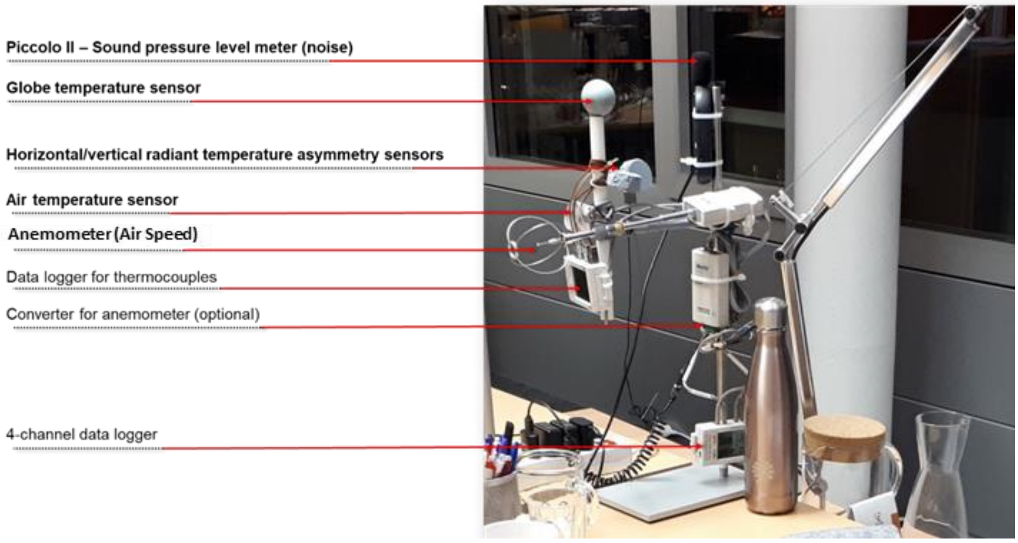

Fig. 2 - Sensor configuration in the stands

printing room that is excluded from the analysis. The floor plan has been divided into three zones out of which Zone 1 consists of two single offices and Zone 2 & 3 are open plan offices. Space heating and cooling is provided by a hydraulic radiant ceiling panel system. The heating/cooling circuit set-point in heating mode is 31°C while set-point in cooling mode is 19 °C. The system is connected to the general heat pump serving multiple buildings in the neighbourhood and an auxiliary heater. The indoor air temperature set-point for all zones is 23 °C and it is not possible to modify the set-point in any individual zones. The changeover between heating and cooling mode is calculated based on the sum of differences between room temperatures in different areas of the building.

The building is equipped with an air handling unit, the set-point of supply temperature depends on the outdoor temperature: if the outside temperature is equal or below 20 °C, the set-point of the supply temperature is 22 °C. The supply set-point than gradually decreases with the increase of outdoor temperature down to 18°C with an outdoor temperature equal or higher than 32 °C. The pressure for air supply and extraction is 180Pa and 140 Pa, respectively. The designed air flow rate for each inlet is 50 m^3/h. The occupants have the possibility to interact with windows and window blinds. Windows are casements windows (tilt-turn) and are all operable. The window blinds are regulated automatically but can be overridden manually. The desk lights are equipped with a motion sensor and turn ON automatically – even though a manual control is possible, it is not used. Ceiling lights installed along the central staircase block are always on during working hours and cannot be individually controlled by the employees.

2.2 Field Study Campaign

The field protocol consists of measurement of thermal environment and local discomfort parameters. The thermal environment variables that are measured and would be discussed in this paper are air temperature, globe temperature, air speed and relative humidity. For the local discomfort factors, ankle level temperature, horizontal and vertical radiant asymmetries are recorded. Air temperature, globe temperature, air speed, horizontal and vertical radiant temperature asymmetries recordings are done every 10 seconds. The ankle temperature measurements have been taken every 5 minutes. Figure 2 shows the typical configuration of the sensors quipped for the current filed study. Figure 1 shows the positioning of the different sensors in the office floor plan. The study was conducted in the winter for a duration of two weeks from 27th January, 2020 to 7th February 2020.

The air temperature, globe temperature and the air speed are measured at a height of 0.6 m above the desk level. It is approximately at the same level as the head of the occupants in a seated position. The ankle temperature sensor is placed near the ankle levels (0.1 m above the floor level). The measurements are used to calculate the vertical temperature differences. Mean radiant temperature and operative temperature are calculated from the measured parameters. Radiant temperature asymmetry sensors are also deployed to measure the horizontal and vertical radiant temperature asymmetry at height of 0.6 m above the desk level to test the presence of local discomfort sources. The globe temperature, air temperature and air speed measurements are accurate to ±0.2 % of the reading. The horizontal and vertical radiant temperature asymmetry are accurate to ±0.6 °C. The relative humidity readings have an accuracy of 2.5 %. And lastly the ankle temperature measurements are accurate to ±0.2 % of the reading. The thermal sensation indicators PMV and PPD was calculated by using the CBE Comfort Tool [19]. Few approximations are made, for example, clothing insulation is considered to be constantly at 0.6 clo and the metabolic rate of 1.1 met is considered which corresponds to seated and light working activity. These values correspond to actual clothing insulation and the activity level encountered in the studied office space.

3. Results and Discussion

In this section the results of the field study are presented along with discussion of the results. All the data represented is for the weekday working hours (7 am to 7 pm). The operative temperature distribution as seen in Figure 3a, shows that during almost all the working hours the temperature is in between 21-25 °C with vast majority of the hours lying in the Category I. The categorization of the parameters has been highlighted in the plots based on the values specified in Table 1. With the exception of a couple of stray spikes, there are almost no hours exposing the occupants to Category IV operative temperature. Similarly, in case of relative humidity (Figure 3b) during majority of the hours, the conditions were in Category I and Category II or between 25-45 %. The air speed lies mostly in the Categories I, II and III i.e. in the range of 0-0.21 m/s. There are also quite a few hours where the air speed lies in the Category IV as can be seen in Figure 3c.

As has already been discussed in the introduction, human beings have the intrinsic ability to adapt to mild cold and mild hot conditions. And this adaptation can be weakened as a result of exposure to constant temperatures for extended period of time. The question that naturally arises is that, would it be better to have a dynamic indoor environment where the temperature, relative humidity and air speed fluctuates within wide ranges rather than always maintaining the indoor conditions within the Category I and II. From the point of view of energy savings, it would definitely be beneficial as operating at lower temperature would save energy which would otherwise have been used for space conditioning.

For the local discomfort parameters, horizontal radiant temperature asymmetry (Figure 3d), vertical radiant temperature asymmetry (Figure 3e) and vertical air temperature differences (Figure 3f) have been presented below. The case study building is equipped with ceiling radiant panels for the cooling and heating purposes. Since the case study has been performed in the winter months, the ceiling panels were working primarily in the heating mode. The presence of these ceiling radiant panels results in vertical radiant temperature asymmetries but since these were working at low temperatures, the vertical radiant temperature asymmetry values are well within the Category I as prescribed by ISO 17772. The range of the values extend between 0-1 °C with a few outliers.

Similarly, the horizontal radiant temperature asymmetry values are quite low, also within the Category I lying between 0-1 °C. It is mainly due to the fact that there was absence of strong heat sources on the vertical surfaces in the building, except for windows. Based on the measurements, the

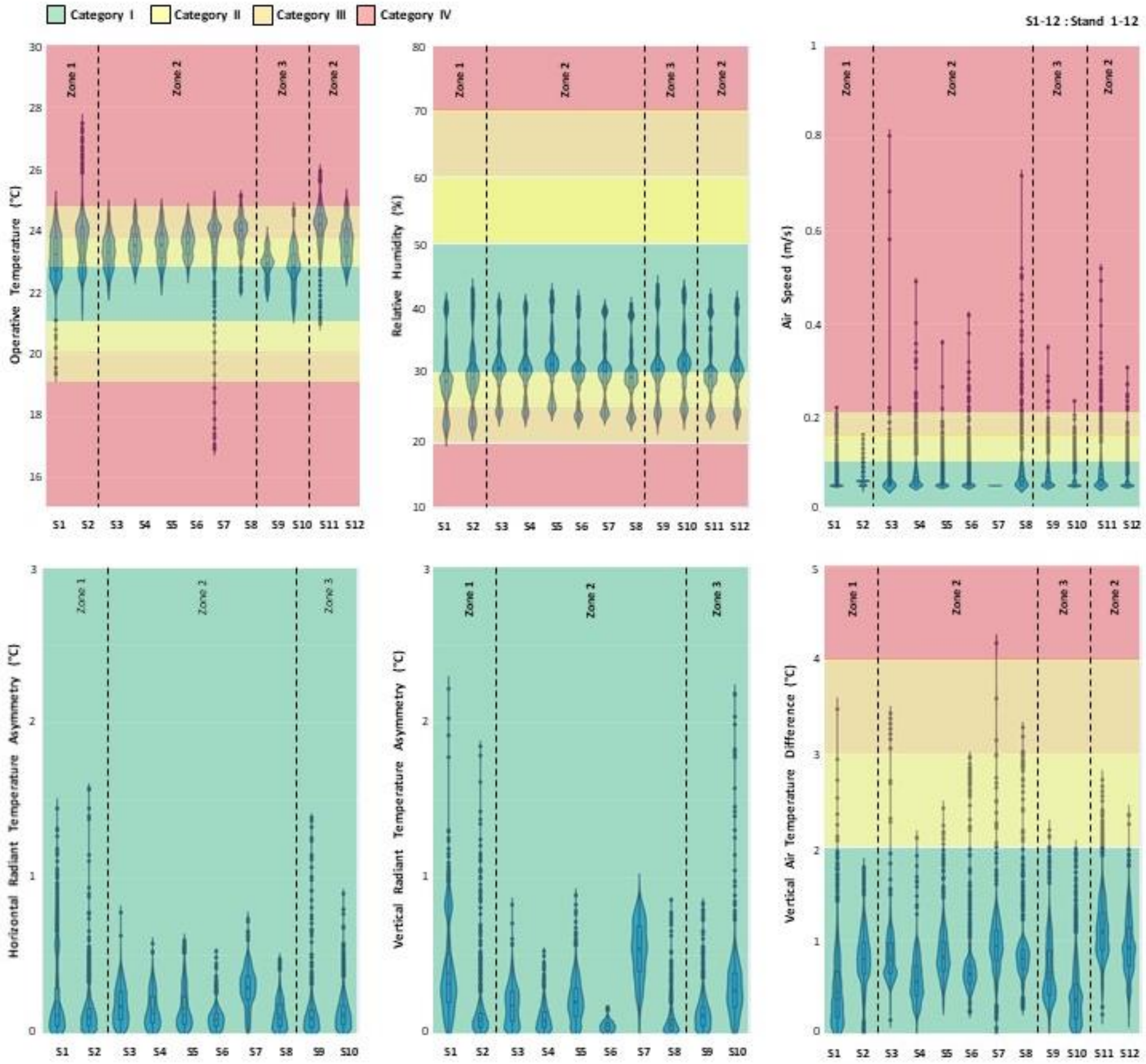

Fig. 3 - Spatial variations in thermal environmental parameters (a) Top, (b) RH, (c) Vair, (d) ΔH, (e) ΔV, (f) ΔT_V

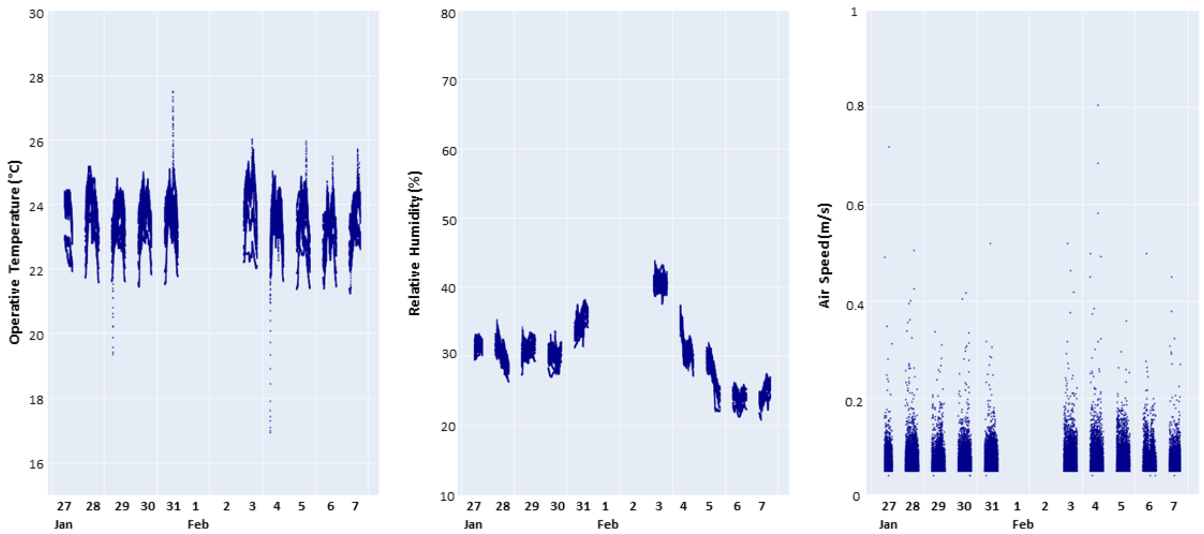

Fig. 4 - Temporal variations in thermal environmental parameters (a) Top, (b) RH, (c) V_{air}

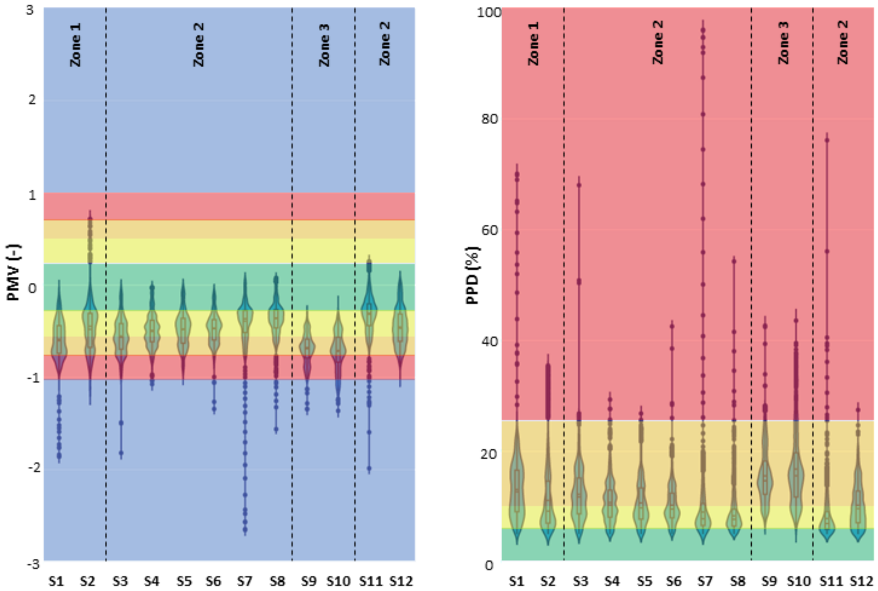

Fig. 5 - Spatial variations in calculated thermal sensation indicators (a) PMV, (b) PPD

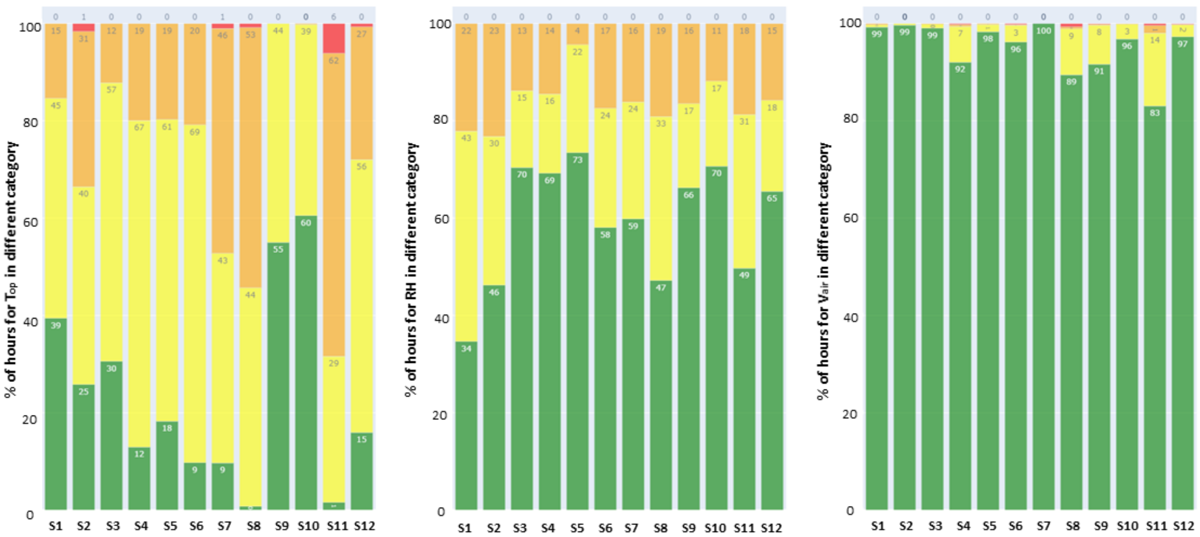

Fig. 6 - Percentage of hours within certain categories of thermal environment for (a) Top, (b) RH, (c) V_{air}

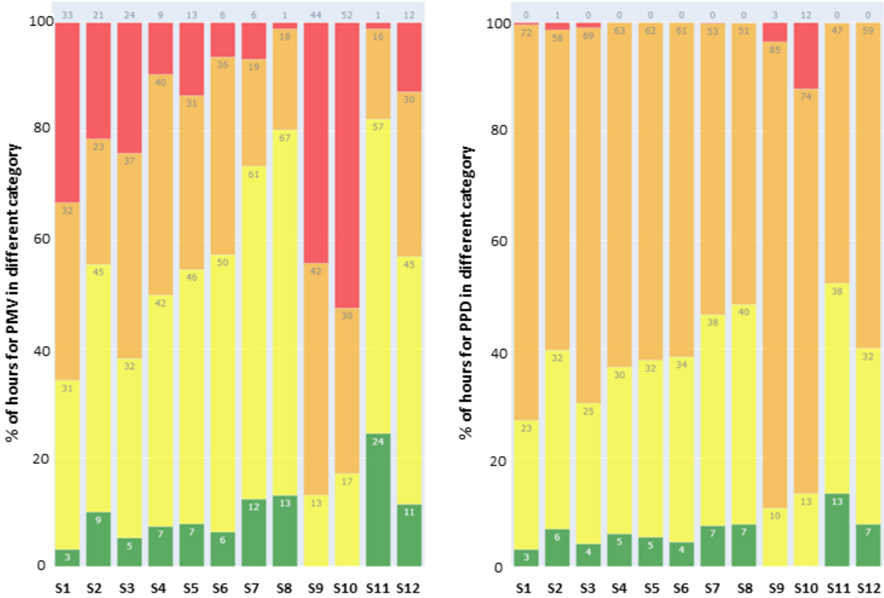

Fig. 7 - Percentage of hours within certain categories of thermal environment for (a) PMV, (b) PPD

shortwave radiation coming through the windows did not have significant effect on radiant temperature asymmetry. The vertical air temperature difference measures the air temperature difference at the head and the ankle level of the occupants. The values range between 0-2 °C with few discrete values above that range. Checking the above values with respect to the limits specified in the standard ISO 17772 for local discomfort parameters, they are within the acceptable range and should not result in uncomfortable condition for the occupants. In Figure 4 we see the temporal variation of the measured and calculated parameters only during the working hours (7 am to 7 pm). In case of the operative temperature a clear pattern can be seen where low temperatures of approximately 21 °C are seen at the beginning and the end of the working hours. While during the peak occupancy hours this temperature goes up to 25 °C. The fluctuations in relative humidity and air speed is apparently not so high to affect thermal comfort. Thus, PMV follows a trend very similar to that of the operative temperature. PMV calculations with respect to ASHRAE Standard 55-2017 leads to PMV values in the range of -0.5 to -1.2.

In the Figure 5a and 5b, the calculated values for Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD) are presented for the whole duration of the field study. They are calculated from the values measured in the study. PMV depends on air temperature, mean radiant temperature, relative humidity, air speed, clothing insulation and metabolic activity level. Mean radiant temperature has been calculated from measured parameters.

All the other values are measured directly and used for the calculation of PMV. As seen in Figure 5, the PMV is mostly on the colder side, lying between -0.2 and -1. This can be attributed to the low clo value of the occupants in this study. PPD is a function of PMV and can be directly calculated from it. Also, the PPD value can be seen to exceed the comfortable limits. In winter normally the occupants tend to wear light sweaters in their office space which can reduce this cool sensation.

Resuming the discussion about dynamic environment, we know that occupants may prefer certain degree of variability in their indoor environment. The changes of temperature provide cold or hot stimulation on the human body, which can increase the pleasure of feelings. In that scenario the above PMV and PPD calculation may not be so significant. Reminding the fact that exposing occupants to narrow range of comfortable temperatures we may be impairing the innate ability of the human body to adapt to mild cold and hot conditions. Our goal should be to make use of this thermal adaptability and promote dynamic indoor environment.

Figure 6 and 7 represents the percentage of hours in different comfort categories for the thermal environmental parameters in the field study. The categorization is with respect to ISO 17772, as seen in Table 1. For the operative temperature in the field study, 10-40% of the working hours lie in Category I, 30-60% in Category II, 10-40% in Category III and almost negligible in Category IV. This translates to the temperature range of 21-26 °C for the majority of hours. In case of relative humidity 35-70% of the occupancy hours lie in the Category I, 15-30% in Category II and about 10% in Category III. While for air speed most of the working hours (about 95%) in all positions lie in Category I according to ISO 17772.

PMV and PPD calculation have been performed by using the web-based tool for thermal comfort calculations developed at the University of California at Berkeley (CBE Comfort Tool). For the PMV values we find that only about 10% of the occupancy hours belong to Category I, 20-50% in the Category II, 20-40% in Category III and 10-20% also in Category IV. Also, for PPD calculations about 85-95% of hours lie in Category II and III. According to the standard ISO 17772, the hours in Category III and IV are supposed to be uncomfortable for the occupants and should be minimized. This is mainly because of the operative temperature which is found to be the in range of 21-26 °C.

Although there are no wild fluctuations in the indoor thermal environment but it is still categorized as uncomfortable according to the limits specified in ISO 17772 which, as we already discussed above, prescribes very narrow limits especially for operative temperature. In the introduction we discussed how temperatures much colder and warmer than 21-26 °C have been regarded as acceptable by the occupants. Thus, the standards need to take into consideration the local climate and thermal adaptability of the occupants when defining comfort category limits. Our objective should be to promote a dynamic indoor environment. The changes of temperature provide cold or hot stimulation on the human body, which can increase the pleasure of thermal sensation. And at the same time, it can reduce the overuse of energy by eliminating overheating and overcooling.

4. Conclusion

A field study was conducted in an open office space in the winter for a duration of two weeks from 27th January, 2020 to 7th February 2020. The field protocol consists of measurement of thermal environment and local thermal discomfort parameters. The thermal environment variables that are measured are air temperature, globe temperature, air speed and relative humidity. For the local discomfort factors, ankle level temperature, horizontal and vertical radiant temperature asymmetries are recorded. The following conclusions can be made:

I) The thermal environmental parameters mostly lie in the Category I, II and III ranges: operative temperature in between 21-26 °C, relative humidity in between 25-45 % and, the air speed in the range of 0-0.2 m/s. There is a certain degree of dynamicity in the indoor environment particularly as seen in the temperature fluctuations. But the temperature values can be reduced by 4-5 °C to be in the range of 16-21 °C which can increase energy savings and may potentially even provide long term health benefits through increased energy metabolism in the occupants.

II) Local thermal discomfort factors did not exceed the limits of Category I: horizontal and vertical radiant temperature asymmetries lie in between 0-1 °C and, the vertical temperature difference is mostly in the range of 0-2 °C. Thus, the indoor conditions remained comfortable with respect to the presence of local discomfort.

III) Thermal sensation indicators showed that the conditions are more on the cooler side. The PMV is in the range of -0.2 to -1 and, the PPD is in between 10-20 %. ISO 17772 specifies very narrow limits for comfort requirements especially with respect to operative temperature values.

IV) In the case study the indoor conditions are dynamic to some extent but they can be categorized as uncomfortable for most of the hours according to ISO 17772. We remind the fact that by exposing occupants to narrow range of temperatures we may be weakening the innate ability of the human body to adapt to mild cold and hot conditions. Our goal should be to make use of this thermal adaptability and create a dynamic indoor environment.

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