A new method for comparing long-term thermal conditions in buildings

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Abstract

This project proposes a new method for assessing the severity of discomfort in buildings over time. The proposed "Exceedance Degree-Hours" uses an equivalent temperature index and, in contrast with other indices, can be paired with various comfort definitions from literature. Importantly, it can be used to assess thermal comfort in mixed-mode buildings, providing a single value, which can be helpful for comparing simulation results, especially in an optimization process. Here, the results of the proposed method are compared to those of existing discomfort indices suggested in thermal comfort standards, and the advantages and limitations of the proposed approach are discussed.

Key Innovations

- Proposes a new method based on the equivalent temperature index to quantify the severity of discomfort
- Takes into account all six environmental and personal factors
- Flexible in terms of selection of multiple comfort definitions and equivalent temperature indices
- Can be used with Predicted Mean Vote (PMV)-based and Adaptive Comfort models within a single analysis
- Useful for design optimization as it provides a single value in terms of building-related parameters

Practical Implications

This proposed method helps users compare different building design options in terms of long-term occupant comfort. The method can be paired with different comfort models (existing and yet-to-be-developed), and therefore is applicable for assessing buildings that are mechanically cooled, free running, mixed-mode, or designed for non-typical comfort conditions such as for sleep comfort.

Introduction

In current practice, thermal comfort is determined by expressing environmental conditions in terms of a given index and comparing the results with thermal comfort ranges suggested in predefined standards or models. According to Carlucci and Pagliano (2012), the majority of indices and standards are based on a comfort model, most often derived from the Adaptive Model (de Dear and Schiller Brager, 2001) or the work of Fanger (1970).

Among the most widely used metrics for air-conditioned buildings are those defined by Fanger's Predicted Mean Vote (PMV) model (ASHRAE 55, 2017; CEN, 2019; ISO 7730, 2005). PMV determines the mean value of expected thermal sensation votes, yet it is difficult to infer the implication of the magnitude of PMV in practice. Therefore, it is more meaningful to couple PMV with Predicted Percentage Dissatisfied (PPD), which specifies the expected percentage of thermally dissatisfied people and is easier to interpret by building engineers (ASHRAE 55, 2017; Fanger, 1970). Conversely, for naturally-ventilated buildings, the Adaptive Thermal Comfort (ATC) model is used, measuring comfort by finding the exceedance of operative temperature relative to the temperature corresponding to the 80% acceptability limit (de Dear and Schiller Brager, 2001).

Despite their popularity, these models each have their limitations. For example, the ATC Model, while useful in non-air-conditioned buildings, does not explicitly consider non-temperature aspects of comfort, such as humidity (ASHRAE 55, 2017). In addition, comfort limits are specified in terms of fixed threshold temperatures in ATC-based indices as opposed to PMV-based indices in which comfort boundaries change according to the variations in environmental and personal factors. On the other hand, the applicability of Fanger's model is somewhat limited, since it is specific to air-conditioned buildings (G. S. Brager and de Dear, 1998). Moreover, although PMV is widely used by national and international standards, its low accuracy beyond comfort ranges has been addressed by various studies (Zhang, 2020). According to these studies (Humphreys and Nicol, 2002; van Hoof, 2008), the accuracy of PMV reduces as the thermal condition deviated from thermal neutrality. In order to enhance the accuracy of the PMV model, previous research studies have proposed several methods, in many of which Standard Effective Temperature (*SET*) model (ASHRAE 55, 2017) is utilized. For instance, Zhang and Lin (2020) (Zhang, 2020) replaced the simplified skin temperature in the PMV model with the more advanced skin temperature from the *SET* model to improve the quality of PMV's thermal condition predictions.

Several national and international standards such as ASHRAE-55, CIBSE Guides, CIBSE TMY52 2013, ISO 7730-2005, EN 15251, and EN 16798-1:2019 (ASHRAE 55, 2017; CEN, 2019; Chartered Institution of Building Services Engineers, 2015; EN 15251, 2007; ISO 7730,

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2005; Fergus Nicol, 2013) have adopted indices based on these models to ensure proper thermal comfort conditions in new and existing buildings. Silva, et al. (2016) identified 37 such indices, and Carlucci and Pagliano (2012) reviewed commonly used indices for long-term evaluation of comfort, grouping them into four main families: 1) Percentage indices, 2) Cumulative indices, 3) Risk indices, and 4) Averaging indices. The first family of indices expresses discomfort as a percentage of occupied hours outside a comfort threshold with respect to the total number of occupied hours, with indices such as the Percentage Out of Range (POR)–Method A in ISO 7730-2005 (ISO 7730, 2005), EN 15251:2007 (EN 15251, 2007) and the subsequent EN 16798-1:2019 (CEN, 2019).

Cumulative Indices, on the other hand, express the total accumulated discomfort as a sum of uncomfortable periods, typically hours. Method A in ISO 7730-2005 (ISO 7730, 2005) and EN:16798-1:2019 (CEN, 2019), Exceedance Hours (Eh) in ASHRAE 55-2017 (ASHRAE 55, 2017), and Hours of Exceedance (HE) in CIBSE TM52 (Fergus Nicol, 2013) are examples of such metrics, measuring the number of occupied hours outside the respective thermal comfort threshold. These standards also allow these indices to be expressed as a percentage of the occupied time. Some indices utilize weighting factors to account for or to include more information. For example, Borgeson and Brager (2011) proposed a cumulative index that measures hours of discomfort weighted by occupancy--ExceedanceM. These indices cannot measure and/or express the severity or degree of discomfort being experienced, treating comfort as a binary state (comfortable vs. uncomfortable).

Several indices that account for the severity or degree of discomfort being experienced have been proposed in standards and research. These typically rely on the use of weighting factors based on the difference in actual and acceptable thermal conditions. The simplest metric measures and sums the difference in the measured or simulated operative temperature and the operative temperature limits per the chosen comfort standard here called Degree-hours (Dh). Degree-hour Criterion (DhC), included in standards such as EN 167798-2:2019(CEN, 2019), ISO 7730 (Annex H, Method B) (ISO 7730, 2005), or Daily Weighted Exceedance in CIBSE TM52 (Fergus Nicol, 2013), are calculated similarly with a weighting factor based on the exceedance of operative temperature during occupied hours. Such weighting factors only account for temperature differences, ignoring other environmental and personal factors affecting thermal comfort.

Other indices address this limitation by using weighting factors based on PMV or PPD. Weighted Exceedance-hours (WEh) in ASHRAE 55 (ASHRAE 55, 2017) uses a weighting factor based on PMV, while the PPDwC—included in a similar form in ISO 7730 (ISO 7730, 2005), EN 16798 (CEN, 2019), and CIBSE TMY52 (Fergus Nicol, 2013)—weighs discomfort hours using weighting factors based on PPD. While these indices include other environmental and personal factors in their underlying equations, they are limited to Fanger's model. Furthermore, focusing on conditions outside thermal neutrality, different combinations of personal and environmental factors may receive equivalent scores via the PMV/PPD methods (Hoyt et al., 2017). Indices such as PPDwC then fail to capture situations that might need different strategies to mitigate discomfort. For instance, a designer may want to provide dehumidification in one case and increase air speed in another in order to reduce discomfort. In addition, such situations e.g. two hours with opposite PMV values (hot versus cold discomfort) yet equal PPD, could be a potentially problematic scenario in building performance optimization. This issue could be even more critical in extreme conditions when PPD leans towards or equal 100%, i.e. when all occupants would be expected to be uncomfortable, but a user still wants to differentiate between severities. After this finite point, all situations are deemed equally uncomfortable (PPD=100%), which can be problematic in optimization studies (Carlucci et al., 2014). While PMV/PPD are forced out of their validation ranges in these situations, LEED's Passive Survivability Pilot Credit (U.S. Green Building Council, 2019) suggests using *SET* for evaluating such thermal conditions, which is the approach used in the proposed Exceedance Degree-Hours index. While one can couple PPD with PMV and optimize for two discomfort indices, having a method that can differentiate conditions stated above and sum up discomfort severities in a single value simplifies the optimization process.

Finally, while mixed-mode buildings, which use a combination of some type of mechanical heating or cooling with natural ventilation from operable windows (Borgeson and Brager, 2011), are growing in popularity (G. Brager and Baker, 2009; Kim et al., 2019; Salcido et al., 2016) because of their hybrid approach and operational flexibility, current standards do not give direction on thermal comfort in such spaces (Borgeson and Brager, 2011). Thermal assessment of these buildings involves using paired indices, which evaluate comfort conditions of mechanically and naturally ventilated periods when applicable using Fanger and adaptive comfort models, respectively, and separately reporting periods of discomfort. Researchers have also developed comfort models that are applicable for mixed-mode buildings, such as the India Model for Adaptive Comfort or IMAC (Manu et al., 2016) yet these are region-specific and suggest more appropriate neutral temperatures, not specific indices to measure discomfort.

The above discussion suggests a need for a new generalized discomfort index that: (1) expresses the severity of discomfort over time; (2) considers combinations of environmental and personal factors; (3) is applicable to both naturally and mechanically ventilated buildings; (4) is compatible with any specified comfort range (and thus, a variety of interests e.g., traditional thermal comfort, sleep comfort, etc.); (5) evaluates both summer and winter discomfort using the upper and lower comfort temperatures (Pagliano, 2012); (6) can be used for comfort level comparison between different buildings;

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(7) is expressible in a single value, making it more informative and useful for building performance simulation and optimization purposes. This paper proposes a new method for quantifying discomfort severity that meets these needs.

Method

Having discussed the current gaps in the literature, this study addresses these issues by proposing a new method of quantifying the severity of discomfort using a comprehensive equivalent temperature index. Using an equivalent temperature index allows the user to consider the six environmental and personal factors affecting thermal comfort. This makes apparent temperature indices useful for long-term evaluations of discomfort. Among existing equivalent temperature indices, *SET* is selected in this paper. Not only is *SET* considered to be one of the most comprehensive indices (Shiel et al., 2017) but also it is correlated to Universal Thermal Comfort Index (UTCI) (Jendritzky et al., 2009) and Wet-bulb Globe Temperature (WBGT) (ISO Committee TC-159 on Ergonomics, 1989) (Zare et al., 2018). While UTCI and WBGT were mainly developed for outdoor applications, *SET* could be used for both indoor and outdoor conditions. In addition, its inputs are familiar to many potential users and readily available as common outputs from building performance monitoring and simulation. Furthermore, *SET* has been used in the past to evaluate thermal conditions in naturally-ventilated buildings (Shiel et al., 2017) and is currently used in a LEED Pilot Credit for passive survivability (U.S. Green Building Council, 2019), suggesting its applicability outside of conditioned spaces.

A common method for displaying comfort conditions and defining comfort boundaries is to plot them on a psychrometric chart (ASHRAE 55, 2017; Hoyt et al., 2017). Because of its familiarity to many users, the proposed method takes advantage of this graphic approach (as shown in Figure 1). After defining reference comfort zones suggested in the literature (such as ASHRAE-55 comfort zone in Figure 1), a comfort zone corresponding to a condition of interest is determined by shifting the reference zone. For instance, the comfort zones proposed by ASHRAE-55 are based on an acceptable range of operative temperature and humidity resulting in two diagonal lines on the psychrometric chart matching a PMV of -0.5 and 0.5, when summer and winter clothing levels are 0.5 and 1 clo, respectively. Using these comfort zones as reference zones with a metabolic rate of 1 met and an average air speed of 0.2 $m/_s$ as reference parameters, any deviations of clothing levels, metabolic rate, and average air speed from the reference values are reflected in the analysis by shifting the reference comfort boundaries to the right or to the left to provide comfortable conditions in which $-0.5 \leq \text{PMV} \leq 0.5$. For average air speeds greater than 0.2 $m/_s$, an elevated air speed comfort zone method is used to account for the cooling effect (ASHRAE 55, 2017). Then, the proposed index determines the severity of discomfort by calculating the difference between the *SET* of the condition (e.g., condition 1 in Figure 1) and that of the closest condition on the boundary line of the comfort zone (e.g., condition 1′ in Figure 1) as follows:

$$SET_{condition} = f\left(t_{op}, t_r, v, rh, met, clo\right) \quad (1)$$

$$Discomfort\ severity = \left|SET_{condition} - SET_{\text{closest condition on the boundary line}}\right| \quad (2)$$

The proposed method is written in Python using pythermalcomfort package (Tartarini and Schiavon, 2020).

The proposed method can be applied to both Fanger and adaptive comfort definitions. For the former, a comfort zone is plotted on the psychrometric chart using graphic and analytical comfort zone methods suggested by ASHRAE-55 to determine comfortable thermal environments, given a set of environmental and personal factors. When applied with the adaptive comfort definition, the proposed method calculates the discomfort severity by determining the difference between the *SET* of the condition in question and that of the corresponding upper or lower limit based on the ATC model (i.e., 80% acceptability limits). For elevated air speed of above 0.3 m⁄s and for operative temperature greater than 25°C, the upper acceptability limit increases.

Results

Here, we present an example group of conditions to demonstrate the output capabilities of the Exceedance Degree-Hours index when applied to both adaptive (free-running) and Fanger (conditioned) comfort models. In the case of the Fanger comfort model, two example comfort zones, representing two different conditions in terms of air speed, metabolic rate, and clothing level are plotted as illustrated in Figure 1-(a), along with four environmental conditions corresponding to these comfort zones. In this figure, conditions 1 and 2 are compared to the closest conditions on comfort boundary A (i.e., ASHRAE-55 summer comfort zone). Since conditions 3 and 4 have higher air speed along with higher personal factors compared to those of conditions 1 and 2, the discomfort associated with these conditions is calculated with respect to comfort boundary B (shifted comfort zone). The proposed method is used to generate discomfort severity and the results are summarized in Table 1. For naturally ventilated cases, conditions 5, 6, and 7 are compared to the closest conditions on the original comfort boundaries of the ATC model. However, the modified upper acceptability limit is used when calculating the discomfort severity of condition 8.

The proposed method leads to Exceedance Degree-Hours of 14.4 °C_set and 11.1 °C_set for four hours of air-conditioned and four hours of naturally-ventilated conditions, respectively. Summing together the resulted Exceedance Degree-Hours of these two comfort models resulted in a total Exceedance Degree-Hours of 25.5 °C_set, for all eight hours. Furthermore, the highest discomfort severity (most uncomfortable) is captured in

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condition 2, as can be seen in Figure 1 and Table 1. Condition 7 has the lowest discomfort severity, as it is outside the comfort zone but still the most comfortable of those tested.

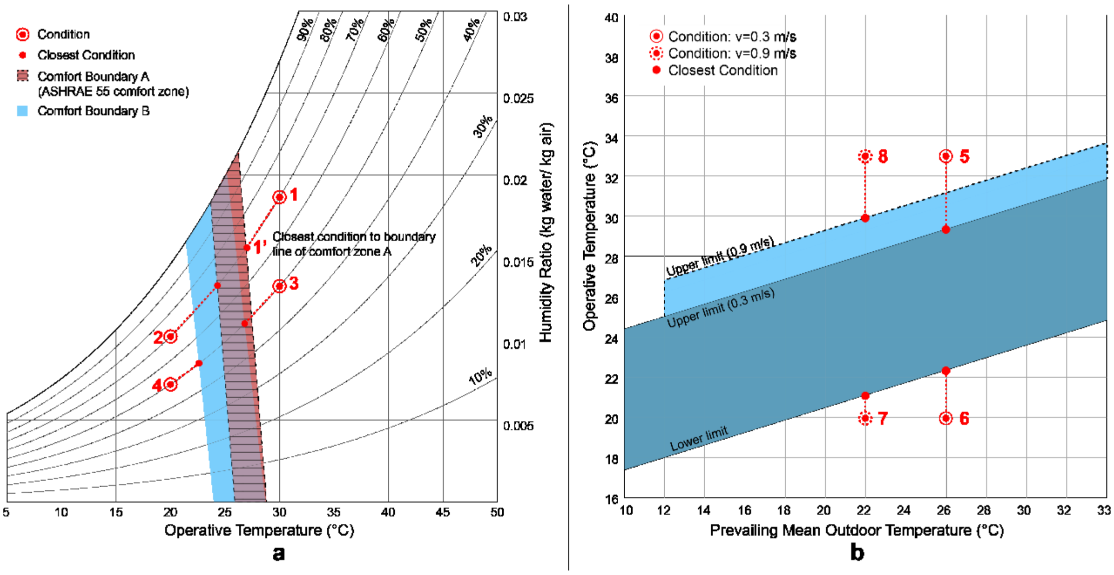

Figure 1. Comfort boundary and discomfort severity for eight test conditions: (a) Fanger comfort; (b) Adaptive thermal comfort (ATC)

Table 1. Discomfort severity for different conditions

	Fanger Comfort				Adaptive Comfort			
Condition	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Prevailing mean outdoor temp. (°C_{out})	-	-	-	-	26	26	26	26
Operative Temp. (°C_{opt})	30	20	30	20	33	20	20	33
Mean radiant Temp. (°C_r)	30	20	30	20	33	20	20	33
Relative Humidity (%)	70	70	50	50	50	50	50	50
Air speed ($^m/_s$)	0.1	0.1	0.3	0.3	0.3	0.3	0.9	0.9
Metabolic rate (met)	1.0	1.0	1.2	1.2	1.0	1.0	1.0	1.0
Clothing level (clo)	0.5	0.5	0.8	0.8	0.5	0.5	0.5	0.5
Closest Comfort Condition *SET* (°C_{set})	27	23.6	27.9	23.8	27.1	19.7	15.8	25.9
Condition *SET* (°C_{set})	31.2	18.9	30.5	20.9	30.9	17	14.4	29.1
Exceedance Degree (°C_{set})	***4.2***	***4.7***	***2.6***	***2.9***	***3.8***	***2.7***	***1.4***	***3.2***

Table 2. Summary of comparison between the Exceedance Degree-Hours and existing indices

	Thermal comfort index					
Condition (Air-conditions buildings)	**Dh**	**DhC**	**PPDwC**	**Eh**	**WEh**	**Exceedance Degree-Hours**
1) Differentiates conditions with equal PPD/PMV values	✓	✓	X	X	X	✓
2) Considers the effects of humidity	X	X	✓	X	X	✓
3) Applies dynamic comfort limits	X	X	✓	X	✓	✓
4) Considers cooling effect and changes in personal factors	X	X	✓	X	✓	✓

	Thermal comfort index		
Condition (Naturally-ventilated buildings)	**Dh**	**Eh**	**Exceedance Degree-Hours**
1) Considers the effect of humidity and other environmental and personal variables	X	X	✓

Comparing the proposed method to Fanger Model-based Indices

As mentioned in the introduction section, one of the most popular ways to evaluate/assess the comfort level of different conditions, including the impact of humidity, is to use PMV or PPD-based indices. When deviating from thermal neutrality, there are conditions where the combinations of environmental and personal factors result in the same PMV or PPD values. PMV or PPD-based indices, such as WEh and PPDwC treat these conditions equally uncomfortable. However, when using other indices, such as WBGT, UTCI, and *SET*, the equivalent

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feels-like temperatures of these situations are different. Thus, different environmental conditions (combinations of temperature and humidity) resulting in different equivalent feels-like temperatures in such situations (which are deemed equally uncomfortable by PMV or PPD-based indices) might need different mitigation actions when designing new buildings using optimization techniques. Therefore, an index that can differentiate between these conditions and quantify the discomfort severity in terms of equivalent feels-like temperatures could help simulation-based optimization to identify mitigation plans that are easier to implement.

Moreover, since fixed temperature limits are used in the DhC approach, this method loses information that is captured by the Exceedance Degree-Hours index with regard to changes in humidity level.

Besides fluctuations in temperature and humidity level, changes in air speed, metabolic rate, and clothing level lead to variations in thermal comfort conditions. Comparing conditions with similar temperature and humidity levels but different environmental and personal factors shows changes in discomfort due to variation in comfort ranges as determined by Exceedance Degree-Hours as well as PMV or PPD-based indices. However, Dh, DhC, and Eh are not able to reflect the effect of changes in personal variables.

Comparing the proposed method to Adaptive Model-based Indices

In this following section, the Exceedance Degree-Hours is compared to Dh and Eh indices. At moderate levels of humidity and without changing personal characteristics, the Exceedance Degree-Hours index produces results very similar to those of the Dh index, while no changes in the thermal condition is captured by Eh. Increasing the relative humidity level and using Exceedance Degree-Hours, values of thermal discomfort associated with these conditions are double those provided by Dh in most cases. This is due to the effect that increasing relative humidity has on *SET*. Given the same groups of comfort conditions and only differentiating humidity levels, the subtotal of discomfort severity by the Exceedance Degree-Hours index increases significantly, while the results produced by Dh and Eh do not change. Although using high levels of humidity falls outside the boundaries of the original experiments and equations in the adaptive model, this conclusion shows the importance of incorporating this parameter when evaluating thermal comfort in naturally-ventilated buildings. Therefore, if new comfort limits are proposed in the future by taking into account variations in humidity, the Exceedance Degree-Hours is still applicable and produces reliable results. Table 2 shows a summary of the comparison between the Exceedance Degree-Hours and existing indices as discussed above.

Discussion

As many existing exceedance-based indices, such as Eh, treat comfort as binary, they do not capture the severity of discomfort an occupant might experience. Moreover, while other existing indices may capture severity using weighting factors, such as WEh and PPDwC, they cannot distinguish between thermal comfort associated with conditions at which PMV or PPD values do not change. Besides, other indices that can address the issue of having the same PMV or PPD values, such as DH and DHC, do not currently take humidity and other environmental and personal factors affecting comfort into account. This index, while including nuances of how changing environmental and personal factors affect thermal conditions, captures discomfort severity in all the above-mentioned conditions based on variations in thermal sensation. Even for extreme conditions, the Exceedance Degree-Hours is aligned with LEED recommendations. Thus, there would be no need to use different indices for various situations and all can be covered by a single index.

As thermal sensation changes with variations in environmental and personal factors, so does the comfort boundaries. Thus, in order to properly evaluate thermal comfort/discomfort, the changes in comfort limits should be properly incorporated. Temperature limits, for instance, change based on variations in humidity in the Fanger model as demonstrated by the diagonal lines of comfort boundaries in a psychrometric chart. Therefore, Fanger model-based indices, such as PPDwC and WEh incorporate these changes when calculating discomfort. In contrast with these indices, however, comfort limits in Dh and DhC indices are specified in terms of fixed threshold temperatures (straight lines on a psychrometric chart) regardless of variations in humidity level. This results in over- or underestimating thermal conditions. Furthermore, the comfort boundaries of the Fanger model move along the temperature axis in a psychrometric chart based on changes in air speed, metabolic rate, and/or clothing level. Similarly, the Exceedance Degree-Hours index accordingly assesses thermal conditions against these dynamic comfort limits.

Although one of the criteria of the application of ATC is the absence of mechanical cooling systems, in current practice, paired indices are used to evaluate the thermal conditions of mixed-mode buildings, which can be helpful in energy-simulation-based optimization processes. In this regard, Fanger- and adaptive model-based indices are separately adopted to report periods of discomfort in mechanically and naturally-ventilated spaces, respectively. However, when it comes to optimization purposes, having an index that can summarize discomfort severity in a single value for both conditioned and free-floating periods plays an important role in simplifying the optimization problem.

To this end, unlike the previous approaches, the Exceedance Degree-Hours is applicable to both adaptive and Fanger models. As *SET* has been used in the past to evaluate thermal conditions in air-conditioned (Dhaka and Mathur, 2017) and naturally-ventilated buildings (Shiel et al., 2017), using a *SET*-based index allows the overall discomfort severity to be summated in a single value, which is expressed in terms of building-related parameters (i.e., *SET* differences). Therefore, when analyzing mixed-mode buildings, optimization engines can easily optimize for comfort using a single variable, regardless of the building's operation mode. This

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applicability along with the ability to differently treat conditions at which PMV or PPD values are equal can be extrapolated to simulation and/or optimization analyses, which would in return benefit the building industry. When doing building design simulation-based optimization analyses, it can be important to differentiate between two conditions leading to the same PPD as they may require different mitigation actions. For instance, a designer may want to provide dehumidification in one case and increase air speed in another in order to reduce discomfort, which is easier by using a *SET*-based index to express the severity of thermal discomfort.

Using *SET* differences to measure discomfort severity, all six environmental and personal factors are reflected in the assessment of thermal conditions in air-conditioned spaces. Although the adaptive comfort model takes changes in metabolic rate and clothing levels into account, these considerations are not included in the acceptability limits equations, which are solely based on temperature. Using *SET* differences makes it possible to not only directly incorporate personal parameters but also to account for humidity variations along with the five other affecting factors in the adaptive model. Although one can argue that the impact of humidity is not reflected in the original ATC model calculations (even though it has been proven to be an affecting factor (F. Nicol et al., 2012; Vellei et al., 2017)), future comfort definitions for free-running buildings may consider variations in relative humidity. As the Exceedance Degree-Hours accounts for different humidity levels, it could be compatible with such future advancements in thermal comfort definitions.

Over the last century, researchers have defined comfort definitions via both advanced physics-based models and empirical methods, such as experimental chamber studies and real-building surveys. While many indices are tied to specific comfort models, this method and its accompanying index allow its user to measure discomfort severity against any comfort definition. As discussed in the previous section, Fanger and the adaptive comfort models could be used with this method to evaluate indoor comfort in air-conditioned and naturally-ventilated buildings, respectively. Similarly, other, more specific comfort models such as IMAC could be used. Thus, this paper is not proposing a new comfort definition; rather, it is proposing a methodology that is compatible with whichever comfort model is being used, which could include new models (e.g. thermal safety).

Furthermore, this flexibility allows the proposed method to be used for multiple comfort definitions, e.g. awake and sleep, within a single analysis. The research underpinning the comfort definitions used today (ASHRAE, ISO, ENSI), including Fanger and the adaptive comfort model, was performed on awake individuals. Researchers are establishing comfort parameters specifically based on sleeping subjects (Dongmei et al., 2012; Lan et al., 2014, 2018), and the proposed method would allow such comfort models to be codified into standards. We know of no other method that can combine two different comfort definitions at different times.

SET is used as an equivalent temperature index in this study, one could alternatively use other feels-like temperature conversion methods, such as WBGT, or UTCI to apply the proposed method depending on thermal condition requirements (e.g., outdoor applications).

Similar to other cumulative discomfort indices, Exceedance Degree-Hours has no upper limit. For "thermal comfort sums" of this type, it can be impractical to compare different buildings (Silva et al., 2016). For example, different buildings may have different quantities of data (e.g., annual versus month-long simulations or measurements), be in different climates, or have other variable factors that render the comparison impractical. To address this problem, the Exceedance Degree-Hours could be normalized. For instance, for buildings with different quantities of data or characteristics, one can divide the Exceedance Degree-Hours by the total occupied hours, occupants' density, areas of occupied spaces, etc. of each building to create Normalized Exceedance Degree-Hours.

As mentioned in the introduction section, buildings with high POR could have a higher quantity of low-severity discomfort instances or vice versa. Although the *SET* difference evaluated by our method acts as the weighting factor in the proposed method, the Exceedance Degree-Hours cannot capture and express the difference between a few highly uncomfortable hours or many slightly uncomfortable ones similar to other exceedance-type discomfort indices. A possible solution to this limitation is to average the index depending on the needs of the user. In addition, to address the cases with extreme nonlinearity, increasing the granularity by introducing smaller analysis windows can help. Such cases can be broken down into intervals where the *SET* differences are of the similar order of magnitude. For example, Average Exceedance Degree-Hours could express the mean hourly discomfort during the monitored period, while Average Exceedance Degree-Days could measure the mean daily discomfort. These could serve as additional information—and not a replacement—to cumulative Exceedance Degree-Hours, helping further understand discomfort in a building. However, the issue regarding summing the discomfort severities in a single value (e.g., for long-term discomfort assessment, such as annual simulations) remains, which is the case with any type of exceedance indices. To address this issue, pairing the exceedance-type discomfort indices with another index that accounts for time-steps with peak exceedance could alleviate the issue.

Conclusion

In this paper, a new method that expresses the severity of discomfort over time is proposed. This new method calculates discomfort by comparing the *SET* of a condition in question to the *SET* of the closest boundary condition in whichever thermal comfort range the user has chosen. The Exceedance Degree-Hours differs from existing metrics in that it is applicable to both Fanger and Adaptive Comfort models, being flexible enough to be

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used with other (and future) comfort definitions. Furthermore, it can evaluate differences in the main six personal and environmental factors affecting thermal comfort. This approach is more complex than some of the most widely used metrics, yet it requires the same data as the popular PMV method. Importantly, this metric can express results for different modes of operation in a single value, and it can distinguish between different conditions leading to the same PMV or PPD. Expressing discomfort as one single value in terms of building-related parameters could be especially useful in building simulation and optimization studies.

As previously mentioned, here *SET* was chosen as the underlying equivalent temperature index of Exceedance Degree-Hours due to its familiarity and the relatively immediate availability of its required inputs from outputs of typical building simulation or comfort monitoring in buildings. Yet, some inputs such as air speed or clothing level can be difficult to assume or measure. Current energy simulation programs such as EnergyPlus56 do not calculate or include zone air speed as an output; more accurate and time-consuming Computational Fluid Dynamics (CFD) or building monitoring using sensors might be required. Future software developments could include these factors, which are heavily used in the industry, as outputs. While other, less comprehensive indices do not require such inputs, they might not capture important information related to thermal comfort, as demonstrated here.

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