COMPARISON OF INDOOR AIR TEMPERATURE AND OPERATIVE TEMPERATURE -DRIVEN HVAC SYSTEMS BY MEANS OF THERMAL COMFORT AND ENERGY CONSUMPTION

Cihan TURHAN*, Department of Energy Systems Engineering, Atılım University, Turkey, cihan.turhan@atilim.edu.tr
(https://orcid.org/0000-0002-4248-431X)

Received: 23.01.2020. Accepted: 17.06.2020

Abstract

The main purpose of Heating, Ventilating and Air-Conditioning (HVAC) systems is to satisfy thermal comfort for the occupants. Conventionally, HVAC systems adjust set-temperature to achieve thermal comfort by continuously measuring indoor air temperature of the environment. However, ASHRAE 55, a standard of acceptable thermal environments, offers to use acceptable ranges of operative temperatures in air-conditioned buildings. Considering operative temperature is a function of indoor air temperature and mean radiant temperature, set-temperature of HVAC system can be controlled by using operative temperature to satisfy neutral thermal comfort for the occupants. This study compares thermal comfort and energy consumption of two exactly same HVAC systems which are operated based on indoor air temperature and operative temperature, respectively. Two office rooms with same architectural configurations -which are located in a university-Ankara-Turkey- were selected as a case study. The HVAC systems were operated based on indoor air temperature and operative temperature, respectively, at the same time and occupancy schedules. The results showed that operative temperature driven controlled HVAC system achieves better thermal comfort while slightly increasing energy consumption. The main findings of this study would be useful not only to design energy-efficient HVAC systems but also create more comfortable environments.

Keywords: Thermal Comfort, Operative Temperature, HVAC System Control, Energy Consumption

Özet

İç hava sıcaklığı ve operatif sıcaklık bazlı HVAC sistemlerinin isil konfor ve enerji tüketimi bakımından karşılaştırılması

Özettir. Soğutma ve Havalandırma (HVAC) sistemlerinin ana amacı kullanıcılar için isıl konforu sağlamaktır. Geleneksel olarak, HVAC sistemleri isıl konforu sağlayabilmek için iç hava sıcaklığını sürekli ölçücü set-değerlerini ayarlar. Ancak, bir kabul edilebilir isıl çevre standartı olan ASHRAE 55, ilkimlendirilmiş binalar için operatif sıcaklık kabılar aralarımı kullanmayı önermektedir. Operatif sıcaklık, iç hava sıcaklığı ve ortalamada radyant sıcaklığın bir fonksiyonu olduğu düşünülürse, kullanıcıların nöt isıl konforunun sağlanması için HVAC sistemlerinin set-değerleri operatif sıcaklık göre kontrol edilebilir. Bu çalışma, biri operatif sıcaklık ve diğer iç hava sıcaklığı bazlı aynı üretkenlikteki iki oda bulunan aynı özellikleri iki HVAC sistemini isıl konfor ve enerji tüketimi bakımından karşılaştırılmaktadır. Örnek çalışma olarak, Ankara-Türkiye’de bulunan aynı mimari özelliklerdeki bir ofis odası seçilmiştir. HVAC sistemleri aynı zamanda ve aynı doluluk oranlarında aynı aynı operatif sıcaklık ve iç hava sıcaklığı bazlı kontrol edilerek çalışılmıştır. Sonuçlar, operatif bazlı HVAC sistemlerin enerji tüketimini az da olsa arttırdığı fakat daha iyi isıl konfor sağladığı göstermiştir. Bu çalışmanın sonuçları sadece enerji verimli HVAC sistemleri tasarlamak için değil, daha konforlu ortamlar yaratma açısından da yol gösterici olacaktır.

Anahtar Kelimele: Isıl Konfor, Operatif Sıcaklık, HVAC Sistem Kontrolü, Enerji Tüketimi

Cite

Turan, C., (2020). “Comparison of indoor air temperature and operative temperature-driven HVAC systems by means of thermal comfort and energy consumption” Mugla Journal of Science and Technology, 6(1), 156-163.

1. Introduction

Heating, Ventilating and Air-Conditioning (HVAC) systems maintain thermal comfort for occupants in buildings [1]. However, measuring or estimating the thermal comfort is usually difficult since the concept depends on multi-parameters. Standards on the thermal comfort such as ASHRAE 55 [1] and ISO 7730 [2] still use Fanger’s Predicted Mean Vote (PMV) index which lays on six parameters (indoor air temperature (T), relative humidity (RH), air velocity (v), mean radiant temperature (MRT), clothing value (clo) and metabolic rate (met)) [3]. PMV index uses a thermal scale which is
between -3 (cold) and +3 (hot). The zero value of PMV is called as neutral thermal comfort which means that the occupants feel fully-comfortable in the environment [1]. However, in ASHRAE 55, a range of ±0.5 of PMV is also accepted as comfortable in a conditioned environment which is the aim to be achieved by an HVAC system. Thermostats generally measure indoor air temperature of the thermal environment in order to control HVAC system operations [4]. However, thermal comfort is a multi-parameter concept where other parameters should be taken into consideration. Operative temperature (OT) (also called as resultant temperature) can be counted as one of significant factor on the thermal comfort. OT is the combination of MRT, T\textsubscript{a} and v\textsubscript{a} and therefore highly affects thermal comfort of occupants [5-7]. Many studies measured OT instead of T\textsubscript{a} in their thermal comfort researches [8-11]. For instance, Kwok and Chun [8] investigated thermal comfort levels in air-conditioned and natural ventilated Japanese schools. OT was calculated by measuring MRT, T\textsubscript{a} and v\textsubscript{a} of the environment and the authors concluded that thermal responses of the students were different in air-conditioned schools due to the expectations from HVAC system and availability of control. In another study by Nicol and Humphreys [9], a strong relationship was found between OT and thermal comfort since OT represents both T\textsubscript{a} and temperature of the walls. The authors also concluded that OT is highly dependent on the outdoor temperature (T\textsubscript{o}).

On the other hand, energy consumption of HVAC system can be decreased by using proper control methods [12]. Adjusting inaccurate set-temperature for HVAC system lead higher energy consumption in buildings. For instance, Kusiak et al. [13] investigated the relationship between the control settings and energy consumption of the HVAC system. The HVAC system was controlled only according to the T\textsubscript{a} and the authors found that a 7.6% of energy could be saved by optimization of HVAC control. However, the study indicated that other uncontrollable parameters such as T\textsubscript{o} and MRT should be taken into account in the studies. To this aim, Jain et al. [14] suggested to use OT-driven control in HVAC systems of highly-glazed buildings. The authors concluded that high temperature of window panes in summer highly affects energy consumption. However, thermal comfort of the occupants was not investigated in the study. Olesen et al. [15] simulated three different HVAC systems including fan-coil system and floor and ceiling based radiant systems by regulating T\textsubscript{a} and OT. The results showed that the use of OT-driven control in fan-coil system achieved better thermal comfort. However, the results were based on simulation, therefore experimental results were not given in the study. Similarly, Wang et al. [16] suggested that T\textsubscript{a}-driven thermostat control be used in fan-coil system while OT-driven thermostat control could be preferred in radiant system in offices according to the simulation results. In addition, Niu and Burnett [17] used OT instead of T\textsubscript{a} in building energy simulation programs. The authors concluded that there was a huge difference in energy consumption between OT and T\textsubscript{a}-based simulations. On the other hand, Turhan and Akkurt [18] investigated thermal comfort of occupants in an office in Mediterranean climate zone by using T\textsubscript{a}-based controller. Although an experimental study was conducted in an office environment, the effect of OT-driven controller on thermal comfort was not evaluated. Even though HVAC systems are typical non-linear multi-parameter systems, most of HVAC system adjust set-temperature according to the T\textsubscript{a}. In addition, temperature of the walls highly affects thermal comfort of occupants due to the radiation between human body and wall surfaces. For this reason, measuring OT instead of T\textsubscript{a} can be a better solution to achieve better thermal comfort However, energy consumption should also be investigated not only with simulations but also with in-situ measurements. Up to now, there exists a few simulation studies which compare OT and T\textsubscript{a}-operated HVAC system controllers [14-18] according to the author’s knowledge. This study distinguishes from previous studies by comparing OT and T\textsubscript{a}-driven HVAC systems in terms of both thermal comfort and energy consumption in a real environment. For this aim, two office rooms which have same architectural configurations, are operated with two same HVAC systems, one is T\textsubscript{a}-driven (in Office A) and another is OT-driven (in Office B) HVAC systems. Each office room is occupied with one occupant by using same occupancy schedules.

2. Case Building

The case building is located in Atılım University campus Ankara/Turkey at latitude 39.9°N and longitude 32.9°E which has Csb climate zone under Köppen-Geiger Climate Classification [19]. Based on the data between 1927 and 2019, the average annual outdoor temperature of Ankara is 12 °C [20]. Two office rooms (Office A and B) which have same architectural configurations are selected as a case study (Fig.1).

![Figure 1. Selected offices for the case study](image)

a) Office A b) Office B

Each office has a total dimension of 3 m (width) × 5 m (depth) × 2.8 m (height), one window and one external wall. The offices face the same south direction. The indoor environment of each office is heated/cooled by an air-conditioner which is set 22°C for winter and summer seasons (Fig.2). The reason of setting a constant temperature is to ensure optimal productivity and efficiency of occupants in office environments [21-22]. A mobile air-conditioner is selected as an HVAC system since it can be easily demodulated and
controlled by an IR receiver and transmitter, respectively. The features of the air conditioner is given in Table 1.

| Heating | 8800 Btu/h |
|---------|------------|
| Cooling | 9000 Btu/h |
| Remote Controller Unit | 38 kHz |
| Energy Supply | 230 Volt |
| COP-heating | 3.10 |
| COP-cooling | 2.91 |

Each office is occupied by a male occupant from 08.30 a.m to 12:30 p.m and 01:30 p.m to 05:00 p.m during weekdays. The occupants are requested to use their offices with same usage intensity and ventilation schedule while no visitors/guests are allowed in order to avoid increased temperature in offices due to the internal heat gains during the measurements. The personal parameters of the occupants are given in Table 2.

| Gender | Office A | Office B |
|--------|----------|----------|
| Age | 34 | 34 |
| Body Mass Index (kg) | 22.7 | 22.9 |

The air-conditioners are kept open only during office hours. The airtightness of the envelope is assumed as 0.5 ACH (air change per hour) for each offices according to the standard value for natural ventilated building in ASHRAE 55 [1]. The overall heat transfer coefficient (U-value) of the external wall is calculated as 0.91 W/m²K while roof and ground is assumed as adiabatic since there exists other air-conditioned office rooms. In addition, U-values of window and door are 1.45 and 1.7 W/m²K, respectively. The radiators, computers and appliances such as photocopiers which exist in the office rooms are kept closed during the experiments in order to avoid internal heat sources.

The features of the air conditioner is given in Table 1.

| Heating | 8800 Btu/h |
|---------|------------|
| Cooling | 9000 Btu/h |
| Remote Controller Unit | 38 kHz |
| Energy Supply | 230 Volt |
| COP-heating | 3.10 |
| COP-cooling | 2.91 |

Each office is occupied by a male occupant from 08.30 a.m to 12:30 p.m and 01:30 p.m to 05:00 p.m during weekdays. The occupants are requested to use their offices with same usage intensity and ventilation schedule while no visitors/guests are allowed in order to avoid increased temperature in offices due to the internal heat gains during the measurements. The personal parameters of the occupants are given in Table 2.

| Gender | Office A | Office B |
|--------|----------|----------|
| Age | 34 | 34 |
| Body Mass Index (kg) | 22.7 | 22.9 |

The air-conditioners are kept open only during office hours. The airtightness of the envelope is assumed as 0.5 ACH (air change per hour) for each offices according to the standard value for natural ventilated building in ASHRAE 55 [1]. The overall heat transfer coefficient (U-value) of the external wall is calculated as 0.91 W/m²K while roof and ground is assumed as adiabatic since there exists other air-conditioned office rooms. In addition, U-values of window and door are 1.45 and 1.7 W/m²K, respectively. The radiators, computers and appliances such as photocopiers which exist in the office rooms are kept closed during the experiments in order to avoid internal heat sources.

The air-conditioners are kept open only during office hours. The airtightness of the envelope is assumed as 0.5 ACH (air change per hour) for each offices according to the standard value for natural ventilated building in ASHRAE 55 [1]. The overall heat transfer coefficient (U-value) of the external wall is calculated as 0.91 W/m²K while roof and ground is assumed as adiabatic since there exists other air-conditioned office rooms. In addition, U-values of window and door are 1.45 and 1.7 W/m²K, respectively. The radiators, computers and appliances such as photocopiers which exist in the office rooms are kept closed during the experiments in order to avoid internal heat sources.

The air-conditioners are kept open only during office hours. The airtightness of the envelope is assumed as 0.5 ACH (air change per hour) for each offices according to the standard value for natural ventilated building in ASHRAE 55 [1]. The overall heat transfer coefficient (U-value) of the external wall is calculated as 0.91 W/m²K while roof and ground is assumed as adiabatic since there exists other air-conditioned office rooms. In addition, U-values of window and door are 1.45 and 1.7 W/m²K, respectively. The radiators, computers and appliances such as photocopiers which exist in the office rooms are kept closed during the experiments in order to avoid internal heat sources.

3. Materials and Methods

The overall process of methodology includes three sections; development of the control methods for HVAC systems, measurement campaign and comparison of the results in terms of thermal comfort and energy consumption. Figure 3 depicts the flow chart of the methodology used in the study.

| Developing Control Method |
|---------------------------|
| 1. Demodulate IR codes of HVAC system |
| 2. Develop software and mobile application for T; and OT-driven controllers |
| 3. Constructs wireless sensor network |
| 4. Re-send IR Codes to adjust set-temperature of HVAC system |

| Measurement Campaign (Office A) |
|--------------------------------|
| 1. Measure T; in Office A |
| 2. Hold T; at 22°C in Office A |
| 3. Obtain thermal comfort for subjective measurements via mobile application |
| 4. Measure energy consumption of HVAC system |

| Measurement Campaign (Office B) |
|--------------------------------|
| 1. Measure OT in Office B |
| 2. Hold OT at 22°C in Office B |
| 3. Obtain thermal comfort for subjective measurements via mobile application |
| 4. Measure energy consumption of HVAC system |

| Comparison of the Results |
|---------------------------|
| 1. Compare thermal comfort |
| 2. Compare energy consumption of HVAC system |

Figure 3. Overview of the methodology

3.1. Developing control methods

Control methods of the HVAC systems lay on simple PID control techniques which regulate the set-temperature by T; and OT for Office A and B, respectively. PID controllers calculate the difference between the desired temperature and set-temperature and operate the HVAC system according to an error function. The set-temperatures of each HVAC system are kept at 22°C. However, set-temperature of Office A is regulated according to T; measurements while OT is regulated for the set-temperature of Office B. For instance, for Office A, if the T; decreases below 22 °C, the developed controller opens the HVAC system via sending IR signals. Similarly, if T; increases above 22 °C, the controller closes the HVAC system. The same procedure is valid for Office B, however, this time, the system is operated according to OT measurements. Finally, it is worth to note that the software of controllers are written in C-programming language.

Two controllers are developed for the study. Controller consists of an IR receiver to demodulate IR codes of HVAC system, an IR transmitter to send signals to HVAC system, two microcontrollers to achieve T; and OT measurements and control HVAC system according to the results and a Wi-Fi Module to communicate among
OT and T₁ sensors, controller and mobile application, wirelessly (Fig.4).

**3.2. Measurement campaigns**

The developed controllers are applied in two office rooms from August 1ˢᵗ, 2019 to January 2¹ˢᵗ, 2020 including cooling and heating modes. Afterwards, an experimental study is conducted to understand the difference between Tᵢ-driven and OT-driven HVAC systems in terms of thermal comfort and energy consumption. ISO 7730 standard [2], which is based on ASHRAE 55 [1], is used to measure indoor environment of offices. Tᵢ, Tᵢ, and OT are measured for each offices. However, the developed controllers use only Tᵢ and OT values to regulate HVAC systems for Office A and B, respectively. As a first step, the set-temperature of HVAC systems (air-conditioners in this study) is adjusted to 22 °C covering heating and cooling seasons. Then, a DHT22 sensor, which measures indoor air temperature, is used to measure Tᵢ for Office A (Fig.5). The measurement results are processed in the controller and controller operates the HVAC system by regulating Tᵢ.

Similarly, for Office B, a well-calibrated globe-thermometer, which is developed by the author, measures OT, continuously (Fig.6). Since there is no mechanical ventilation in the office rooms, OT is taken as in Equation 1 according to ASHRAE 55 [1] for νₘ at or below 0.1 m/s.

\[
OT= \frac{(T₁ + MRT)}{2} \tag{1}
\]

MRT is calculated by using a k-type thermometer which is located at the center of a hollow copper-sphere of the developed globe thermometer. The temperature obtained from globe thermometer (T₉) is then recorded on a server and MRT is calculated automatically by the controller as in Equation 2 [23]. The emissivity (Є) of the matt-black copper sphere is taken as 0.95 while diameter (D) of the sphere is 150 mm.

\[
MRT= \left[ (T₉ - Tᵢ) \times e^{(0.25 \times 10^9) \cdot e} \cdot \left( \frac{1}{a} \right) \cdot (T₉ - Tᵢ) \right]^{1/7} - 273 \tag{2}
\]

The results of the developed sensors are reliable when they provide that they are calibrated. To this aim, developed globe thermometer is calibrated with a well-known commercial globe-thermometer.
The energy consumption of the air-conditioners is measured in kWh by a three phase-power analyzer. The list of the used instruments and their accuracy are given in Table 3. Finally, it is worth to note that the objective and subjective measurement results are stored in a web-server and mathematical operations are made by microcontrollers which exist in both office rooms.

### Table 3. Specifications of the instruments

| Instrument | Measured parameter | Accuracy |
|------------|--------------------|----------|
| DHT 22 T_i, T_o | < 1 °C |
| Globe-Thermometer (developed by the author) | OT | < 1 °C |
| Extech Power Analyzer | Energy consumption in kWh | ± 2% for kWh |

### 3.3. Comparison of the results

The results are compared in two ways; thermal comfort and energy consumption. Energy consumption of the HVAC systems is measured via power analyzers while TSV of the occupants is obtained with the help of mobile application. The aim of the comparison of T_i and OT-driven HVAC systems is to show which method is efficient in terms of thermal comfort and energy.

### Table 5. Measured T_o, T_i, and OT values in measurement period

| Experiment Days | Office A | Office B |
|-----------------|---------|---------|
| Heating Min     | -1.5    | 21.4    |
| Heating Max     | 20.9    | 23.1    |
| Heating Average | 3.5     | 22.4    |
| Cooling Min     | 21.8    | 21.2    |
| Cooling Max     | 22.5    | 21.1    |
| Cooling Average | 22.2    | 21.1    |
| Cooling Min     | 24.5    | 24.5    |
| Cooling Max     | 22.6    | 22.4    |
| Cooling Average | 22      | 22      |

Table 5 indicates that T_o values vary between -1.5 and 26.4 °C. In addition, T_i and OT are highly affected by T_o which leads more energy consumption to reach set-temperature for both controllers. Figure 8 depicts trends of daily average T_o, T_i, OT and TSV values for Office A. It is worth to remind that the black lines show TSV values of the occupant.

### Table 4. Dates for experiments

| Mode   | Experiment dates              |
|--------|-------------------------------|
| Cooling| August 1\textsuperscript{st}, 2019 - October 31\textsuperscript{st}, 2019 |
| Heating| November 1\textsuperscript{st}, 2019 - January 21\textsuperscript{st}, 2020 |
The TSV values of the occupants are obtained via mobile application. Figure 8 and 9 also state comparison of TSV for two control methods. The TSV values are almost zero for OT-driven HVAC system, however, the range of TSV varies between -2 and 1.5 for Tₐ-driven HVAC system. In other words, occupant feels neutral on 82% of total days while OT-driven HVAC system is operated. This value is merely 26% for Tₐ-driven HVAC system.

Figure 9. Measurement results for Office B

The reason of the increase in energy consumption of OT-driven HVAC system could be temperature differences in different zones of same office. For instance, the OT could vary from Tᵢ in several areas of an office, which receive a lot of radiant heat from building elements such as wall and window. In addition, the OT differs from Tᵢ in buildings with large windows where temperature of the window are different from measured Tᵢ [14]. The window to wall ratio of the case office is 3.6 which is a very high ratio that makes greater difference between OT and Tᵢ. Thus, the OT-driven HVAC system consumes slightly more energy from Tₐ-driven one in order to reach set-temperature.

Figure 10. Comparison of energy consumption of OT and Tₐ-driven HVAC systems

The average values of TSV compares energy consumption of two control methods. OT-driven HVAC system consumes 2.4% more energy compared to Tₐ-driven HVAC system. Total energy consumption for 131 days-experiment period is 526.8 kWh and 539.6 kWh for Tᵢ and OT-driven HVAC systems, respectively. However, it is worth to remind that occupants feel neutral in OT-driven HVAC system.

Figure 11. Daily energy consumption of offices

Figure 11 depicts that energy consumption of OT-driven HVAC system is higher than Tₐ-driven HVAC system in the heating mode. This could be the reason of the cooler temperature of walls than Tᵢ due to the cold weather in Ankara. The average values of Tᵢ and OT for both offices are lower than their set-temperatures (Table 5). This result increases energy consumption for OT-driven HVAC system in heating season.

The general findings of the study can be summarized as the following:

1. Occupant mostly feels neutral in OT-driven HVAC system.
2. TSV value is zero only 26% of total measurement days in Tₐ-driven HVAC system. The reason could be the temperature differences of walls and windows from Tᵢ which make occupant to feel uncomfortable.
3. OT-driven HVAC system consumes more energy. However, considering occupant feels more comfortable, the low energy saving of Tₐ-driven HVAC system (2.4%) is negligible.

The next section provides further results regarding the uncertainty analysis of the measurements.

4.1. Uncertainty Analysis

Uncertainty analysis relies on Monte-Carlo method which depends on the measurement errors [24]. Therefore, the analysis is performed by assuming measurement results with mean values while minimum and maximum values are obtained from the accuracy of the measurement devices for every measurement. Table 6 depicts the analysis results in terms of energy consumption.

| Office Type | Maximum (kWh) | Average (kWh) | Minimum (kWh) |
|-------------|---------------|---------------|---------------|
| Office A    | 547.1         | 526.8         | 501.6         |
| Office B    | 549.3         | 539.6         | 529.1         |

In the case of an experiment with measurement errors, OT-driven HVAC system still consumes more energy than Tₐ-driven HVAC system. However, it is worth to remind that these results could change with low-accuracy devices. Moreover, in presence of uncertainty...
and modelling errors, Monte-Carlo method seems to facilitate the validation of the measurements to compare two different HVAC systems.

5. Conclusions

The purpose of this paper is to compare Td-driven and OT-driven HVAC systems by means of thermal comfort and energy consumption. Two office rooms, which have exactly same architectural configurations, are selected as a case study. Two different control methods which regulate set-temperatures of HVAC system according to Td and OT, respectively, are developed and applied in the office rooms. Each office room is occupied with one male occupant and measurements are conducted during office hours. Objective measurements including Td, Tw, and OT are taken via objective sensors while TSV is obtained with the help of a developed mobile application. The results showed that OT-driven HVAC system satisfied better thermal comfort while slightly increasing energy consumption.

In the study, TSV values are obtained from one-occupant. However, the results could be verified with larger occupancy. Although two occupants with almost same physiological parameters are used in the study, some other parameters such as psychology could affect TSV and energy consumption behaviors.

On the other hand, the case office is relatively small office building. Compared to the larger offices, the temperature of walls or windows have higher effect on thermal comfort of occupants. To this aim, as a future study, the experiments will be conducted in different type of offices with larger occupancy.

6. References

[1] ASHRAE 55, Thermal Environment Conditions for Human Occupancy, 2017.
[2] ISO 7730, Moderate Thermal Environments- Determination of the PMV and PPD indices and Specification of the Conditions for Thermal Comfort, International Standards Organization, 1995.
[3] Fanger, P., Thermal Comfort, Danish Technical Press, Copenhagen, 1970.
[4] Calvino, M., Gennusa, M.L., Morale, M., Rizzo, G. and Scaccianocce, G., “Comparing Different Control Strategies for Indoor Thermal Comfort Aimed at the Evaluation of the Energy Cost Quality of the Building”, Journal of Process Control, 24 (6), 703-713, 2014.
[5] Oktay, H., Argunhan, Z., Yumrutaș, Y., Işık, M.Z. and Budak, N., “An Investigation of the Influence of Thermophysical Properties of Multilayer Walls and Roofs on the Dynamic Thermal Characteristics”, Muciga Journal of Science and Technology, 2 (1), 48-54, 2016.
[6] Wu, Z., Li, N., Wargocki, P., Peng, J., Li, J. and Cui, H., “Adaptive Thermal Comfort in Naturally Ventilated Dormitory Buildings in Changsha, China”, Energy and Buildings, 186, 56-70, 2019.
[7] Becchio, C., Corgnati, S.F., Vio, M., Crespi, G., Prendin, L., Ranieri, M. and Vidotto, D., “Toward NZEB by optimizing HVAC system configuration in different climates”, Energy Procedia, 140, 115-126, 2017.
[8] Kwok, A.G. and Chun, C., “Thermal Comfort in Japanese Schools”, Solar Energy, 74 (3), 245-252, 2003.
[9] Nicol, F. and Humphreys, M., “Derivation of the Adaptive Equations for Thermal Comfort in Free-Running Buildings in European Standard EN15251”, Building and Environment, 45 (1), 11-17, 2010.
[10] Wong, N.H. and Khoo, S.S., “Thermal Comfort in Classrooms in the Tropics”, Energy and Buildings, 35 (4), 337-351, 2003.
[11] Atmaca, I., Kaynaklı, Ö. and Yiğit, A., “Effects of Radiant Temperature on Thermal Comfort”, Building and Environment, 42 (9), 3210-3220, 2007.
[12] Turhan, C., Simani, S., Zajic, I. and Gökçen Akkurt, G., “Performance Analysis of Data-Driven and Model-based Control Strategies Applied to a Thermal Unit Model”, Energies, 10 (1), 67, 2017.
[13] Kusiaj, A., Tang, F. and Xu, G., “Multi-objective Optimization of HVAC system with an Evolutionary Computational Algorithm”, Energy, 36, 2440-2449, 2011.
[14] Jain, V., Garg, V., Mathur, J. and Dhaka, J., “Effect of Operative Temperature Based Thermostat Control as Compared to Air Temperature Based Control on Energy Consumption in Highly Glazed Buildings”, Proceedings of Building Simulation, 1, 2687-2695, 2011.
[15] Olesen, B.W., Wang, H., Kazanci, O.B. and Coakley, D., “The Effect of Room Temperature Control by Air or Operative Temperature on Thermal Comfort and Energy Use” Proceedings of Building Simulation, 1, 1-8, 2019.
[16] Wang, H., Olesen, B.W. and Kazanci, O.B., “Using Thermostats for Indoor Climate Control in Offices: The Effect on Thermal Comfort and Heating/Cooling Energy Use, Energy and Buildings, 188, 71-83, 2019.
[17] Niu, J.I. and Burnett, J., “Integrating Radiant/Operative Temperature Controls into Building Energy Simulations”, ASHRAE Transactions, 104 (2), 210-217, 1998.
[18] Turhan, C. and Gökçen Akkurt, G., “Assessment of Thermal Comfort Preferences in Mediterranean Climate: A University Office Building Case”, Thermal Science, 22 (5), 2177-2187, 2018.
[19] Köppen-Geiger Climate Classification, 2009. Retrieved March 3, from http://koeppen-geiger.vu-wien.ac.at/
[20] Turkish State Meteorological Service, 2019. Retrieved December 3, from https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistikaspx.
[21] Seppänen, O., Fisk, W.J., Lei, Q.H., “Effect of temperature on task performance in office”,
Lawrence Berkeley National Laboratory, Report No: LBNL – 60946, July, 2006.

[22] World Health Organization, Indoor environment: health aspects of air quality, thermal environment, light and noise, 1990.

[23] ISO 7726, Ergonomics of the Thermal Environment-Instruments for Measuring Physical Quantities, 1998.

[24] Rugen, P. and Callahan, B., “An overview of Monte Carlo—a fifty year perspective”, Human and Ecological Risk Assessment, 2, 671-680, 1996.

Y.Wang, X. Meng, L. Zhang, Y. Liu, E. Long, Angle factor calculation for the thermal radiation environment of the human body.