Modified Physiologically Equivalent Temperature to Realize Evaluations of Humid-cold and Humid-hot Conditions

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Introduction

Thermal environments involve the energy consumption of building and thermal sensations of human beings. Various thermal indices have been developed to estimate thermal conditions in many fields such as human biometeorology, building environment, urban climate, and public health for several decades. Physiologically Equivalent Temperature (PET) as one of these thermal indices has been widely applied because of the effective estimations of the sensible and radiant heat fluxes between subjects and environments. However, PET has been known as limited on estimating the influences of humid impacts.

The first version of the mPET (mPET,$_1$st) (Chen & Matzarakis, 2017) implements an adaption including (1) a human thermoregulatory system with multi-segments, (2) multi-layer garment model, and (3) the influence of clothing vapor resistance to calculate dynamic balance between the skin vapor pressure and air vapor pressure instead of the steady statured vapor pressure on the shell layer according to the skin temperature, which is applied to estimate the latent heat (Q_{latent}) in the original PET-model. mPET,$_1$st has been considered as an effective and comprehensive tool to estimate the influence of humid-hot stress on thermal environments (Lin et al, 2018).

In this study, a further improved of mPET,$_2$nd is proposed to include (1) the water vapor absorption mechanism (Brunauer–Emmett–Teller (BET) theory) in clothing model, and (2) the actually relative humidity correlated skin vapor pressure to appropriately evaluate the impacts of both humid-cold and humid-hot conditions on the thermal strains of human beings.

Comparisons of sensitivity tests for the relative humidity (RH) between PET, mPET,$_1$st , mPET,$_2$nd , Universal Thermal Climate Index (UTCI), Mean Predicted Vote(PMV), and Standard Effective Temperature* (SET*) are shown in results.

Methodology and Implements

1. Equations of the latent heat fluxes in PET model:

$$\frac{dm_{sw}}{A_{sk}dt} = \frac{0.3049 \times \left(\left(0.1 \times T_{sk} + 0.9 \times T_{core}\right) - 36.6 \right)}{3600} \quad (kg/m^2s)$$

$$Q_{sw,physic} = f_{gender} \times \frac{\lambda_{H2O}}{A_{sk}} \frac{dm_{sw}}{dt} \quad (W/m^2)$$

$$Q_{sw,potential} = \frac{\left(VP_{sk,sat} - VP_{air}\right)}{f_{e,cl} \times R_{e,sk}} \quad (W/m^2)$$

$$r_{sk,moist} = \frac{Q_{sw,physic}}{Q_{sw,potential}}$$

$$f_{gender} \times \frac{\lambda_{H2O}}{A_{sk}} \frac{dm_{sw}}{dt} + \left(1 - r_{sk,moist}\right) \times \frac{VP_{sk,sat} - VP_{sk}}{R_{e,sk}} = Q_{latent} \quad (W/m^2)$$

2. Equations of the latent heat fluxes in UTCI and mPET, 1st model:

$$\frac{dm_{sw}}{dt} = \left[0.8 \tanh\left(0.59\Delta T_{sk} - 0.19\right) + 1.2\right] \Delta T_{sk} + \left[5.7 \tanh\left(1.98\Delta T_{core} - 1.03\right) + 6.3\right] \Delta T_{core} \quad (g/min)$$

$$\frac{\left(VP_{sk} - VP_{air}\right)}{R_{e,cl,total \;\; or \;\; e,sk,total}} = \frac{\lambda_{H2O}}{A_{sk}} \frac{dm_{sw}}{dt} + \frac{VP_{sk,sat} - VP_{sk}}{R_{e,sk}} = Q_{latent} \quad (W/m^2)$$

3. Equations of the latent heat fluxes in mPET, 2nd model:

$$\frac{dm_{sw}}{A_{sk}dt} = \frac{0.001}{60} \left[0.43 \tanh\left(0.59\Delta T_{sk} - 0.19\right) + 0.65\right] \Delta T_{sk} + \left[3.06 \tanh\left(1.98\Delta T_{core} - 1.03\right) + 3.44\right] \Delta T_{core} \quad (kg/m^2s)$$

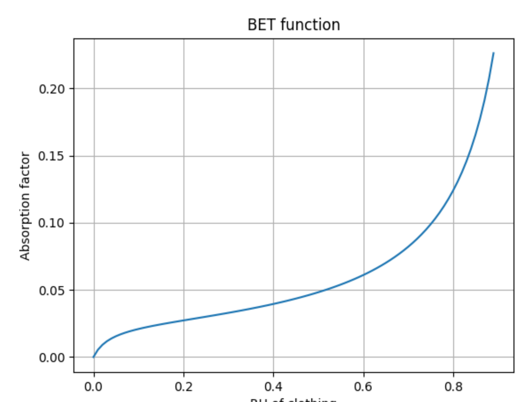
$$\frac{\left(VP_{sk} - VP_{air}\right)}{R_{e,cl,total \;\; or \;\; e,sk,total}} = \frac{\lambda_{H2O}}{A_{sk}} \frac{dm_{sw}}{dt} + \frac{f\left(RH_{air}\right) \times VP_{sk,sat} - VP_{cl,in \;\; or \;\; air}}{R_{e,sk}} = Q_{latent} \quad (W/m^2)$$

$$VP_{cl,in} = VP_{sk} - \frac{R_{e,cl,in}}{R_{e,cl,total}} \times \left(VP_{sk} - VP_{air}\right) \quad (hPa)$$

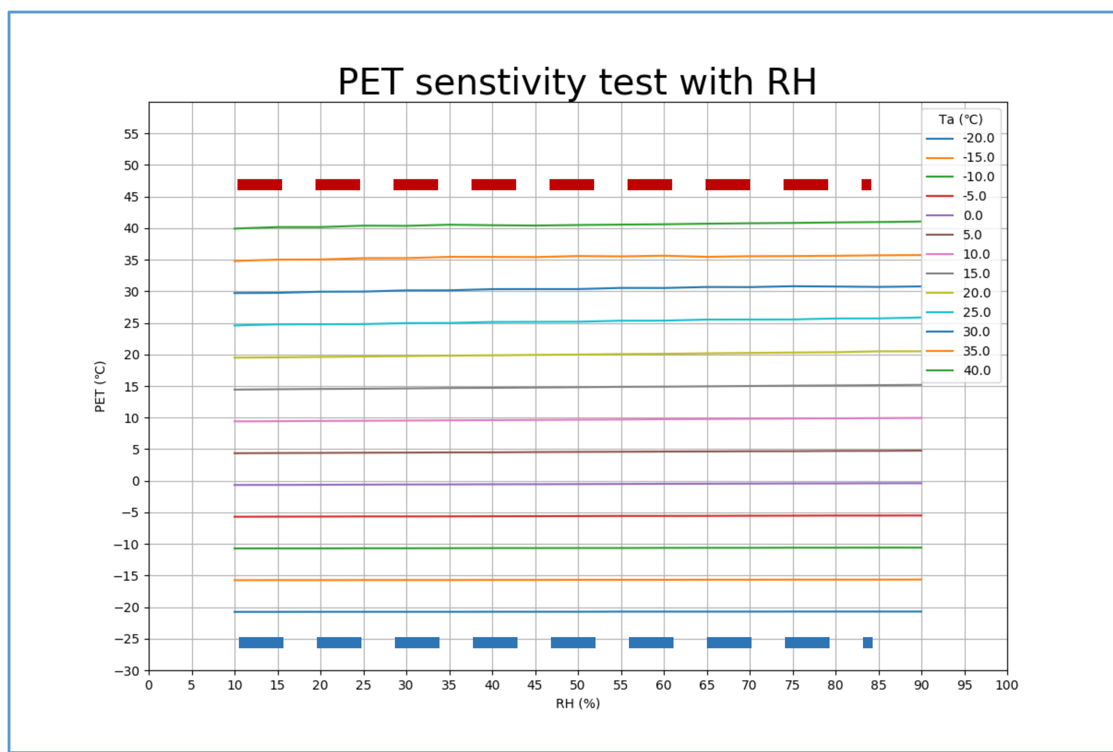
$$R^{t+1}_{e,cl,in,out} = \frac{R^{t}_{e,cl,in,out}}{\left(1 - f_{absorb}\right)} \quad (hPa \cdot m^2/W)$$

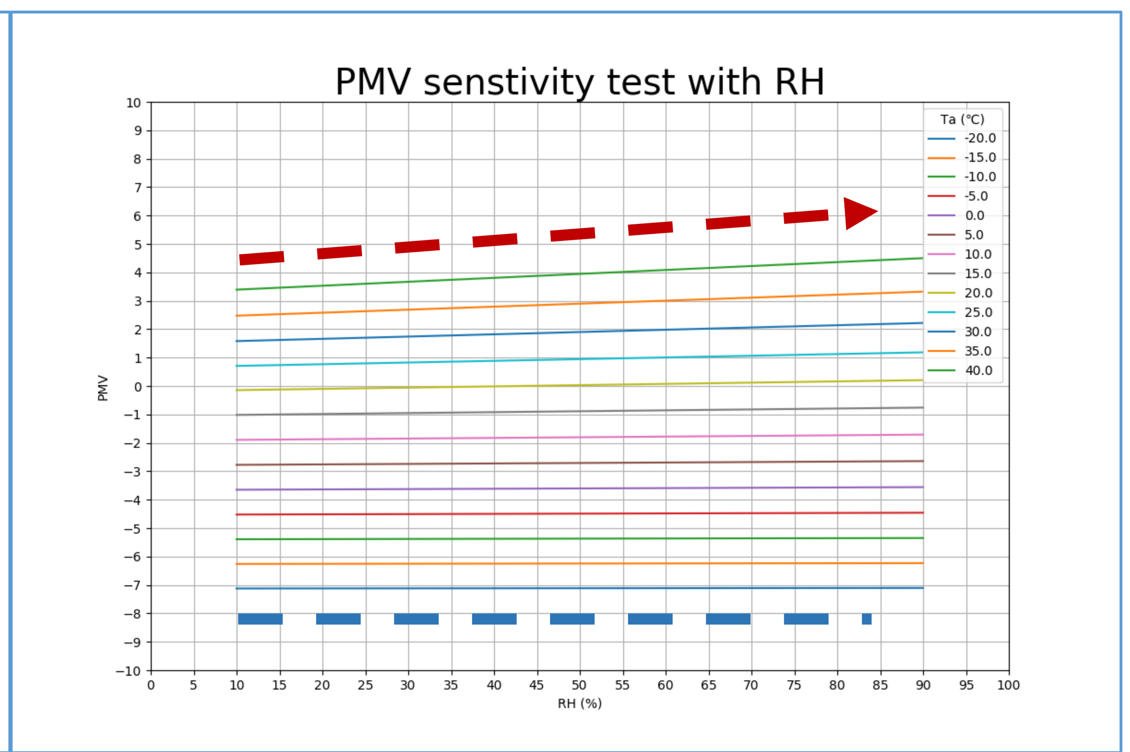
$$f_{absorb} = \frac{\alpha\beta \times RH_{cl}}{\left(1 - RH_{cl}\right)\left(1 - RH_{cl} + \alpha RH_{cl}\right)}$$

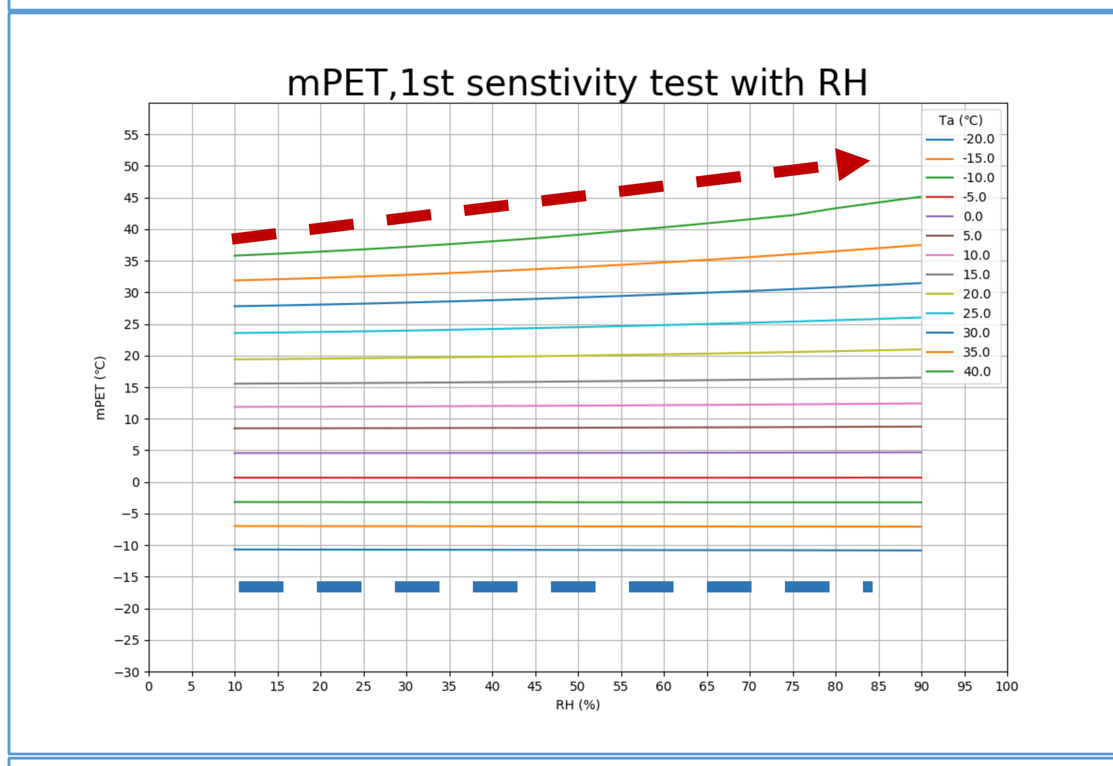
$$f\left(RH_{air}\right) = RH_{air}$$

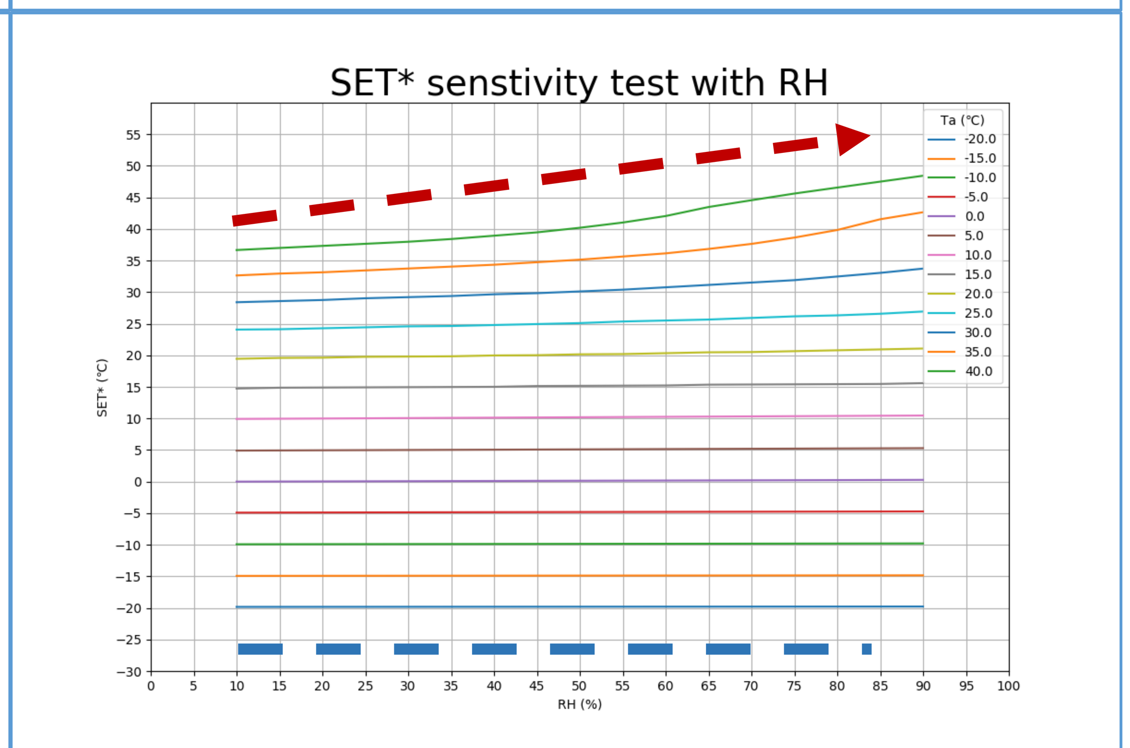


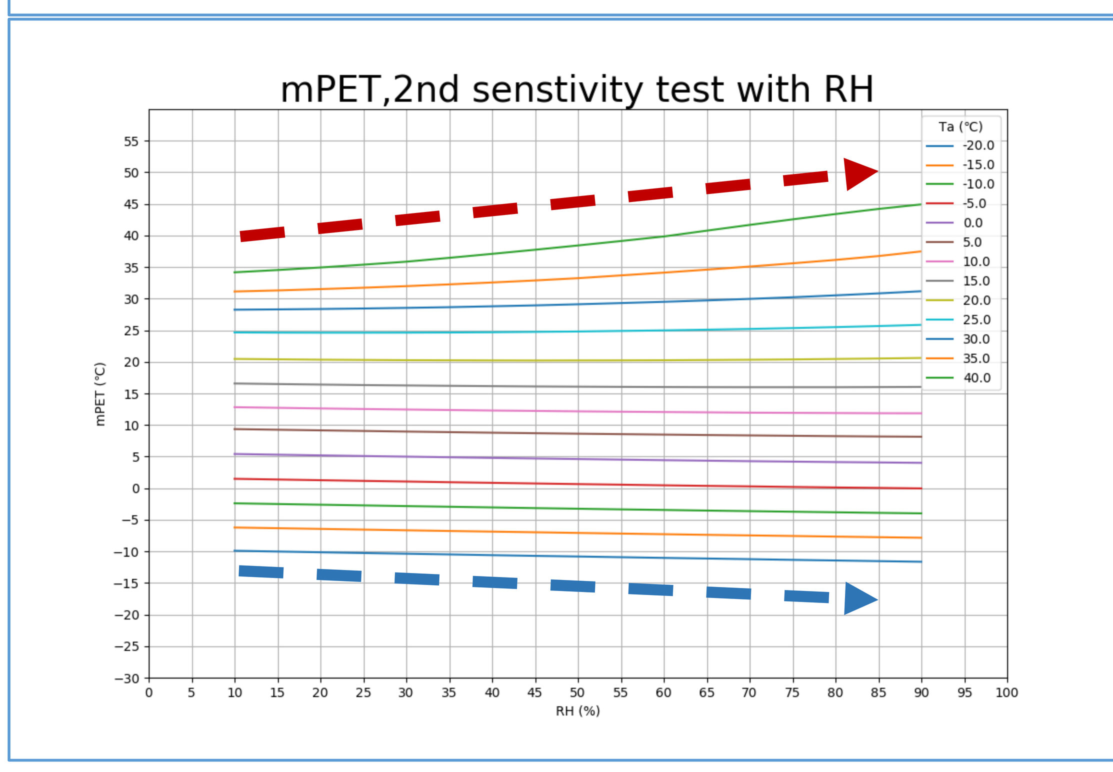
Results: Comparison of thermal indices

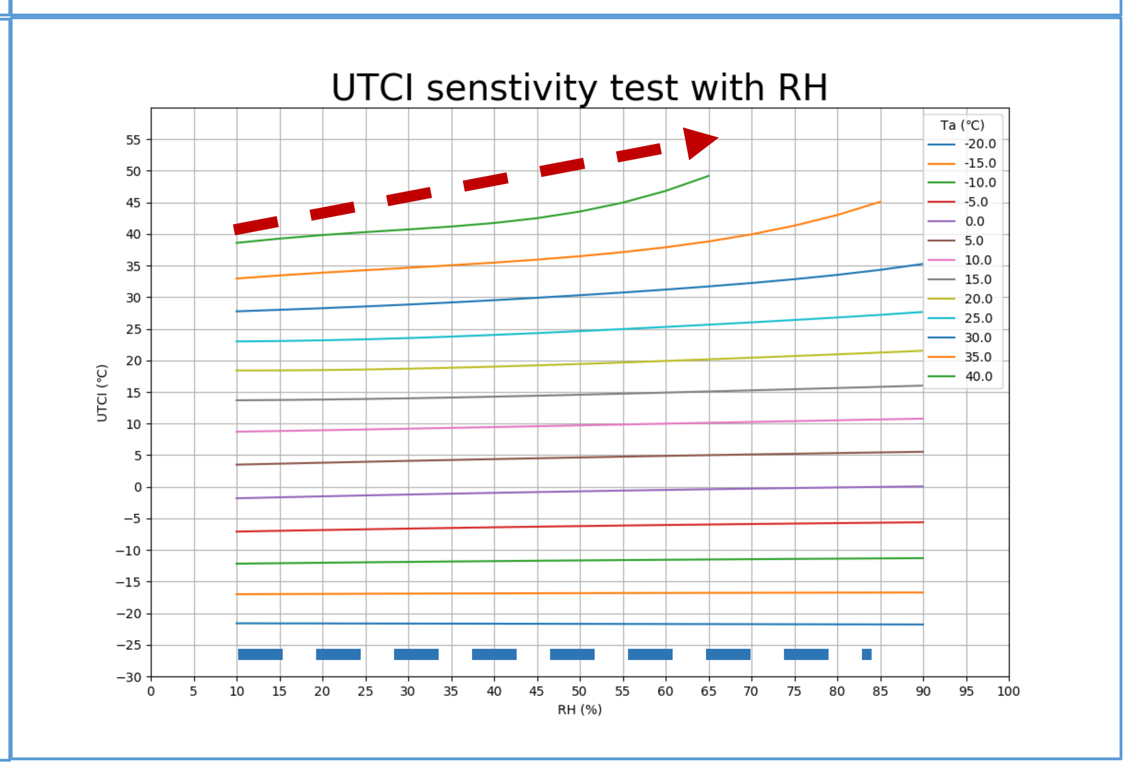




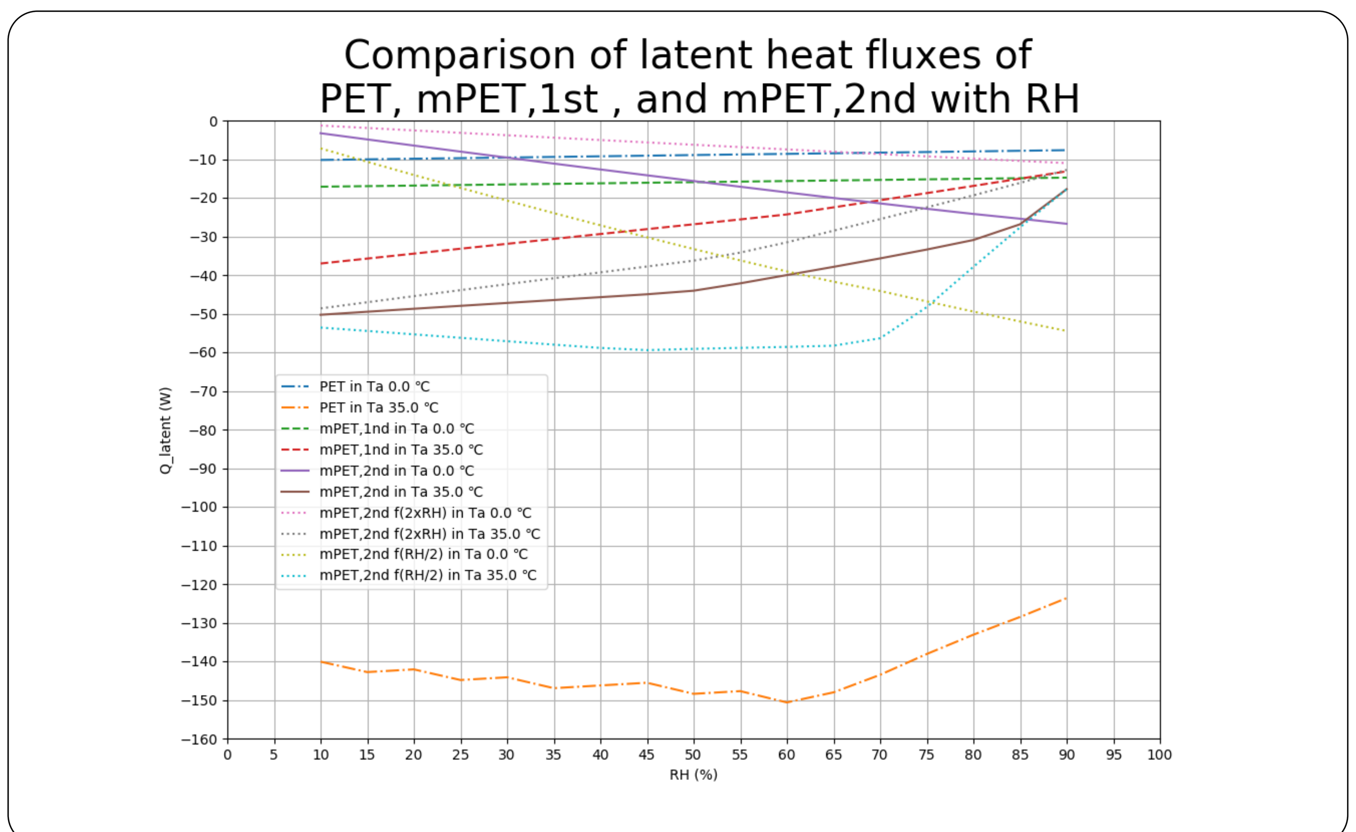








Results: Comparison of latent heat fluxes



Discussion

1. The latent heat fluxes of mPET,2nd show a negative tendency in cold condition but a positive tendency in warm condition. It is a more reasonable estimation than others for humid-warm and humid-cold environments.
2. The modified equation of latent heat fluxes indicates that RH of outer skin will be regulated to close to ambient RH.
3. A probable argument for the modified equation of latent heat fluxes is that stratum corneum of skin absorbs the water generated by sweating glands and diffuses water vapor to environment (Li et al, 2016). Thus, vapor diffusion varies with water content of stratum corneum.

References

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Conclusions

1. The modified equations of latent heat fluxes and of clothing water vapor resistance lead to a realistic estimation for humid-cold conditions.
2. The comparison of the six mentioned thermal indices show that only mPET,2nd has a negative variance according to increasing RH in cold environments.
3. The theory of considering outer skin vapor pressure in the mPET,2nd model requires furthermore validation and argumentation.

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