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Human Thermal Comfort
"The Factors Influencing the Human Thermal Comfort"
الراحة الحرارية للانسان
العوامل المؤثرة على تحقيق الراحة الحرارية

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Abstract

The study aims to discuss the elements of achieving the thermal comfort of humans. Where thermal comfort is one of the most important human needs as it affects the functional performance of man and thus affect economically, healthily and socially on the general environment. There are many different dimensions and levels to achieve the appropriate thermal satisfaction for human needs by knowing the concept of thermal comfort and how to measure it? What are the factors affecting thermal comfort? Such as (Air temperature, Mean radiant temperature, Air velocity, Relative humidity, Clothing insulation and Metabolic rate) By choosing methods of thermal comfort and then how to create thermal comfort?

Keywords:

Thermal comfort – CBE thermal comfort tool – Environmental Architecture – Sustainable Architecture

الخلاصة :

تهدف الدراسة الى مناقشة عناصر تحقيق الراحة الحرارية للأنسان . حيث ان الراحة الحرارية من اهم احتياجات الانسان حيث تؤثر على الاداء الوظيفى للانسان وبالتالى تؤثر اقتصاديا وصحيا واجتماعيا على البيئة العامة . وهناك العديد من الابعاد والمستويات المختلفة لتحقيق الرضا الحرارى المناسب لاحتياجات الانسان وذلك من خلال معرفة مفهوم الراحة الحرارية وكيفية قياسها ؟ وما هى العوامل المؤثرة على الراحة الحرارية ؟ مثل (درجة الحرارة، متوسط الاشعاع الحراري، سرعة الرياح، الرطوبة النسبية، معمل الايض و نوع الملبس) وذلك بأختيار نماذج من الراحة الحرارية ومن ثم الوصول الى كيفية انشاء الراحة الحرارية ؟

الكلمات المفتاحية:

الراحة الحرارية – CBE اداة الراحة الحرارية– العمارة البيئية -العمارة المستدامة

Research objective:

The objective of this research is to investigate the importance of human thermal comfort which acts as a human need as it increases human productivity.

Research problem

The lack of interest from many Architects about the importance of human thermal comfort and how to be achieved.

Research methodology

The research starts with a theoretical approach stating the definitions of thermal comfort, the factors affecting thermal comfort and the thermal comfort methods, then finalizing with introducing a thermal comfort tool "CBE thermal comfort tool"

1- Introduction

Man has always striven to create a thermally comfortable environment. This is reflected in building traditions around the world - from ancient history to present day. Today, creating a thermally comfortable environment is still one of the most important parameters to be considered when designing buildings.

2- What is Thermal comfort?

It is defined in the ISO 7730 standard as being "That condition of mind which expresses satisfaction with the thermal environment". A definition most people can agree on, but also a definition which is not easily converted into physical parameters.

The complexity of evaluating thermal comfort is illustrated by the drawing. Both persons illustrated are likely to be thermally comfortable, even though they are in completely different thermal environments. This reminds us that thermal comfort is a matter of many physical parameters, and not just one, as for example the air temperature.

Figure 1:The indoor and outdoor thermal comfort, (Instruments, 2018)

2-1- Why do we look for thermal comfort?

Thermal environments are considered together with other factors such as air quality, light and noise level, when we evaluate our working environment. If we do not feel the everyday working environment is satisfactory, our working performance will inevitably suffer. Thus, thermal comfort also has an impact on our work efficiency.

Thermal comfort has a great effect on the employee's performance, so it affects economically, healthily and socially on the overall work environment.

2-2- Measuring thermal comfort

The most common approach to characterizing thermal comfort for the purposes of prediction and building design has been to correlate the results of psychological experiments to thermal analysis variables. (A large number of the experiments have been performed at universities with college students as the human subjects.) That is, human subjects with various clothing levels and performing different activities are placed in environments with different air temperatures and surface temperatures, different humidities, and different airflow velocities and patterns. The subjects are then asked to express their level of comfort. The level of comfort is often characterized using the ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) thermal sensation scale. The average thermal sensation response of a large number of subjects, using the ASHRAE thermal sensation scale, is called the predicted mean vote (PMV) (Charles, 2003, p. 5).

Table 1: ASHRAE Thermal Sensation Scale

Value	Sensation
+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

There has been a tendency to combine all environmental variables in an effective or apparent temperature, and all personal response in a few degrees of comfort (or discomfort); the 7-scale thermal feeling is:

- Uncomfortable cold, when >95% of people in a significant group complain of being cold.
- Cool or bearable cold, when some 75% of people in a significant group complain of being cold.
- Slightly cool, when only some 25% of people in a significant group complain of being cold.
- Comfortable, when <5% of people in a significant group complain of being cool or warm.
- Slightly warm, when only some 25% of people in a significant group of being hot.
- Warm or bearable hot, when some 75% of people in a significant group complain of being hot.
- Uncomfortable hot, when >95% of people in a significant group complain of being hot.

3- What are the factors influencing thermal comfort?

Perhaps the most commonly cited experiments on the human perception of thermal comfort have been performed by Fanger (1982). His analysis indicated that the sensation of thermal comfort was most significantly determined by narrow ranges of skin temperature and sweat evaporation rate, depending on activity level. (More active people were comfortable at low skin temperatures and higher evaporation rates.) By combining this information with the thermal energy balance equations above, he developed a set of correlations giving the PMV as a function of six variables: air temperature, mean radiant temperature, air velocity, air humidity, clothing resistance, and activity level.

3-1- Air temperature

The air temperature is the average temperature of the air surrounding the occupant, with respect to location and time. According to ASHRAE 55 standard, the spatial average takes into account the ankle, waist and head levels, which vary for seated or standing occupants. The temporal average is based on three-minute intervals with at least 18 equally spaced points in time. Air temperature is measured with a dry-bulb thermometer and for this reason it is also known as dry-bulb temperature.

3-2-Mean radiant temperature (MRT)

The Mean Radiant Temperature of an environment is defined as that uniform temperature of an imaginary black enclosure which would result in the same heat loss by radiation from the person as the actual enclosure (Instruments, 2018, p. 7).

The equation for the calculation of Mean Radiant Temperature is:

$$i_t = \sqrt[4]{\sum_n F_{p-i}(t_i + 273)^4} - 273$$

t_i Surface temperature of surface i [°C]

F_{p-i} Angle factor between the person and surface i

$\sum F_{p-i} = 1$

Measuring the temperature of all surfaces in the room is very time consuming, and even more time consuming is the calculation of the corresponding angle factors. That is why the use of the Mean Radiant Temperature is avoided if possible.

3-3- Air velocity

It is defined as the rate of air movement at a point, without regard to direction. According to ANSI/ASHRAE Standard 55, it is the average speed of the air to which the body is exposed, with respect to location and time. The temporal average is the same as the air temperature, while the spatial average is based on the assumption that the body is exposed to a uniform air speed, according to the SET thermo-physiological model. However, some spaces might provide strongly non uniform air velocity fields and consequent skin heat losses that cannot be considered uniform. Therefore, the designer shall decide the proper averaging, especially including air speeds incident on unclothed body parts, which have greater cooling effect and potential for local discomfort.

3-4- Relative humidity

Relative humidity (RH) is the ratio of the amount of water vapor in the air to the amount of water vapor that the air could hold at the specific temperature and pressure. While the human body has sensors within the skin that are fairly efficient at feeling heat and cold, relative humidity is detected indirectly. Sweating is an effective heat loss mechanism that relies on evaporation from the skin. However at high RH, the air has close to the maximum water vapor that it can hold, so evaporation, and therefore heat loss, is decreased. On the other hand, very dry environments (RH < 20-30%) are also uncomfortable because of their effect on the mucous membranes. The recommended level of indoor humidity is in the range of 30-60% in air conditioned buildings, but new standards such as the adaptive model allow lower and higher humidities, depending on the other factors involved in thermal comfort.

3-5- Clothing insulation

The amount of thermal insulation worn by a person has a substantial impact on thermal comfort, because it influences the heat loss and consequently the thermal balance. Layers of insulating clothing prevent heat loss and can either help keep a person warm or lead to overheating. Generally, the thicker the garment is the greater insulating ability it has. Depending on the type of material the clothing is made out of, air movement and relative humidity can decrease the insulating ability of the material.

1 clo is equal to 0.155 m²·K/W (0.88 °F·ft²·h/Btu). This corresponds to trousers, a long sleeved shirt, and a jacket. Clothing insulation values for other common ensembles or single garments can be found in ASHRAE 55.

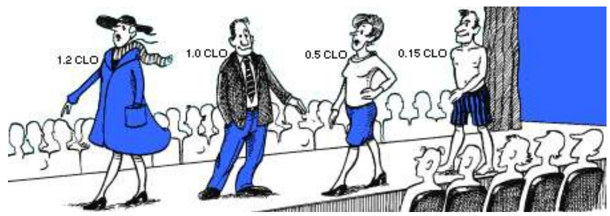

Figure 2:Different types of clothing with different clothing insulation

http://mapadeconfortclimaticodegrancanaria.blogspot.com/2012/07

Table 2: ASHRAE Clothing Insulation Values for Typical Ensembles

Clothing Description	Garments Included	I_{cl} (clo)
Trousers	1) Trousers, short-sleeve shirt	0.57
	2) Trousers, long-sleeve shirt	0.61
	3) #2 plus suit jacket	0.95
	4) #2 plus suit jacket, vest, T-shirt	1.14
	5) #2 plus long-sleeve sweater, T-shirt	1.01
	6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/Dresses	7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	8) Knee-length skirt, long-sleeve shirt, full slip	0.67
	9) Knee-length skirt, long-sleeve shirt, half-slip, long-sleeve sweater	1.10
	10) Knee-length skirt, long-sleeve shirt, half-slip, suit jacket	1.04
	11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	12) Walking shorts, short-sleeve shirt	0.36
Overalls/Coveralls	13) Long-sleeve coveralls, T-shirt	0.72
	14) Overalls, long-sleeve shirt, T-shirt	0.89
	15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	16) Sweat pants, long-sleeve sweatshirt	0.74
Sleepwear	17) Long-sleeve pajama tops, long pajama trousers, short 3/4 length robe (slippers, no socks)	0.96

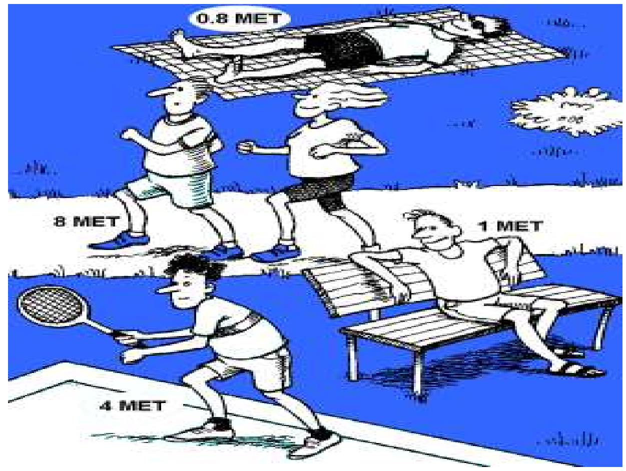

Figure 3: Different types of activity showing different metabolic rate
https://www.researchgate.net/figure/Local-thermal-discomfort-1-Cooling-or-heating-of-parts-of-the-body-by-radiation-

3-6- Metabolic rate

People have different metabolic rates that can fluctuate due to activity level and environmental conditions. The ASHRAE 55-2010 Standard defines metabolic rate as the level of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface. Metabolic rate is expressed in met units, which are defined as follows:

1 met = 58.2 W/m² (18.4 Btu/h·ft²), which is equal to the energy produced per unit surface area of an average person seated at rest. The surface area of an average person is 1.8 m² (19 ft²) (Instruments, 2018, p. 5).

Table 3: ASHRAE Metabolic Rates for Typical Tasks

Activity		Metabolic Rate		
		Met Units	W/m²	(Btu/h·ft²)
Resting	Sleeping	0.7	40	13
	Reclining	0.8	45	15
	Seated, quiet	1.0	60	18
	Standing, relaxed	1.2	70	22
Walking (on level surface)	0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	37
	1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	48
	1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	70
Office Activities	Reading, seated	1.0	55	18
	Writing	1.0	60	18
	Typing	1.1	65	20
	Filing, seated	1.2	70	22
	Filing, standing	1.4	80	26
	Walking about	1.7	100	31
	Lifting/packing	2.1	120	39
Driving/Flying	Automobile	1.0-2.0	60-115	18-37
	Aircraft, routine	1.2	70	22
	Aircraft, instrument landing	1.8	105	33
	Aircraft, combat	2.4	140	44
	Heavy vehicle	3.2	185	59
Miscellaneous Occupational Activities	Cooking	1.6-2.0	95-115	29-37
	House cleaning	2.0-3.4	115-200	37-63
	Seated, heavy limb movement	2.2	130	41
	Machine work			
	sawing (table saw)	1.8	105	33
	light (electrical industry)	2.0-2.4	115-140	37-44
	heavy	4.0	235	74
	Handling 50 kg (100 lb) bags	4.0	235	74
	Pick and shovel work	4.0-4.8	235-280	74-88
Miscellaneous Leisure Activities	Dancing, social	2.4-4.4	140-255	44-81
	Calisthenics/exercise	3.0-4.0	175-235	55-74
	Tennis, single	3.6-4.0	210-270	66-74
	Basketball	5.0-7.6	290-440	90-140
	Wrestling, competitive	7.0-8.7	410-505	130-160

4- Thermal comfort methods

When discussing thermal comfort, there are two main different models that can be used: the static model (PMV/PPD) and the adaptive model (Charles, 2003).

4-1- PMV/PPD method

The PMV/PPD model was developed by P. O. Fanger using heat balance equations and empirical studies about skin temperature to define comfort. Standard thermal comfort surveys ask subjects about their thermal sensation on a seven-point scale from cold (-3) to hot (+3). Fanger's equations are used to calculate the Predicted Mean Vote (PMV) of a large group of subjects for a particular combination of air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation. Zero is the ideal value, representing thermal neutrality, and the comfort zone is defined by the combinations of the six parameters for which the PMV is within the recommended limits ($-0.5<PMV<+0.5$). Although predicting the thermal sensation of a population is an important step in determining what conditions are comfortable, it is more useful to consider whether or not people will be satisfied. Fanger developed another equation to relate the PMV to the Predicted Percentage of Dissatisfied (PPD). This relation was based on studies that surveyed subjects in a chamber where the indoor conditions can be precisely controlled.

This method treats all occupants the same and disregards location and adaptation to the thermal environment. It basically states that the indoor temperature should not change as the seasons do. Rather, there should be one set temperature year-round. This is taking a more passive stand that humans do not have to adapt to different temperatures since it will always be constant.

ASHRAE Standard 55-2010 uses the PMV model to set the requirements for indoor thermal conditions. It requires that at least 80% of the occupants be satisfied.

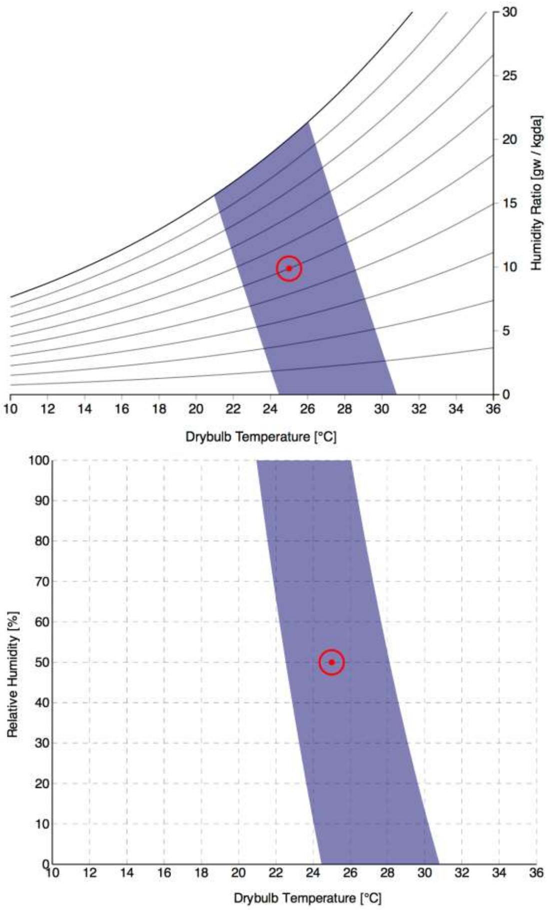

Figure 4: Diagram showing different thermal comfort range
http://cbe.berkeley.edu:
http://cbe.berkeley.edu/comforttool/

The CBE Thermal Comfort Tool for ASHRAE 55 allows users to input the six comfort parameters to determine whether a certain combination complies with ASHRAE 55. The results are displayed on a psychometric or a temperature-relative humidity chart and indicate the ranges of temperature and relative humidity that will be comfortable with the given the values input for the remaining four parameters.

4-2- Adaptive comfort method

The adaptive model is based on the idea that outdoor climate influences indoor comfort because humans can adapt to different temperatures during different times of the year. The adaptive hypothesis predicts that contextual factors, such as having access to environmental controls, and past thermal history influence building occupants' thermal expectations and preferences. Numerous researchers have conducted field studies worldwide in which they survey building occupants about their thermal comfort while taking simultaneous environmental measurements. Analyzing a database of results from 160 of these buildings revealed that occupants of naturally ventilated buildings accept and even prefer a wider range of temperatures than their counterparts in sealed, air-conditioned buildings because their preferred temperature depends on outdoor conditions. These results were incorporated in the ASHRAE 55-2004 standard as the adaptive comfort model. The adaptive chart relates indoor comfort temperature to prevailing outdoor temperature and defines zones of 80% and 90% satisfaction.

The ASHRAE-55 2010 Standard has introduced the prevailing mean outdoor temperature as the input variable for the adaptive model. It is based on the arithmetic average of the mean daily outdoor temperatures over no fewer than 7 and no more than 30 sequential days prior to the day in question. It can also be calculated by weighting the temperatures with different coefficients, assigning increasing importance to the most recent temperatures. In case this weighting is used, there is no need to respect the upper limit for the subsequent days. In order to apply the adaptive model, there should be no mechanical cooling system for the space, occupants should be engaged in sedentary activities with metabolic rates of 1-1.3 met, and a prevailing mean temperature greater than 10 °C (50 °F) and less than 33.5 °C (92.3 °F).

This model applies especially to occupant-controlled, natural conditioned spaces, where the outdoor climate can actually affect the indoor conditions and so the comfort zone. In fact, studies by de Dear and Brager showed that occupants in naturally ventilated buildings were tolerant of a wider range of temperatures. This is due to both behavioral and physiological adjustments, since there are different types of adaptive processes. ASHRAE Standard 55-2010 states that differences in recent thermal experiences, changes in clothing, availability of control options and shifts in occupant expectations can change people thermal responses.

There are basically three categories of thermal adaptation, namely Behavioral, Physiological and Psychological. The latter, which refers to an altered thermal perception and reaction due to past experiences and expectations, is an important factor in explaining the difference between field observations and PMV predictions (based on the static model) in naturally ventilated buildings. In these buildings the relationship with the outdoor temperatures is twice as strong as predicted.

Adaptive models of thermal comfort are implemented in other standards such as European EN 15251 and ISO 7730 standard. While the exact derivation methods and results are slightly different from the ASHRAE 55 adaptive standard, they are substantially the same. A larger difference is in applicability. The ASHRAE adaptive standard only applies to buildings without mechanical cooling installed, while EN15251 can be applied to mixed-mode buildings provided the system is not running.

5- <u>How to create Thermal Comfort?</u>

When evaluating a workplace, we often talk about the Comfortable Temperature (t_{co}), which is defined as the Equivalent Temperature where a person feels thermally comfortable. We rarely talk about comfortable humidity, this is partly due to the difficulty of feeling the humidity in the air and partly due to humidity having only a slight influence on a person' s heat exchange when they are close to a state of thermal comfort (Instruments, 2018).

The comfort temperature in a given environment can be calculated from the comfort equation:

$$M – W = H + E_c + C_{res} + E_{res}$$

Where,

M is the "Metabolic rate"

W is the "Effective mechanical power"

H is the "Dry Heat Loss"

E_c is the "Evaporative heat exchange at the skin"

C_{res} "is the Respiratory convective heat exchange"

E_{res} "is the Respiratory evaporative heat exchange"

In the figure a few results from such calculations can be seen. Notice how warm it should be if someone is sitting doing work wearing a light summer dress.

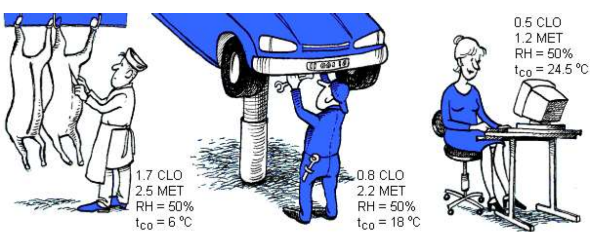

Figure 5: Different work conditions leads to different thermal comfort, (Instruments, 2018)

If a room contains many people, wearing different types of clothing and carrying out different types of activities, it can be difficult to create an environment which provides thermal comfort for all the occupants. Something can be done by changing the factors that affect the thermal comfort locally, for example, if the equivalent temperature is lower than the comfort temperature, the mean radiant temperature can be increased by installing heated panels (Instruments, 2018, pp. 9-10).

Fortunately, individuals can often optimize their own thermal comfort simply by adjusting their clothing to suit the conditions, for example, by removing a jumper, rolling up shirt sleeves or alternatively putting on a jacket.

Table 4: ASHRAE Thermal Comfort Conditions

Season	**Optimum Temperature**	**Acceptable Temperature Range**	**Assumptions for other PMV inputs**
Winter	22 °C	20-23 °C	relative humidity: 50% mean relative velocity: < 0.15 m/s mean radiant temperature: equal to air temperature metabolic rate: 1.2 met clothing insulation: 0.9 clo
Summer	24.5 °C	23-26 °C	relative humidity: 50% mean relative velocity: < 0.15 m/s mean radiant temperature: equal to air temperature metabolic rate: 1.2 met clothing insulation: 0.5 clo

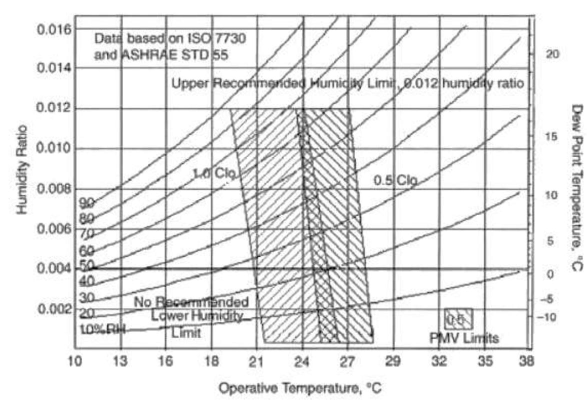

Figure 6: diagram illustrating the above table for thermal comfort in certain conditions https://www.researchgate.net/figure/ASHRAE-comfort-chart-ASHRAE-Standard-55-2004-A-

window-influences-thermal-comfort-in_fig1_319186098

6- CBE Thermal Comfort Tool

CBE Thermal Comfort Tool is a free online tool for evaluating comfort according to ASHRAE Standard-55 (Tyler, Stefano, Alberto, Dustin, & Kyle, 2013).

CBE (Center for the Built Environment) develop a web-based graphical user interface for thermal comfort prediction according to ASHRAE Standard-55. Include models for conventional building systems (predicted mean vote) and also for comfort using the adaptive comfort model, and with increased air speeds (for example, when using fans for cooling). Provide ongoing upgrades and new features, such as visualization of comfort boundaries within the psychrometric and temperature-humidity charts, and automatic generation of LEED documentation for thermal comfort credits.

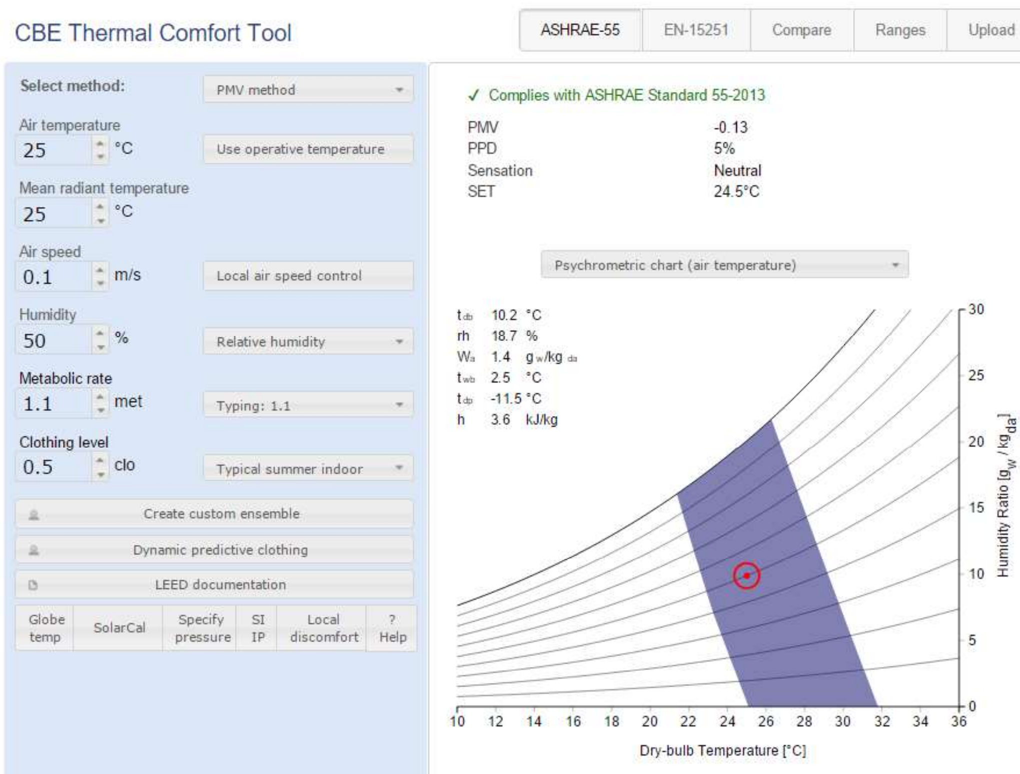

Figure 7: An Example with the application of CBE thermal comfort tool using the temperature 25℃
http://cbe.berkeley.edu: http://cbe.berkeley.edu/comforttool/

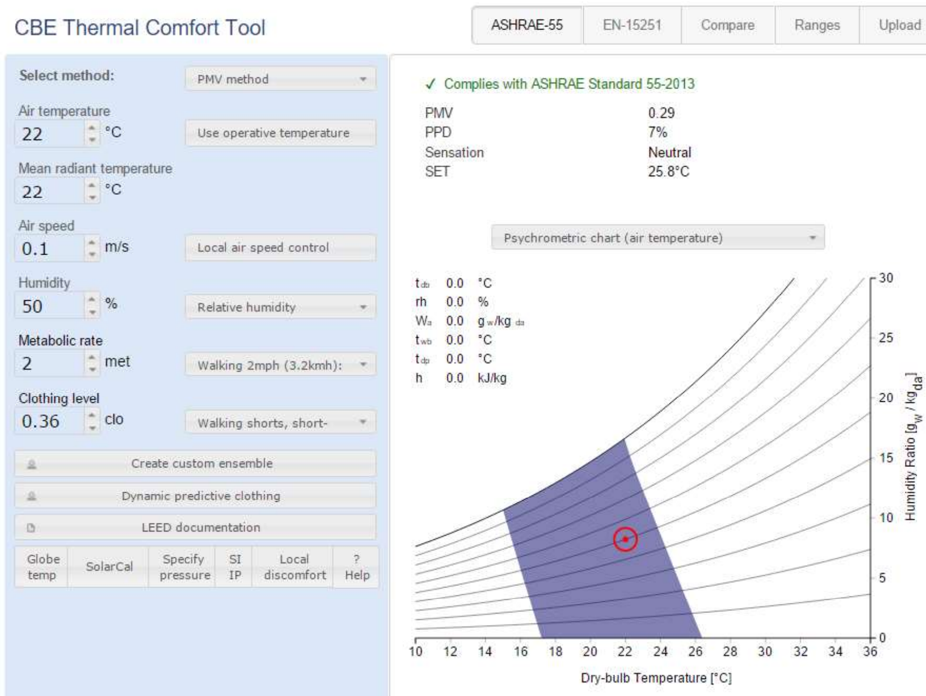

Figure 8: An Example with the application of CBE thermal comfort tool using the temperature 22℃

http://cbe.berkeley.edu: http://cbe.berkeley.edu/comforttool/

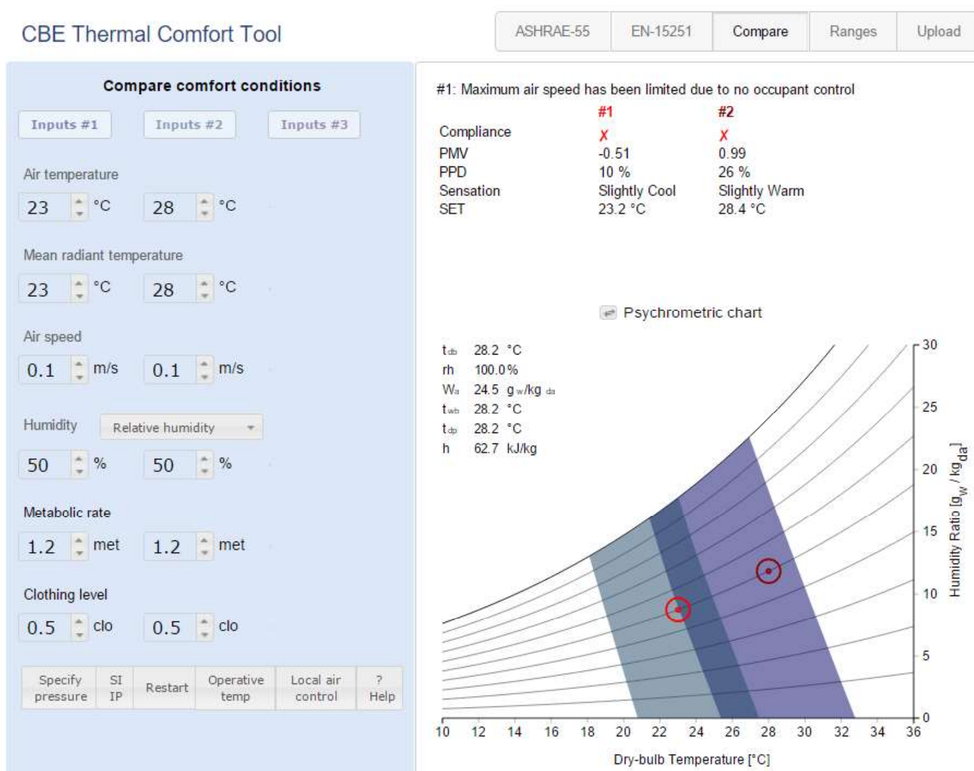

Figure 9: An Example with the application of CBE thermal comfort tool showing the comparison between two different temperatures

http://cbe.berkeley.edu: http://cbe.berkeley.edu/comforttool/

7- Conclusion:

Thermal comfort is one of the most important human needs that interact with the human and affect him. As it is one of the most important criteria that must be taken into account in the design of buildings. A person must live in a suitable thermal environment in order to increase his productivity and efficiency. Therefore, thermal comfort depends on a range of factors such as (Air temperature, Mean radiant temperature, Air velocity, Relative humidity, Clothing insulation and Metabolic rate) which the architectural designer should consider in order to reach the maximum thermal comfort bikes for man. Which will have a positive effect on the environment economically and socially, the right choice of architectural materials and clothing type that is suitable with the type of work will lead to thermal comfort.

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