Prediction of Indoor Thermal Environment and Heat stress (WBGT, PHS, PMV) in Tropical University Classrooms

Biplob Kanti Biswas, Yasuhiro Hamada, Nusrat Jannat

Abstract— In tropical hot humid condition, indoor climatic condition fluctuates from the comfort range during summer seasons. University classrooms are one of the building categories, where occupants experience this phenomenon most. Student's regular classroom activities and limited scope of clothing adjustment cause trouble during their fixed schedule. Additionally, it creates more discomfort when they spend a long time in the classrooms. In this research work, we focus on figuring out the present thermal condition and heat stress at university classrooms in Bangladesh and evaluate the acceptable adaptive thermal comfort. Field monitoring was conducted at a university classroom during lesson period, in summer time (April-July) and basic climatic information was recorded. Heat stress parameters Wet Bulb Globe Temperature (WBGT), Predicted Heat Strain (PHS) and Predicted Mean Vote (PMV) were evaluated from the field measurement data. It was observed that hot indoor temperature and high relative humidity have an adverse impact on both physical and physiological condition of the occupants. It leads to health risk and create heat stress. From field study, it was found that around 30-32% WBGT remains above the moderate zone, 35-40% skin temperature exceeds the normal condition and PMV reach at its dissatisfaction level near about 40-45% during lesson period. By the time period of 12:00 to 15:00, regularly heat stress reaches its peak and creates health issues. Finally, from field observation, this study specifies that temperature between 26-28°C, humidity 65-70% with a significant air velocity 0.4-0.6 ms-1 indicate the acceptable comfort condition during the summer season in classrooms.

Index Terms— Heat stress, Indoor thermal comfort, Tropical climate, University classrooms.

1 INTRODUCTION

UNIVERSITY grants commission of Bangladesh (UGC) is the governing body of universities in Bangladesh. According to UGC [1], there are 37 government universities all over the country. Here student's performances in terms of attention, concentration, learning and hearing mostly depend on a healthy and comfortable indoor climatic condition [2-5]. But the alarming situation is that, most of the cases the indoor climate remains unconcerned about the health of the students. Moreover human performance is also overlooked during health impact analysis [6] like other tropical countries. Most of the classrooms are designed only to shelter the students as much as possible because of the vast population. In hot and humid climate, it has an unfavorable effect on thermal comfort for occupants. People in residences can adjust their clothing and activities according to thermal stress, where occupants at university classroom have a small extension of adaptive opportunities [7-8]. They have some limited parameters like adding or removing clothes, controlling windows and adjusting moving sun shading devices [9-12]. They face heat stress which increases discomfort and decreases the physical and mental performance [13-15]. Heat stress is the net heat load caused by metabolic heat, clothing and environmental factors (air temperature, relative humidity, air movement and radiant heat). By field monitoring observation, it was found that the indoor climate of university classrooms is highly affected by hot humid tropical climate. Basic thermal condition like air temperature (AT) °C, relative humidity (RH) % and air velocity (v) ms^{-1} are not always in satisfactory level according to ASHRAE [16]. According to ASHRAE, thermal comfort is the condition of mind, which can be expressed at its satisfaction level with the thermal environment and assessed by subjective evaluation. From observation, during summer time indoor climate creates serious health issues like dehydration, heavy sweating, breathe which can trigger allergies, asthma attacks, even heat stroke [17,20] when the students are spending a long period of time for sitting at their desk. Even heat-related deaths can occur at a high temperature. The primary purpose of this study was to figure out the thermal condition in classrooms via objective measurement and comparison with ASHRAE standards [21] for the hottest months of the year, April, May, June and July and also find out the adaptive comfort condition for the occupants. The objectives are:

- To investigate the wet bulb globe temperature (WBGT) which is well-established heat index for an indoor climate with different metabolic rate specified in international standards [22, 23].
- To establish predicted heat strain (PHS) (It is one of the-indexes for evaluating heat stress, which can be defined as the physiological response resulting from heat stress) [24], skin temperature (t_{sk}) and core temperature (t_{cr}) [25], to determine the risk in the classrooms and evaluate the safety of students.
- To explore predicted mean vote (PMV) [26, 27] as per International Standard ISO 7730 [28], which is most widely used index of thermal comfort in indoor climate.

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- To estimate the adaptive thermal comfort condition for the occupants in this climatic condition.

2 Research Methodology

This study was concentrated to investigate the present indoor climatic condition of the university classrooms by means of the objective and subjective approaches. For understanding the thermal condition, it is essential to explore the relationship between the indoor environments with comfort parameters [29, 30]. The field study was conducted in a university classroom at Chittagong University of Engineering and Technology, Bangladesh. Fig.1 shows the overall research work structure.

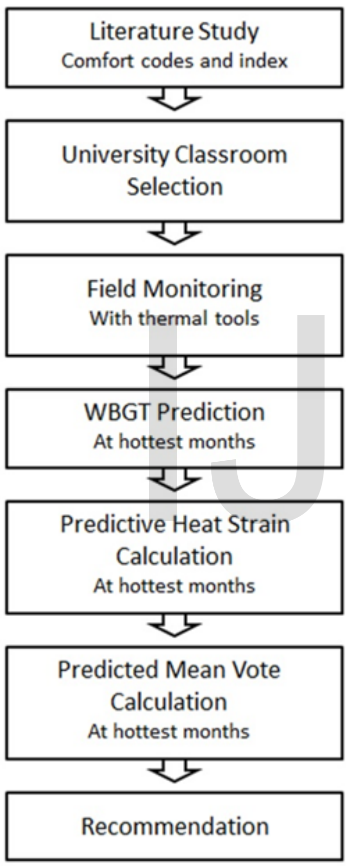

Fig. 1. Research structure

2.1 Classroom Selection Criteria

For the study, we have selected the classroom which is exposed to worse climatic conditions due to its location. In Chittagong, the climate is mostly hot and humid. The Bay of Bengal is very near to it on the west side, as a result the humidity goes higher than the other parts of the country. For selection of the building, local construction materials like concrete and brick with plaster were preferred. The building is 12 storied and has concrete floor slabs with 127mm brick wall, cladding with plaster. Field monitoring was conducted at the 3rd floor (East part) of the building. In Bangladesh, most of the academic buildings are 4-5 storied. Generally, ground floor and top floor serve as laboratory, seminar room, meeting room, teachers' room and other multiple usages. So 3rd floor can be considered as a middling zone of regular classrooms at different floor levels. The building is surrounded by hill at the east side and a 3 storied building at the west side. North and south parts of the building are enclosed by large trees. Fig.2 shows the basic layout of the surveyed space and the location of the measuring point. Fig.3 illustrates the sectional detail of the classroom. The building has a natural ventilation (NV) system with mechanical ventilation (MV) facility like electric ceiling fans. Table 1 shows the basic information about the surveyed space.

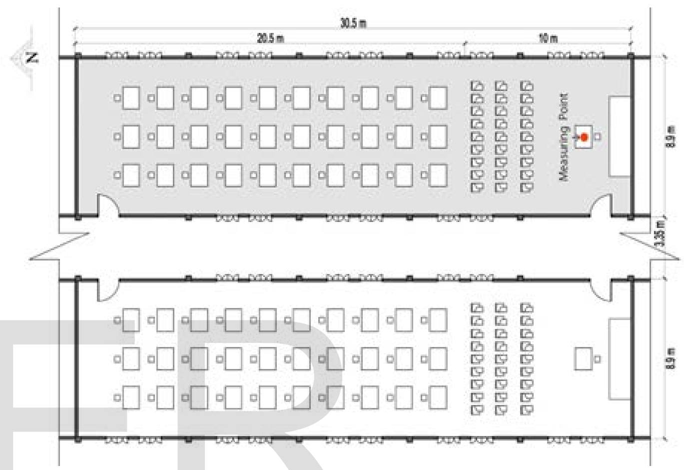

Fig. 2. Floor plan of the classroom.

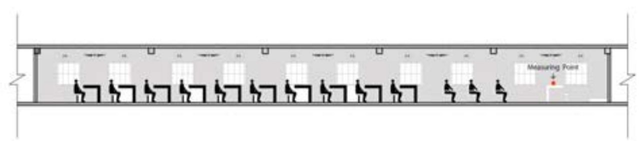

Fig. 3. Longitudinal section of the classroom

TABLE 1
Basic Information of the Study Space

Input consideration	
Area	271.45 m2
Length	30.5 m
Width	8.9 m
Height	2.9 m
Building material	Brick, Concrete, Plaster
Occupants	30 (Male 15, Female 15)
Window size	1.22 m X 1.22 m
Window ratio against wall	1 : 9.6
No. of Fan	15 nos. (75 W, air delivery 250 m3/min)
No. of Light	40 nos. (60 W)

3 Data Collection

3.1 Objective Approach

For Bangladesh, the most hot and humid months are April, May, June and July. Fig. 4 displays annual AT and RH of Chittagong region in Bangladesh correspondingly [31]. We conducted field monitoring once in a week (total 17 days), during April to July in the year of 2016. Data were collected from 9:00 to 17:00 with one hour interval in regular lesson period. Physical measurements were carried out at the point shown on Fig. 2 and Fig. 3. Because of uniform placement of windows at sidewalls and flat arrangement of air fans, basic climatic conditions were found similar at everywhere of the classroom and sampling point was selected depending on that condition. Indoor air temperature, relative humidity, and air velocity were measured by using LM-8102 (accuracy: 1% rdg ±1°C and ≥70% RH, 4% rdg ±1.2% RH). At the sampling point, the tool was left to run 3 minutes before taking the values and parameters were recorded at one hour interval. All data were recorded at 1.1 m height of the floor, which recommended the seated level of the occupants [32]. Clear height of the classroom was 2.9 meters. During the measurement time, windows were open, and fans were switched on for ventilation. After measuring the environmental parameters, metabolic rate and clothing insulation were estimated from ASHRAE standards [33]. This standard has a specific metabolic rate for corresponding activities. While university classroom activities are diverse, the metabolic rate can be changed. Considering this issue the data was collected from the steady state, at least for 15 min. For this study metabolic rate was taken 1.1 met, where students were seated and involved in light activities such as reading, writing, speaking etc. Clothing of the subject was considered by checklist. For boys, it was long pants and shirt or T-shirt with underwear, where for girls, it was salwar kameez and underwear mostly. Some of the students have different choices. The average clothing insulation was taken 0.53 clo with a 0.1 clo deviation for male and 0.15 clo for female. To determine the clothing insulation, subjects were asked to write about their clothing information before the data collection procedure. After summing and averaging the value was found 0.53 clo according to ASHRAE standards [16].

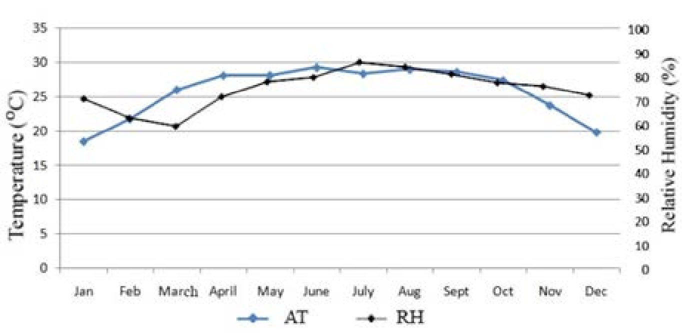

Fig. 4. Annual Air temperature (AT) and Relative humidity (RH)

TABLE 2

Description of Occupants

Input consideration	
Total occupants	30 nos. (For every measurement same sample).
Male	15 nos. (For every measurement same sample).
Female	15 nos. (For every measurement same sample).
Age	21-23 years
Health condition	Good
Male cloths	Pants and shirt or T-shirt, underwear. (0.53 clo, deviation 0.1 clo)
Female cloths	Salwar kameez, underwear. (0.53 clo, deviation 0.15 clo)
Activities	Listening lectures, reading, writing
Metabolic rate	1.1 met

TABLE 3

Subjective Consideration for Heat Stress Calculation

Input consideration	unit	
Height (h)	m	1.72
Weight (m)	kg	61
Body mass index (BMI)	m^2	1.50
Metabolic rate (M)	met	1.1
Clothing rate (I_{clo})	clo	0.53
Rectal Temperature (t_{re})	^{o}C	38.00
Moistness cloths thermal efficiency (g_{cl},W)		0.122
Oxygen uptake (VO_2 max %)	%	30-40

TABLE 4

WBGT Risk Factor

WBGT (^{o}C)	Risk Factor	Metabolic Rate, M Limit (1 MET=58.2 W/m²)
≤ 26.6 (°C)	Lower	Very High Activity M>260
26.7 - 29.3 (°C)	Moderate	Moderate to High Activity, 200 < M ≤ 260
29.4 - 31.0 (°C)	Moderate to Risk	Moderate Activity, 130 < M ≤ 200
31.1 - 32.1 (°C)	Risk	Light Activity, 65 < M ≤ 130
≥ 32.2 (°C)	High Risk	Very Light Activity, M ≤ 65

3.1 Subjective Assessment

The subjective approach was conducted for finding the judgment about the thermal comfort of the indoor environment. The objective was to figure out the thermal sensation vote of the ASHRAE 7 point scale, i.e. −3, −2, −1, 0, 1, 2 and 3 representing cold, cool, slightly cool, neutral, slightly warm, warm and hot, respectively [27]. In order to assess the thermal comfort condition, a group of 30 students was performed in the classroom for every sampling time. Among them, 50% were male students and 50% were female. During the measurement time, they were asked to write the basic information about thermal calculations (age, sex and clothing). After that height, weight and blood pressure of the selected students were measured. Most of them were between 21 to 23 years old and had a good health to commit the study works. Table 2 shows the summarized information of the subjects and Table 3 illustrates the subjects' demographic parameters for heat stress calculation. Students were uniformly distributed during the class hours in their classroom and did their normal lesson tasks. During the monitoring time they used to wear normal summer clothing. For predicting health risk according to WBGT, PHS and PMV, thermal data (AT, RH and V) were collected at a regular class time. The recorded information was elaborated to evaluate thermal comfort WBGT, PHS and PMV where metabolic rate and clothing were also considered as standard.

4 RESULT ANALYSIS AND DISCUSSION

4.1 WBGT Prediction Calculation

WBGT is a heat exposure index, a combination of air temperature (T_a, measured by dry thermometer), wet bulb temperature (T_{nwb}, measured by wetted thermometer exposed to air) and black globe temperature (T_g, measured by a 150 mm diameter globe). Because of, not direct radiation in the indoor the equation of WBGT is

$$WBGT = 0.7\ T_{nwb} + 0.3\ T_g \quad (1)$$

When air velocity is $v \geq 0.25\text{-}3\ ms^{-1}$, $T_w = T_{nwb}$; $T_g = T_a$ [26]. Here, wet bulb temperature (T_w) was calculated by using air temperature (AT) and relative humidity (RH) by the following equations:

$$T_w = (((0.00066 \times P) \times T_a) + ((4098 \times E)/((T_{dc} + 237.7)^2 \times T_{dc}))/((0.00066 \times P) + (4098 \times E)/((T_{dc} + 237.7)^2 \quad (2)$$

Here, $T_{dc} = ((T_a - (14.55 + 0.114 \times T_a) \times (1-(0.01 \times RH)) - ((2.5 + 0.0007 \times T_a) \times (1- (0.01 \times RH)))^3 - (15.9 - 1.117 \times T_a) \times (1- (0.01 \times RH))^{14}))$ (3)

$$E = 6.1078 \exp((17.269*T) / (237.3+T)) \quad (4)$$

All the equations were formulated according to ISO 7243.

Wet bulb temperature indicates the efficiency of body cooling by sweat evaporation [34]. Table 4 shows the risk factors and M limit correlations, according to WBGT [35]. Here we found that below 26.6°C risk factor is lower, where 26.7–29.3°C it is moderate, 29.4-31.0°C it is moderate to risk, 31.1-32.1°C it is risky and above 32.2°C it is in the high-risk zone. Table 4 also shows the M limit (activity recommendation) according to risk factor [35, 36], at lower risk M can exceed 260 M, at moderate it should be between 200-260 M, at moderate to risk zone it is between 130-200 M, at risk zone it should be 65-130 and when it is in high risk zone it should not exceed 65 M. Fig. 5, Fig. 6 and Fig. 7 show the measured indoor data of AT, RH and air velocity V from April to June respectively. Indoor air velocity at a particular time (data collection time) was mostly constant all over the class room because of uniform distribution of electric fans and even window position at both east and west walls. These data were collected by using the measurement tool once per week from 9:00 to 17:00 when regular class activities were ongoing. The obtained result is an anxiety for the students' health. Here elevated AT and high RH are not in comfort range. As a result it can cause dehydration and sweating which can lead to heat stroke, if they stay without drinking for a long time and do some heavy tasks than the regular activities. For tropical country like Bangladesh AT between 25.5- 28 °C, RH between 30-60% is considered as a comfort range [37], when air velocity is 1.6-5.4 ms^{-1} [38]. Field measurement displays elevated values from these comfort standard. In this period of time AT fluctuates from 30-38°C during day time where RH remains between 70-100% and indoor air velocity was mostly constant in all over the study zone for uniform window positioning and electric fan orientation. But lack of adequate ventilation also causes problem for the indoor comfort gain [39].

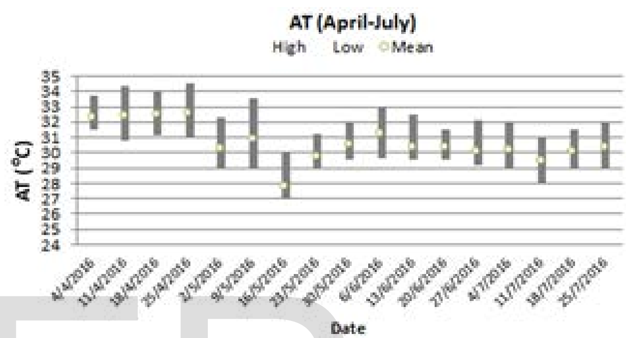

Fig. 5. Indoor Air Temperature (AT)

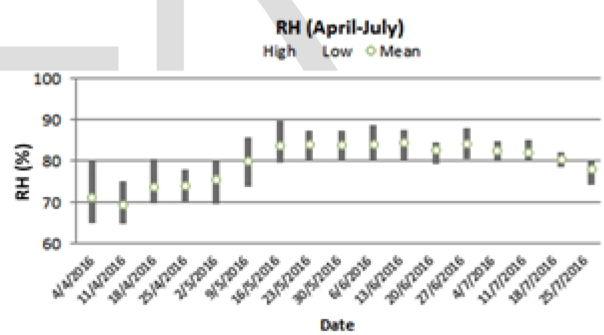

Fig. 6. Indoor Relative Humidity (RH)

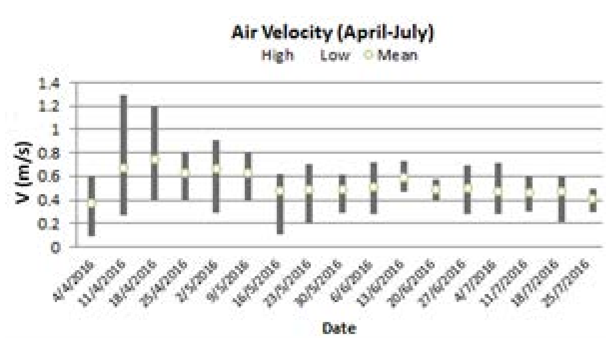

Fig. 7. Indoor Air Velocity (V)

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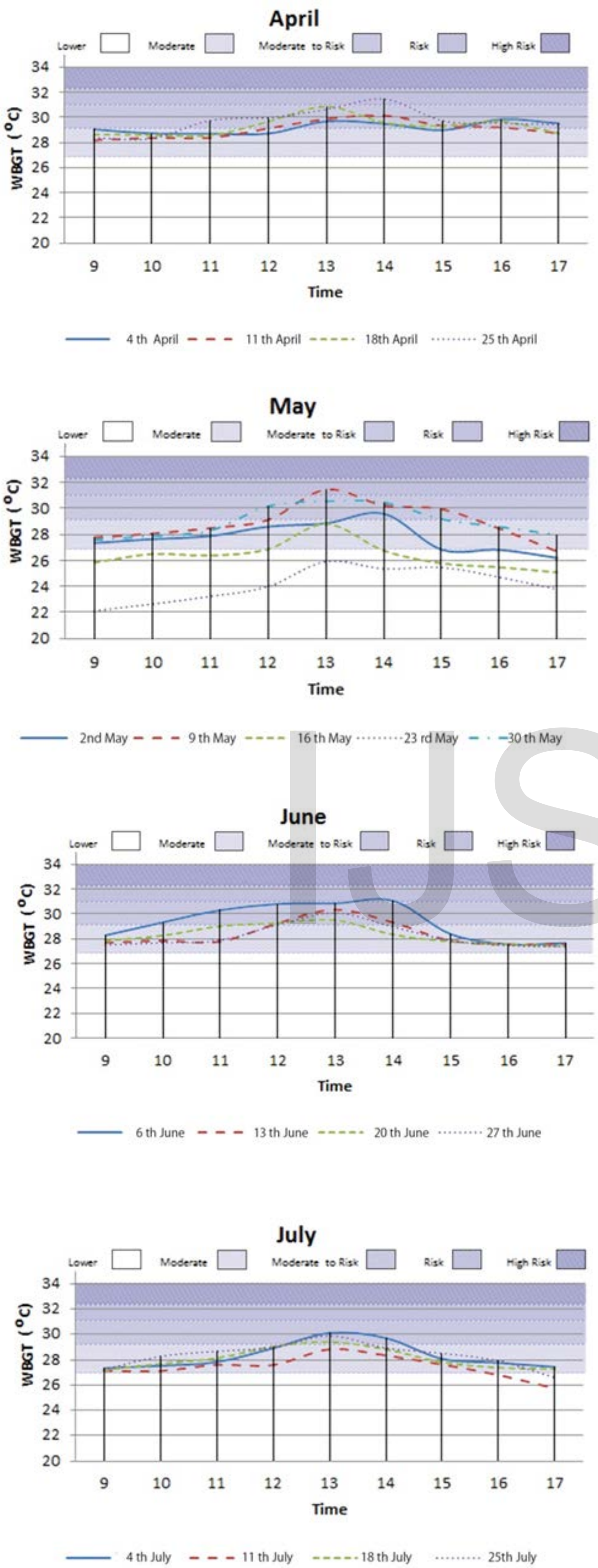

Fig. 8. Predicted WBGT (April-July)

Fig. 8 shows the actual WBGT for the active time from 9:00 to 17:00. From the field measurement, it was observed that the maximum WBGT goes up to 31.5°C at mid of the day time which is in the risky zone in risk factor chart. At morning, and afternoon time it is 26-28°C which is quite comfortable. Analyzing the collected data it was found that during 12:00 to 15:00 the value rises to its maximum level and almost 69% cases it is found around at moderate, 23% at moderate to risk and 2% at a risk zone (Fig. 9). During this period of time, the indoor temperature went higher around 32-34°C and the humidity was around 75-85%, which put WBGT at a risky zone. It has been illustrated that 12:00 to 15:00 is the peak time of health risk according to WBGT and suggested for very light activities. But in university, sometimes students need to do different activities like experimental work, model making, performing activities and many other moderate to high activities which can be risky for the M limitations.

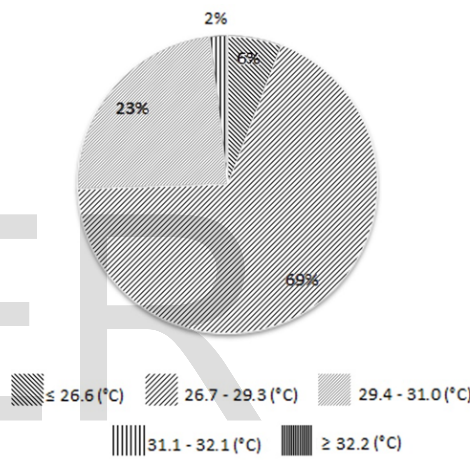

Fig. 9. Comparison of WBGT during April-July

TABLE 5
PMV INDEX

Scale	Prediction
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

4.2 PHS Prediction Calculation

To derive PHS criteria, here established formulas were in term according to ISO standards 7933. For calculation of PHS these formulas have been conducted.

For clothed subject skin temperature $t_{sk} = 12.17 + 0.020\ t_a + 0.044\ t_r + 0.194\ P_a - 0.253\ V_a + 0.003\ M + 0.513\ t_{re}$ (5)

Here for light work like studying, sitting metabolic rate was considered as 1.1 met = 58.2 W/m^2.

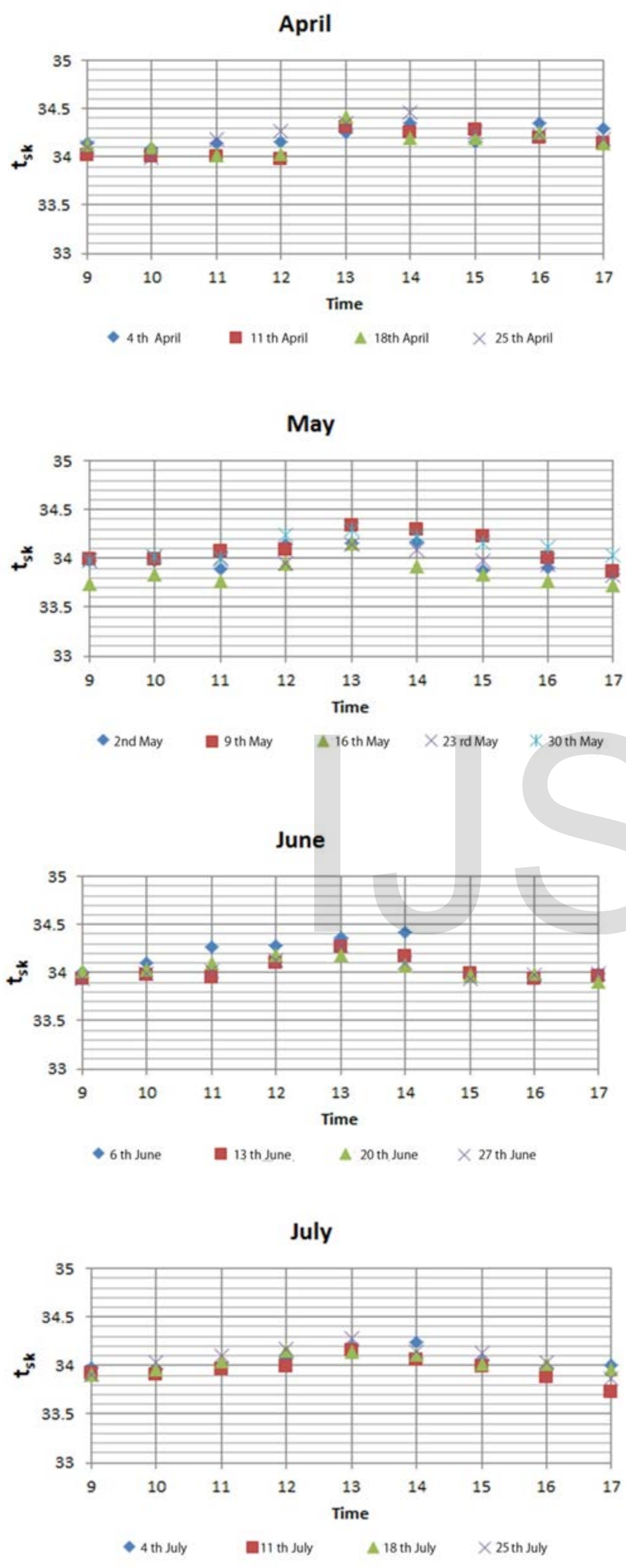

Fig.10. Predicted PHS (April-July)

Following equations have been also considered for evaluating the PHS criteria.

$[\ t_{cr} = t_{crn}\ ,\ HR = HR_n\ ]$ (6)

For moderate heat strain range,

$[\ t_{cr} = t_{crn} + k_b\ (t_{sk} - t_{skp}),$ (7)

$HR = HR_n + k_b,\ HR\ (t_{sk} - t_{skp})]$ (8)

And for high heat strain range,

$[\ t_{cr} = t_{crn} + (t_{sk} - t_{skp}),$ (9)

$HR = HR_n + k_c,\ HR\ (t_{sk} - t_{skr})]$, where $t_{skr} = 36\ ^oC$ (10) and for t_{sk} and t_{cr} the acceptance range is,

Everyday life (body surface temperature), t_{sk} = 34.8 – 35°C. Emergency evacuation and exercise (in the case of body temperature), t_{cr} > 37.6 -38°C.

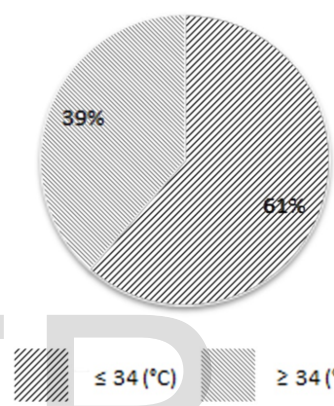

Fig.11. Comparison of PHS during April-July

For the evaluation of PHS, all students' height, weight, body surface, metabolic rate, clothing and age are considered as per Table 3, where the data were the average of 30 subjects. From the study, it was found that during the month of April to July indoor AT become very high near about 34.5°C and RH about 75-85% which leads to risk factor according to PHS criteria. During this time period t_{sk} leads to higher than the regular comfortable approximate skin temperature 34°C [23, 35]. Fig. 10 represents the calculated skin temperature throughout the research work. Data is plotted in hourly basis, and it shows that almost every time the temperature is above 34°C which indicates an uncomfortable climatic condition. Fig. 11 shows that normal body surface temperature (approximately 34°C) [23, 35] goes high about 61% during class time. Moreover, because of high RH it creates an uncomfortable environment. Mostly at morning and noon time observed data shows that it is above the comfort range (approximate 34°C). Further t_{cr} became higher than the normal 38°C (approximate) for high AT at indoor climate. It was found that due to lack of adjustment of clothing the t_{sk} creates problems in terms of comfort where it is highly humid.

4.3 PMV Prediction Calculation

For the prediction of thermal comfort, PMV is a mostly used function nowadays. Fanger's thermal comfort model was used to calculate PMV in the following equation according to ISO 7730.

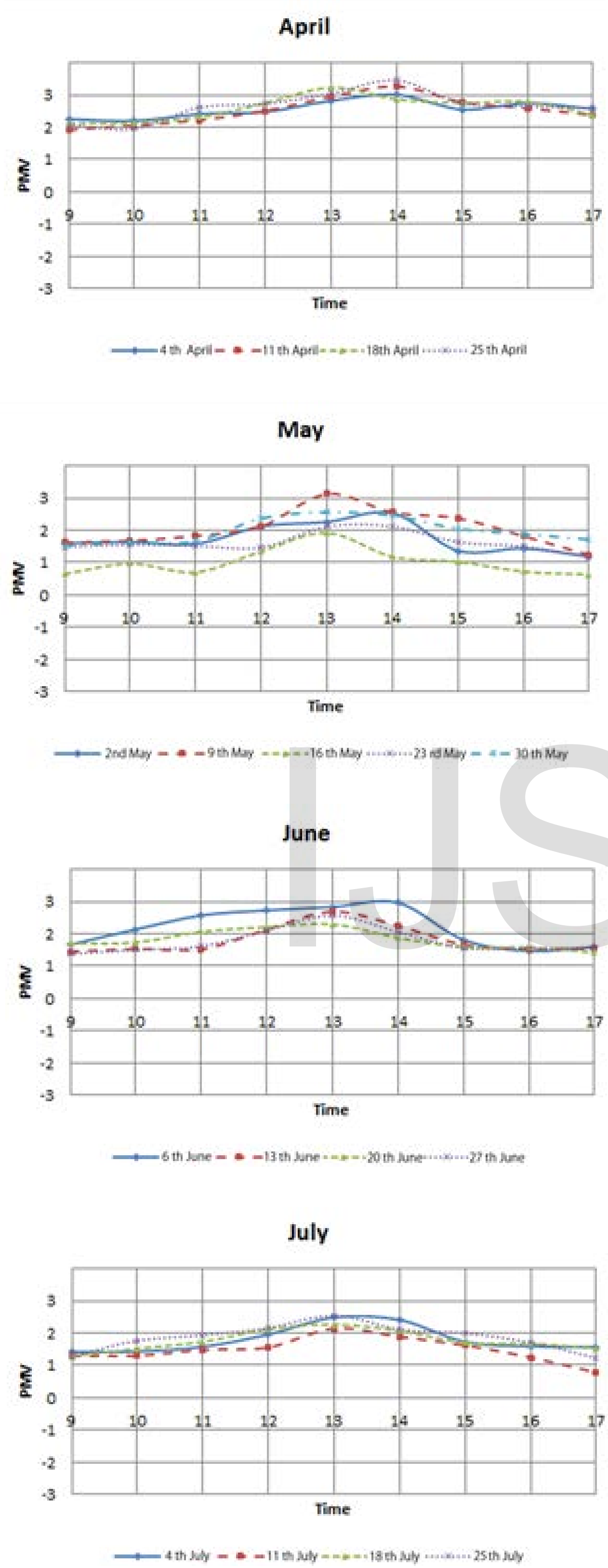

Fig. 12. Predicted PMV (April-July)

PMV = [0.303e -0.036M + 0.028]{(M – W) – 3.96 E -8 f_{cl} [(t_{cl} + 273)^4 – (t_r +273)^4] – $f_{cl}h_c$ (t_{cl} – t_a) – 3.05 [5.73 -0.007 (M-W) - p_a] – 0.42 [(M-W) – 58.15] - 0.0173M (5.87 – p_a) – 0.0014M (34 –t_a)} (11)

Where, f_{cl} = 1.0 + 0.2 I_{cl} , 1.05 + 0.1 I_{cl} (12)

t_{cl} = 35.7 – 0.0275 (M-W) – R_{cl}{(M-W) – 3.05[5.73 – 0.007(M-W) – p_a] – 0.42[(M-W) – 58.15] – 0.0173M (5.87 – p_a) – 0.0014M (34 – t_a)} (13)

R_{cl} = 0.155 I_{cl}

h_c = 12.1 (V)$^{1/2}$

Here, e = Euler's number (2.718), f_{cl} = clothing area factor, h_c = convective heat transfer coefficient (W/m^2.°C), I_{cl} = clothing intrinsic clothing insulation (clo), M = metabolic rate (W/m^2), p_a = vapor pressure of air (kPa), R_{cl} = thermal resistance of clothing (m^2.°C/W). t_a = air temperature (°C), t_{cl} = surface temperature (°C), t_r = mean radiant temperature (°C), V = air velocity (m/s) and W = external work (here, 0.0).

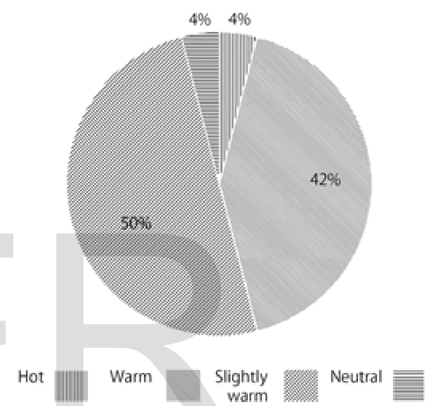

Fig. 13. Comparison of PMV during April-July

Table 5 shows the PMV scale where it runs from cold (-3) to hot (+3). From the case study it was derived that at the time period 12:00 to 15:00 it goes around the hot scale where it sometimes exceeds the high range of the scale. Larger values than +3 can be found from the equations, but beyond definition it's not possible to collect actual vote. Due to lack of proper ventilation with hot AT and high RH the comfort level goes down. Fig. 12 shows the PMV for the month of April – July, during regular class time. Data is plotted counting the measured value and it shows that most of the time it is between the ranges of +1 to +3, which indicates slightly warm to warm range. Therefore, it is appearing that around 4% time it is hot and 42% it is warm, where 50% time it is slightly warm and 4% time at normal range (Fig. 13).

4.4 Comparison of WBGT with PHS and PMV

A relationship among WBGT, t_{sk} and PMV was plotted at Fig. 14 using practical thermal condition. It was observed that WBGT, t_{sk} and PMV were extremely affected by the high AT and RH. WBGT remained at moderate to risk zone at 12:00 to 15:00, sometimes it also exceeded the risk line. In the case of t_{sk} it constantly remianed above the normal skin temperature line (approximate 34°C) and this was an indication of the high health risk level during class time. Beside that from PMV calculation, it was observed that it remained slightly warm to warm range while it was in the warm to hot range during the mid-time from 12:00 to 15:00. For appropriate condition PMV should be maintained between -0.5 to +0.5 range. From the comparison, it is found that in indoor climate condition, it creates a threat to the health of the students.

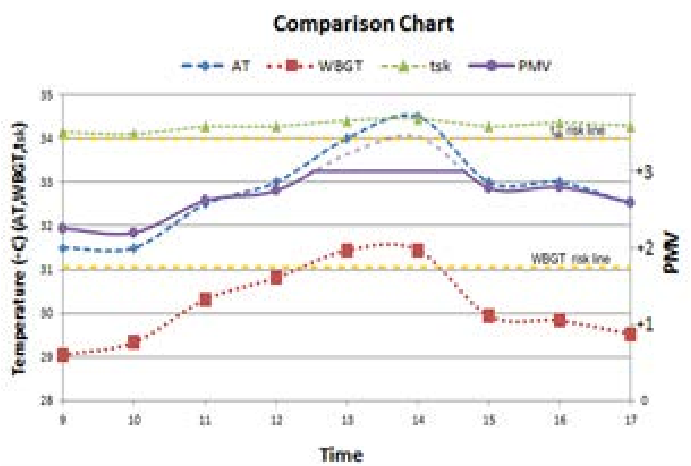

Fig. 14. Correlation matrix of AT, WBGT, tsk and PMV (April-July)

5 Conclusions

This study was conducted to find out the practical thermal scenario of University classrooms of Bangladesh. In this study, heat stress criteria were observed for the hottest month of April to July at the regular class time. The environmental parameter influenced a lot on thermal comfort and finally, the following precise conclusion has been drawn from that:

a) From the study, it is found that at Chittagong region AT remains between 30-34°C while RH is constant between 75-85% in indoor climate.

b) From measurement and prediction WBGT, t_{sk} and PMV is found deflecting from the comfort level at university classrooms at mid of the daytime.

c) In the perception of WBGT 23% times it is under moderate to risk zone, and 2% times it is in a risk zone at mid of the day when students have a minimum scope of adjustment.

d) During this summer time, PHS goes higher at noon (12:00 to 15:00) from the normal skin temperature (34°C) which can cause a health risk.

e) For PMV criteria, it is found that, about 4% times it is in the hot zone, where 42% times in warm to hot zone while 50%times it is in slightly warm to hot zone at day time.

f) From field survey it is observed that temperature in between 26-28°C, with 65-70% RH and 0.4-.6 ms^{-1} air movement in indoor condition, is a satisfactory comfortable condition for classroom activities.

From obtained data, risk from WBGT perspective is very few, because students are used to do light works. PHS is always above 34°C, indicating health issues. In the case of PMV, for comfortable condition it should be maintained between -0.5 to +0.5 range, but here we have found it within +1.5 to +2.5 mostly. So it's not a pure comfortable condition for the occupants which creates health issues. This study was only for the university classrooms in Bangladesh which has natural ventilation with a mechanical ventilation system. It is not integrated with the air conditioning situation. Building materials and orientation can be examined to understand the situation more relatively for further analysis.

Nomenclature

AT, t_a, T_a	Air temperature, °C
e	Euler's number
E	Saturation vapor pressure
f_{cl}	Clothing factor
h_c	Convective heat transfer coefficient
HR	Heart rate, bpm
HR_n	Equilibrium heart rate, bpm
I_{cl}	Clothing insulation
k_b	Rate of increase in body temperature, °C
$k_{b/c,hr}$	Heart rate increase, bpm/K
M	Metabolic rate, W/m^2
MV	Mechanical ventilation
NV	Natural ventilation
P	Air pressure, kPa
PHS	Predicted heat strain
PMV	Predicted mean vote
p_a	Vapor pressure of air, kPa
R_{cl}	Clothing thermal insulation
RH	Relative humidity, %
t_{cl}	Surface temperature of clothing, °C
t_{cr}	Core temperature, °C
t_{crn}	Permanent body temperature, which is proportional to the work intensity , °C
T_{dc}	Dew point, °C
T_g	Globe temperature, °C
T_{nwb}	Natural wet bulb temperature, °C
t_r	Mean radiant temperature, °C
t_{re}	Rectal temperature, °C
t_{sk}	Skin temperature, °C
t_{skp}	Upper limit skin temperature, °C
T_w	Wet bulb temperature, °C
v	Air velocity, ms^{-1}
W	External work
WBGT	Wet bulb globe temperature, °C

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