The Human Bio-Meteorological Chart

A design tool for outdoor thermal comfort

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ABSTRACT: A simplified method is proposed to estimate human outdoor thermal comfort for a given situation using hourly climate data of ambient temperature and humidity. This so called human bio-meteorological chart is overlaid on the psychrometric chart and can be used to study and compare very quickly the effect of outdoor comfort strategies such as sun exposure, shading, sky cooling or wind protection on thermal comfort. To calculate human comfort indices, typically 8 parameters need to be known. In particular the calculation of the long wave mean radiant temperature and the complex effect of the direct and diffuse radiation on the mean radiant temperature (MRT) is time consuming and requires detailed modeling of the radiant field. The simplifications to estimate the MRT and to reduce the numbers of parameters are justified in the second part of this paper. The simplification can be used for any kind of comfort index where the MRT is required as input.

Keywords: outdoor comfort, perceived temperature, mean radiant temperature, climate data analysis

INTRODUCTION

In an outdoor situation people have many adaptive opportunities and they can adjust their thermal requirements according to the weather conditions. However there is a lack of design tools that provide analysis of outdoor thermal comfort strategies, design tools especially for a quick statistical analysis of the strategies are in need.

There are typically 8 major parameters which define the comfort perception in outdoor situations: direct and diffuse solar radiation, long wave radiation, air temperature and humidity, wind velocity, activity and clothing (see *Figure 1*). When designing for outdoor comfort these parameters need to be analyzed with thermal dynamical simulation tools such as TRNSYS 17 3D which consider building materials, 3D geometry, hourly climate data, etc.. Modeling and simulating an open outdoor space e.g. a plaza can be time consuming.

To reduce the complexity and to quickly identify opportunities of the urban design to enhance outdoor comfort, the number of parameters can be reduced. It was found that with reasonable accuracy the local outdoor comfort can be qualified with a human bio-meteorological chart and design options can be evaluated quickly based on hourly climate data. This method targets on the identification of simplified parameters and is thus independent of the applied comfort measure. Once identified, the parameters can be used to calculate various outdoor comfort indices such as the Perceived Temperature, UTCI, WBGT, Thermal Sensation, etc.. For this study the outdoor comfort index of Perceived Temperature, PT is calculated with the algorithm given in [1] and applied for demonstration.

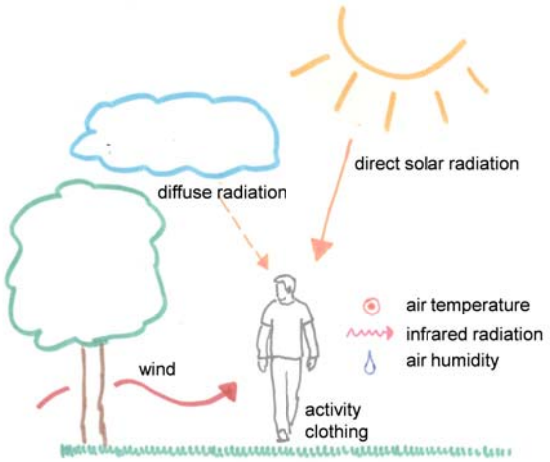

Figure 1: 8 major parameters to characterize outdoor comfort

EVALUATION OF HUMAN BIO-METEREOLOGICAL PARAMETERS

The German guideline VDI 3787 [1] is intended to provide evaluation methods linking together human biometeorology and overall physical planning. The first part of the guideline describes human bio-meteorological factors (comfort parameters). The amendment from 2008 provides details about the Perceived Temperature (PT) which is especially useful when the impact of high air humidity on thermal comfort is of particular interest [1]. The second part contains methods for evaluation of the different climatic parameters; in particular methods for evaluation of the radiant environment are explained. The methods are expanded to hourly and statistical analysis and are used in this paper.

REDUCTION OF PARAMETERS

The key parameters for a human bio-meteorological evaluation are ambient air temperature and air humidity. The combined envelope of both parameters can be overlaid in a psychometric chart as data points. See example in *Figure 2* with hourly climate data for Riyadh.

The parameter of the wind velocity at a location is assumed to be fixed to study questions like: what would be the thermal comfort if the wind velocity would be low (wind velocity < 0.1 m/s) or high (e.g. 1.5 m/s).

The complex radiant environment of short and long wave radiation can be reduced to one factor of the local mean radiant temperature (*MRT*) (see second part of this paper). To correlate the *MRT* to the ambient temperature it is useful to calculate the deviation:

$$DMRT = MRT - T_{amb} \tag{1}$$

Values for *DMRT* range from –18 K (very clear nights) to +58 K (in the sun around noon at high altitudes) [2]. This range is too broad for a useful estimation of the *DMRT*. For the sake of simplification, the total *DMRT* can be estimated with eq. 2 as the sum of long wave, diffuse and direct constituents which can be estimated sufficiently with the diagrams in *Figure 7* and *Figure 8*. For example, for a dry sunny day, when the dew point temperature is 0 °C the $DMRT_{lw}$ can be estimated with *Figure 7* to –10 K. According to *Figure 8* the $DMRT_{dir}$ is +20 K and the $DMRT_{diff}$ +10 K for a sunny day with about 500 W/m² for direct and diffuse radiation each. Summing up these three constituents the *DMRT* results in +20 K for a person fully exposed to solar and sky radiation. This is also shown in the detailed example of *Figure 10*.

$$DMRT = DMRT_{lw} + DMRT_{dir} + DMRT_{diff} \tag{2}$$

The two remaining parameters related to the activity and clothing of the person can be treated as “given” for a situation. For example, evaluating the PT of a “standard male person” walking at 4 km/h, this person is assumed to be able to adapt his clothing factor in a range from 0.5 to 1.75 clo if feeling cool or hot [1].

HUMAN BIO-METEOROLOGICAL CHART

Summarizing this approach the human bio-meteorological outdoor situation can be characterized with 4 parameters only:

- ambient air temperature
- ambient air humidity
- wind velocity
- mean radiant temperature

from which sophisticated comfort parameters e.g the Perceived Temperature, can be calculated and overlaid as a parameter field on the psychometric chart, see *Figure 2*. In this example, the PT ranges of slightly warm (20 to 26 °C), warm (26 to 32 °C) and hot (32 to 38 °C) are overlaid for *DMRT* = 0 K and wind velocity < 0.1 m/s. Overlaid are also colored lines with constant PT. The areas between the lines are highlighted and indicate different thermal physiological perceptions of the human body. The dots underneath the highlighted areas represent the (considered) hours of the year with a thermal perception related to the color of the area (see comfort key in *Figure 2*).

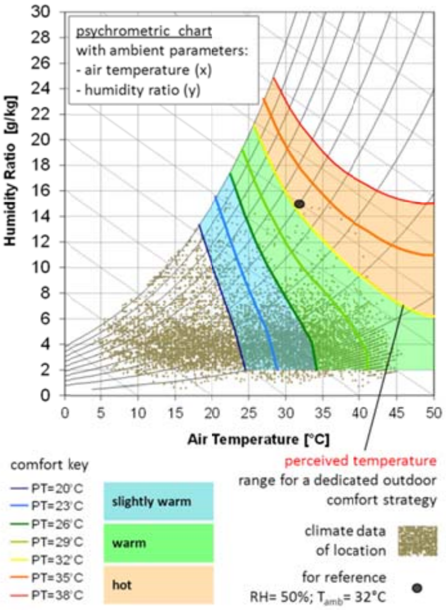

Figure 2: Human bio-meteorological chart with ranges of Perceived Temperature; considered time: year 0:00 – 24:00

Once the ranges for the PT are correlated with the psychometric data for a specific scenario, the hours of PT in the range of interest can be summarized and different strategies can be compared. Depending on the strategy (unshaded, shaded, increased wind velocity) the thermal perception changes, therefore the colored areas shift on the psychrometric chart to cover more or less hours of the year as discussed in the following. This simplified approach is only based on air temperature, humidity and MRT assumptions, but it was found that to be a powerful tool to quickly access design strategies.

HUMAN BIO-METEOROLOGICAL CHART FOR THE CLIMATE OF RIYADH, SAUDI ARABIA

As an example the proposed analysis was done for the extreme hot and dry climate of Riyadh where PT between 26 °C and 32 °C can be rated as good and below 26 °C as excellent for outdoor comfort.

Three different scenarios to demonstrate the effect of a changing *DMRT* are selected (see section example):

- *DMRT* = +20 K (full exposition to sun)
- *DMRT* = ± 0 K (fully shaded)
- *DMRT* = –10 K (night time)

These scenarios are evaluated with a low wind velocity of 0.1 m/s to represent times when a wind shelter is given. Additionally, a scenario with *DMRT*= ±0 K was used to demonstrate the effect of higher wind speed of 1.5 m/s (no wind shelter) on the PT.

Figure 3 shows the human bio-meteorological chart for the scenario where *MRT* is 20 K above ambient temperature. This means that a person would be fully exposed to the sun during daytime. Due to this, 94% of the considered hours PT exceed 32 °C which is rated as hot and causes a great thermal physiological heat stress [1]. Only 6% of the time is rated as comfortable.

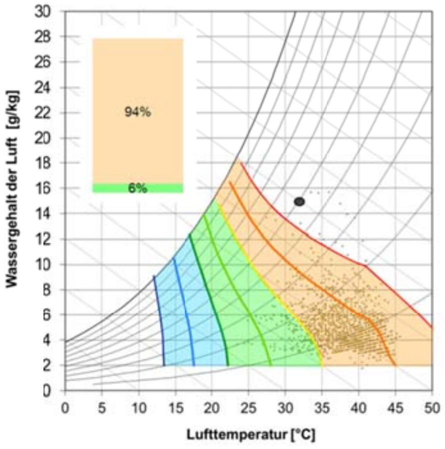

Figure 3: Human bio-meteorological chart for Riyadh with DMRT = +20 K (full exposition to sun); wind velocity = 0.1 m/s; considered time: May to September 9:00 - 18:00

Figure 4 shows the human bio-meteorological chart for a scenario where *DMRT*= ± 0 K, or where the *MRT* is equal to ambient temperature. This is the case when the person is fully shaded so that he is not exposed to direct solar radiation and sky temperature. This can be rated as the best passive design during the daytime. Due to the reduced *MRT* in comparison to *Figure 3*, the overlaid PT lines move to the right in the psychometric chart in the direction of higher air temperatures. As a result, more hours are collected in lower PT ranges "as the dots do not move". *Figure 4* shows that nearly all considered hours are below a PT of 32 °C. This scenario is related to a slightly warm perception and a slight thermal physiological heat stress [1] and reflects well the experience that in the shade and with low wind a person can balance thermal comfort in hot very dry ambient conditions.

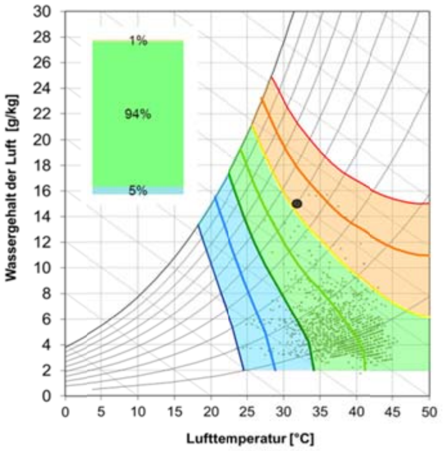

Figure 4: Human bio-meteorological chart for Riyadh with DMRT = ± 0 K (best passive design); wind velocity = 0.1 m/s; considered time: May to September 9:00 - 18:00

Figure 5 shows the human meteorological chart for the scenario where *MRT* is 10 K below ambient temperature. Here the sky cooling effect decreases the *MRT* significantly. This scenario represents night time conditions when no solar radiation occurs and the person is exposed to a clear night sky. Due to this further reduction of the *MRT* compared to *Figure 3* and *Figure 4*, the PT ranges move further right in direction of higher air temperatures and therefore 98% of the considered hours the PT is below 26 °C during this situation.

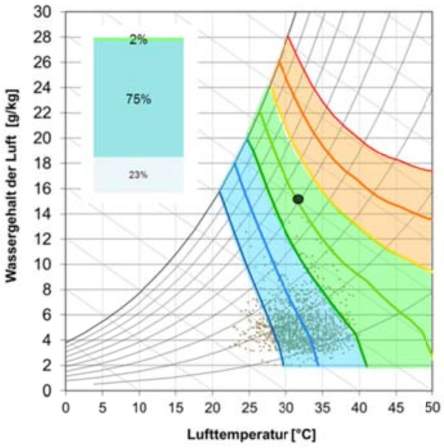

Figure 5: Human bio-meteorological chart for Riyadh with DMRT = - 10 K (night time); wind velocity = 0.1 m/s; considered time: May to September 21:00 – 06:00

Figure 6 shows the human meteorological chart for the scenario where *MRT* is equal to ambient temperature comparable to *Figure 4* but with a reduced wind shelter. This means that the wind velocity is increased from 0.1 m/s to 1.5 m/s which causes a "movement" of higher PT lines to lower air temperatures (increased wind velocity causes further heat stress due to hot wind). The "neutral point" is when air temperature equal the surface temperature of the human being with about 32 to 34 °C. Therefore, the increased wind velocity cause more hours with PT ≥ 32 °C compared to *Figure 4*.

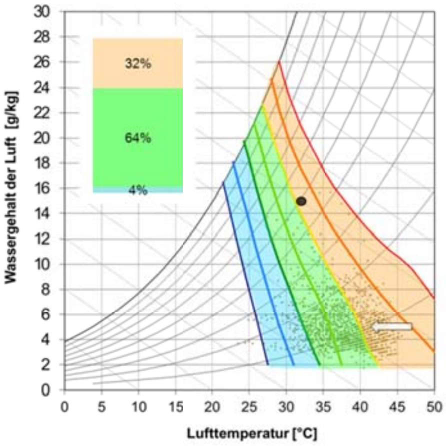

Figure 6: Human bio-meteorological chart for Riyadh with DMRT = ± 0 K (best passive design); increased wind velocity = 1.5 m/s; considered time: May to September 9:00 - 18:00

MODELING THE RADIANT ENVIRONMENT

A description how to calculate the mean radiant temperature in outdoor spaces including solar effects is given in Fanger [2] and VDI 3787 [1] and is briefly summarized in the following.

The mean radiant temperature *MRT* is defined as "the uniform temperature of a surrounding surface giving off blackbody radiation which results in the same radiant energy gain of a human body as the prevailing radiation fluxes" [1,2]. In open outdoor space conditions, the consideration of radiant heat exchange between the human body and its environment in general must take the following long-wave and short wave radiant fluxes into account [1]:

- thermal radiation from the ground and other surrounding surfaces
- thermal radiation in the atmosphere
- direct solar radiation
- diffuse solar radiation
- reflected solar radiation

The influence of these radiant fluxes to the *MRT* of a human being has to be determined for every possible situation as it depends on the person's exposure to surrounding surfaces and the sun. The MRT_{lw} is calculated from the long wave radiation of n isothermal surrounding surfaces with the temperature T_i and emission coefficient ε_i (eq. 3). The radiation is weighted by the angle factor F_i of each surface.

$$MRT_{lw} = \left[\sum_{i=1}^{n} \varepsilon_i \cdot T_i^4 \cdot F_i \right]^{1/4} \tag{3}$$

The MRT_{diff} is calculated with the diffuse short wave radiation D_i emitted from n surfaces (eq. 4), a_s the short wave absorption coefficient of a person, ε_p for the emission coefficient of clothing or skin and the Stefan-Boltzmann-constant σ.

$$MRT_{diff} = \left[\sum_{i=1}^{n} a_s \cdot \frac{D_i}{\varepsilon_p \cdot \sigma} \cdot F_i \right]^{1/4} \tag{4}$$

For an upright standing (or walking) human being exposed to direct sun, the MRT_{dir} can be calculated with eq. 5. In this case I^* is the radiation intensity of the sun on a surface perpendicular to the incident radiation [1].

$$MRT_{dir} = \left[f_p \cdot a_s \cdot \frac{I^*}{\varepsilon_p \cdot \sigma} \right]^{1/4} \tag{5}$$

The projected area factor f_p depends on the elevation of the sun [2]. To keep it simple - for a rotationally symmetric human being - the angle factors are about 0.175 for sun elevation of 60° and about 0.27 for 30°. With eq. 3 to 6 the total mean radiant temperature can be calculated with:

$$MRT = \left[MRT_{lw}^4 + MRT_{diff}^4 + MRT_{dir}^4 \right]^{1/4} \tag{6}$$

The intention of the follow sections is to evaluate the mean radiant temperature and to give diagrams for quick reference for the different constituents of the *MRT*.

ESTIMATION OF LONG WAVE MEAN RADIANT TEMPERATURE

It was found that the MRT can be represented with a good accuracy by the average of the lower surroundings (ground) and upper half space (sky), so considering each with an angle factor of $F_i=0.5$.

The mean surface temperature for the lower surroundings (e.g. of a plaza covered with dry stone), as a first guess, can be estimated to be close to ambient temperature. During night time with clear sky conditions, the surface temperature will drop below ambient temperature; during daytime, especially when exposed to direct solar radiation, the surface temperature will be higher. Dynamic thermal simulation showed that with sufficient accuracy the typical temperature differences are less than ±5 K. The clear sky temperature can be calculated with the simplified eq. (7) as a function of the ambient temperature T_{amb} and the dew point temperature at ground level T_{dew} [4]:

$$T_{sky} = \left(T_{amb} + 273.15\right) \cdot e_l^{1/4} - 273.15 \qquad (7)$$

$$e_l = 0.7122 + 0.0056 \cdot T_{dew} + 0.000073 \cdot T_{dew}^2 + 0.00884$$

In *Figure 7* the clear sky temperature according to eq. (7) is given for ambient temperatures of 5, 15, 25 and 35 °C. The lower the dew point temperature, the lower the sky temperature. Given the sky temperature and the temperature of the lower surroundings the mean radiant temperature or more useful the delta to the ambient temperature can be estimated with:

$$DMRT_{lw} = \frac{T_{amb} + T_{sky}}{2} - T_{amb} \qquad (8)$$

The $DMRT_{lw}$ represents the deviation of long wave mean radiant temperature from the ambient temperature and is shown in *Figure 7*. The graph shows that with reasonable accuracy the $DMRT_{lw}$ is only a function of the dew point temperature. For dry conditions the $DMRT_{lw}$ is –10 to –12 °C and for humid conditions the $DMRT_{lw}$ is about –5 °C. For a quick calculation of the $DMRT_{lw}$, the following polynomial fit can be used:

$$DMRT_{lw} = -11.369 + 0.259 \cdot T_{dew} + 0.00196 \cdot T_{dew}^2$$

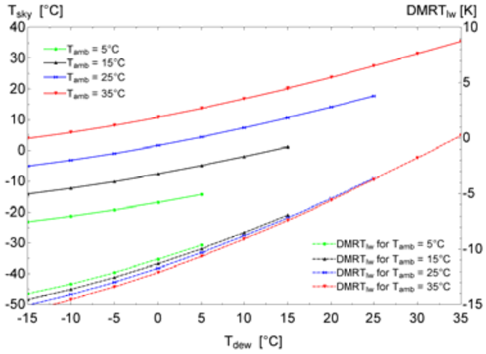

Figure 7: Sky temperature (T_{sky}) and delta of mean radiant temperature ($DMRT_{lw}$)

ESTIMATION OF SHORT WAVE COMPONENT OF THE MEAN RADIANT TEMPERATURE

The approach of the VDI [1] does not include the effects of reflection of short wave radiation by surrounding surfaces. A more detailed method to calculate the short wave component of the *MRT* and its effect on human comfort is provided by Hiller et al. [3]. Based on this method *Figure 8* was generated for further reference.

For a clear sunny day, the total horizontal solar radiation can be around 1000 W/m² with e.g. about 500 W/m² direct and 500 W/m² diffuse. *Figure 8* shows $DMRT_{dir}$ of about +15 to +20 K depending of the solar elevation. The $DMRT_{diff}$ is about +10 K.

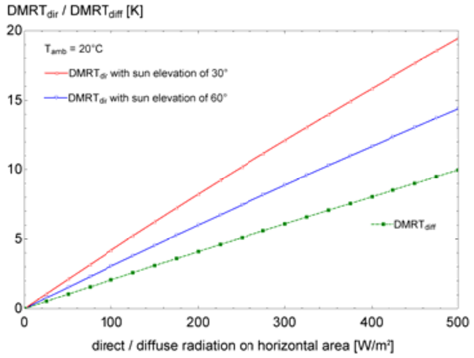

Figure 8: Delta of mean radiant temperature for diffuse radiation $DMRT_{diff}$ and for direct radiation for sun elevation of 30° and 60° $DMRT_{dir}$

EXAMPLE: MEAN RADIANT TEMPERATURE FOR DIFFERENT CONDITIONS

For the location of Riyadh, the MRT calculations were performed for the entire year on an hourly basis using the same detailed modeling as provided by [3] but with the simplification of 2 surfaces only. For the long wave radiation exchange, two angle factors for the lower surroundings (ground) and upper hemisphere each with $F_i=0.5$ were used. The calculations were done for a person fully exposed to the sun (scenario 1) and for a shaded person (scenario 2). For the shading a membrane with 10% short wave transmission was used. During nighttime in both cases the person is not shaded and hence exposed to the sky radiation. A schematic diagram of the calculate scenarios is given in *Figure 9*.

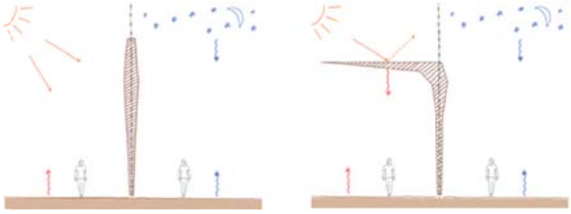

Figure 9: Simplified scheme of MRT calculation model, left scenario 1 and right scenario 2.

Figure 10 shows the MRT for an unshaded and shaded person on a hot summer day with ambient temperature peaking at 45°C. During the daytime, the *MRT* under fully sun exposed conditions is around 20 K higher than the ambient temperature. The use of a sun shading device reduces the *MRT* to ambient temperature during daytime. At night, the *MRT* is about 10 to 15 K lower than the ambient temperature in both cases, due to the effect of the low sky temperature.

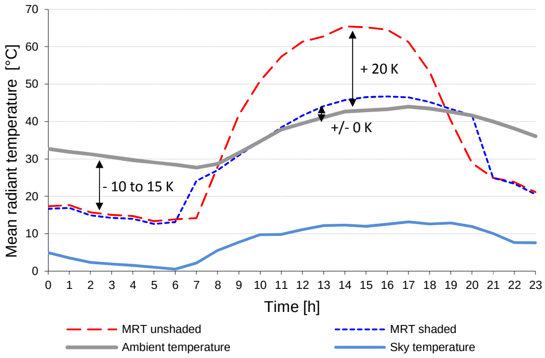

Figure 10: MRT comparison of different scenarios on a typical Riyadh summer day

Figure 11 and *Figure 12* show an hourly analysis of *MRT* depending on ambient temperature. The diagonal lines represent the *DMRT*. The bisecting line indicates where the *MRT* is equal to ambient temperature or where *DMRT* = 0 K. In *Figure 11* it can be seen that under unshaded conditions during sunshine hours (09:00 – 18:00) the *DMRT* is in the range of + 10 K to + 30 K with the highest occurrence at about +20 K which can be taken as a good *DMRT* approximation for unshaded daytime conditions and is the basis for the human bio-meteorological chart for unshaded conditions (*Figure 3*).

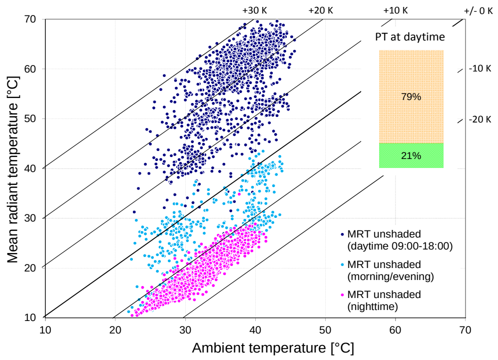

Figure 11: Yearly statistical analysis of MRT depending on ambient temperature under unshaded conditions, scenario 1

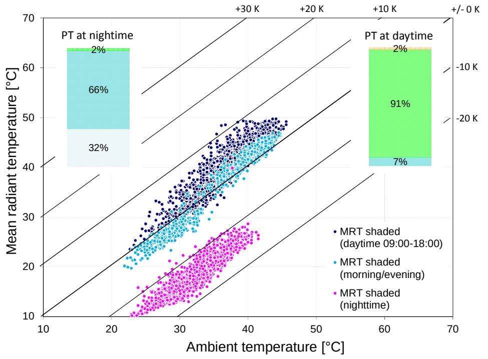

Figure 12: Yearly statistical analysis of MRT under fully shaded conditions during daytime, scenario 2. PT statistics are evaluated for May to September only.

In *Figure 12* the shading device is applied during sunshine hours, which reduces the *DMRT* to the range of -5 K to +10 K. On average, a *DMRT* of ±0 K for well-shaded conditions can be used for the best passive design scenario as it is applied in human bio-meteorological chart (*Figure 4*). During night in both cases (pink dots in *Figure 11* and *Figure 12*) the person is fully exposed to a clear sky. Due to the low sky temperature the *DMRT* is in the range of -10 K to -20 K. Therefore -10 K can be taken as conservative *DMRT* approximation for nighttime conditions and is the base for the human bio-meteorological chart for nighttime (*Figure 5*).

Calculating the statistics of PT with the detailed hourly MRT modeling for about 79% of the time a PT of 32 °C is exceeded for the unshaded scenario. With the simplified approach of the human bio-meterological chart about 94% have been identified just by using climate data and a guess for the MRT. For the scenario 2 at daytime the statistics are 91% with the detailed versus 94% with the simplified approach, at nighttime it is 66% versus 75% The reason for the larger deviation of the daytime statistics is explained with the larger deviation of MRT in the course of day, especially as operation hours from 9:00 to 18:00 are considered. If the period is more focused, say 11:00 to 16:00 the results are closer.

CONCLUSION

With the human bio-meteorological chart, outdoor comfort strategies can be evaluated easily and quickly with reasonable accuracy. It provides the possibility to analyze the potential of an outdoor comfort strategy in advance before using time consuming design tools. Assumption and simplifications for the *DMRT* for have been justified and validated versus a more detailed simulation model for shaded, un-shaded and night time conditions. Without further evidence in this paper, it was found in several analyses of outdoor comfort strategies that the quick statistical findings with the human biometereological chart and the ones of more detailed simulations are in good agreement.

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