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Thermal comfort conditions at the platforms of the Athens Metro

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Abstract

The current study aims at the comparison of the field measurements at the platforms of the Athens Metro with those recommended by international standard thermal comfort and to the investigation of the relationship of environmental parameters between platforms and the outdoor space. The levels of air, operative and globe temperature as well as air humidity and air velocity were continuously monitored at the platform space of two stations with different depth and design features in summer. The predicted mean vote (PMV) model and the predicted percentage of dissatisfied (*PPD*) index were used. The results reveal that the operative temperature at both stations is far from the traditional still-air comfort zones. For the case of elevated air movement of 1.2 ms^{-1} and considering the occupants have local control of air speed, 20.3% of the values at the station with the greatest depth do not exceed the upper limit. Furthermore, 64% of the variation in air temperature at the platform of the station with the smallest depth is explained by outdoor air temperature, while the corresponding percentage for the station with the greatest depth is 29%. Passengers experience sudden change of air temperature and *PMV*, especially at the station with the smallest depth, during their transition from the platform to the interior of air-conditioned train carriages and vice versa.

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Keywords: Human exposure; Subway platforms; Passengers' thermal comfort

1. Introductory remarks

The strong majority of the research studies concerning the underground urban transport are mainly focused on the air quality issues inside and outside the railing network [1-8]. However, since it is suitable for the carriage of high

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passenger flows, the prevailing thermal conditions both inside the trains and on the platforms is of importance for the passengers' thermal comfort.

The international standards literature for thermal comfort classes are based on *PMV* and *PPD* indices [9,10]. Ampofo et al. [11] worked on the definition of acceptable criteria for thermal comfort in the subway. This study demonstrated that *PPD* values up to 50% can be considered as acceptable for a typical subway environment [11]. This happens because in rapid transit systems passengers spend a relatively short period of time unlike in other cases [11].

A recent field study in the interior of train coaches of Athens Metro showed that during the warm period the thermal regime within air-conditioned cabins is "slightly warm" while within mechanical ventilation cabins it is "warm" [12]. In the Seoul field study it was found that there was a weak linear correlation between the number of passengers and the train cabin air temperature in rush hours [7].

Similar performance was identified for the Budapest Metro stations, the *PMV* ranged between -1.4 and 0 in winter in the passenger areas, suggesting "slightly cool" or "cool" thermal environment, while in summer, the *PMV* ranged from 0 to +1.4, indicating "slightly warm" thermal environment [13]. Other relevant work referring to Tehran, Shanghai and Seoul experimental campaigns showed interesting findings the details of which can be found in the international literature [14-16]. More details concerning the Athens Metro cabin measurements can be found elsewhere together with the description of the experimental campaign methodology and the instrumentation details [12].

The present study aims to compare the field measurements of air temperature, operative temperature and vapour pressure on platforms with those recommended by international standards for thermal comfort, between two subway stations of Athens Metro, with different depth and design features, in summer. The *PMV* levels were also compared with the recommended thermal comfort classes. Furthermore, the relationship of air temperature and relative humidity between platform space and outdoor environment was investigated. Finally, the diurnal differences of thermal conditions between the platform and the air-conditioned carriage of the train that just have arrived at the platform were studied.

The experimental data were collected from two stations of Line 3, Doukissis Plakentias and Syntagma. The metro station at Syntagma is approximately 200 m below ground and it has four underground levels, while the platforms of Line 3 are situated at the fourth sub-level. Due to its depth the station acts as a zero-identity "black hole" in relation to the urban environment [17]. It is one of the busiest stations of the Athens Metro since it is located in the centre of Athens and it is an interchange station between Lines 2 and 3 of the network, while it is a transportation hub for the buses and the tram.

The metro station at Doukissis Plakentias is approximately 50 m below ground and it has two sub-levels. The Line 3 platforms are located at the second underground level. Furthermore, in a distance of about 1 km after the station Line 3 emerges at the surface.

The ventilation system at the platform and passenger areas provide fresh air from the outdoor environment under normal operation conditions, while in the case of emergency it extracts smoke as well.

Standards ISO-7730 [10] and ASHRAE-55 [9] propose PMV model and the indices *PMV* and *PPD* so that to predict the degree of discomfort and the thermal sensation of individuals exposed to a moderate indoor thermal regime. This model uses the heat exchange theory in order to associate four physical variables. In the present case the air and the mean radiant temperature, the air humidity, the air velocity and two other personal variables, i.e. metabolic rate and clothing insulation was used. The 7-point thermal sensation scale, i.e. +3 = hot; +2 = warm; +1 = slightly warm; 0 = neutral; -1 = slightly cool; -2 = cool; -3 = cold, is also employed.

The clothing insulation was estimated at 0.5 clo, while the average metabolic rate for the passengers was selected to be 70 Wm^{-2}.

Mean radiant temperature was computed using the globe temperature by employing the formula [18]:

$$t_r = \left[\left(t_g + 273\right)^4 + \frac{1.10 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} \left(t_g - T_{air}\right) \right]^{1/4} - 273 \qquad (1)$$

where t_r is the mean radiant temperature (^oC), t_g is the globe temperature (^oC), V_a is the air velocity (ms^{-1}), T_{air} is the air temperature (^oC), D is the globe diameter (0.15 m) and ε is the emissivity (0.98).

Relative humidity was converted to vapour pressure by following the formula [19]:

$$P_w = \frac{RH}{100\%} \cdot A \cdot 10^{\frac{m \cdot T}{T+T_n}} \quad (2)$$

where P_w is the vapour pressure (hPa), RH is the relative humidity (%), T is the temperature (^oC), A is the constant 6.116441, m is the constant 7.591386 and T_n is the constant 240.7263.

The calculations of *PMV* were based on a computer code developed in R language [20] in accordance with International Standard, ISO-7730 [10]. The beanplot technique [21] in R language was used in order to present the estimated density of the distribution.

2. Results and discussion

The beanplots illustrate the distribution of vapour pressure (Fig. 1a) and air temperature (Fig. 1b) on the platform space of the studied stations. Each plot has a dashed line which represents the overall average of the continuous variable on the y-axis. The average for every subset is represented by a thick black like on each beanplot. Moreover, the coloured curved area depicts the theoretical probability density distribution for every case. ASHRAE Standard 55 [9] requires that systems aimed at controlling humidity should maintain a humidity ratio up to 0.012 $kg_{water}/kg_{dry\ air}$. This corresponds to an upper vapour pressure limit of 19.1 hPa. A visual inspection of the vapour pressure beanplot reveals that the main core of the distribution (96%) does not exceed this upper limit, while the average value is significantly lower of 15.3 (hPa) for the station with the smallest depth (Fig. 1a). On the contrary, more than 73% of vapour pressure values exceed the aforementioned limit at the station with the greatest depth, with an average value of 20.4 hPa. There is no lower humidity limit according to the ASHRAE Standard 55 [9] for thermal comfort. Nevertheless, low levels of humidity can lead to skin drying, dry eyes and irritation of mucous membranes, and thus it is recommended that the dew point temperature should not be less than 2.2 ^oC [22]. This means that the vapour pressure should not be less than 7.2 hPa. All vapour pressure values exceed this recommended lower limit at both stations and thus, the platform space cannot be considered as extremely dry (Fig. 1a).

The air temperature values are evenly distributed with small dispersion at the station with the greatest depth (Fig. 1b). In particular, the values range from 29.9 ^oC to 31.3 ^oC. On the contrary, at the station with the smallest depth, the distribution of air temperature presents greater dispersion and higher values than that of the station with the greatest depth. The values range from 30.2 ^oC to 34.8 ^oC. ASHRAE Standard 55 [9] does not specify air temperature limits for thermal comfort but specifies limits for operative temperature.

The recommendations of the ASHRAE-55 [9] for an acceptable indoor thermal environment are PPD values lower than 10% and PMV values ranging between -0.5 and +0.5. Thus, the operative temperature should be between 22.6 ^oC and 27.7 ^oC for the summer comfort zone, when the air velocity is 0.1 ms^{-1}, the activity level is 70 Wm^{-2} (or 1.2 met), the clothing insulation is 0.5 clo and the humidity ratio ranges from 0 to 0.012 $kg_{water}/kg_{dry\ air}$. It is worth mentioning that as clothing conditions and metabolic rates increase, the aforementioned limits of operative temperature are shifted to lower values. Further, elevated air movement increases the maximum operative temperature that occupants will find acceptable, so equivalent comfort can be maintained in a wider range of operative temperatures [9]. Thus, the operative temperature should be between 26.5 ^oC and 30.4 ^oC for the summer comfort zone, when the air velocity is 0.8 ms^{-1}, the activity level is 70 Wm^{-2} (or 1.2 met), the clothing insulation is 0.5 clo and the humidity ratio is 0.010 $kg_{water}/kg_{dry\ air}$. The permissible operative temperature further increases and ranges from 27.2 ^oC to 31.2 ^oC, when the air velocity is 1.2 ms^{-1} and the occupants have local control of air speed.

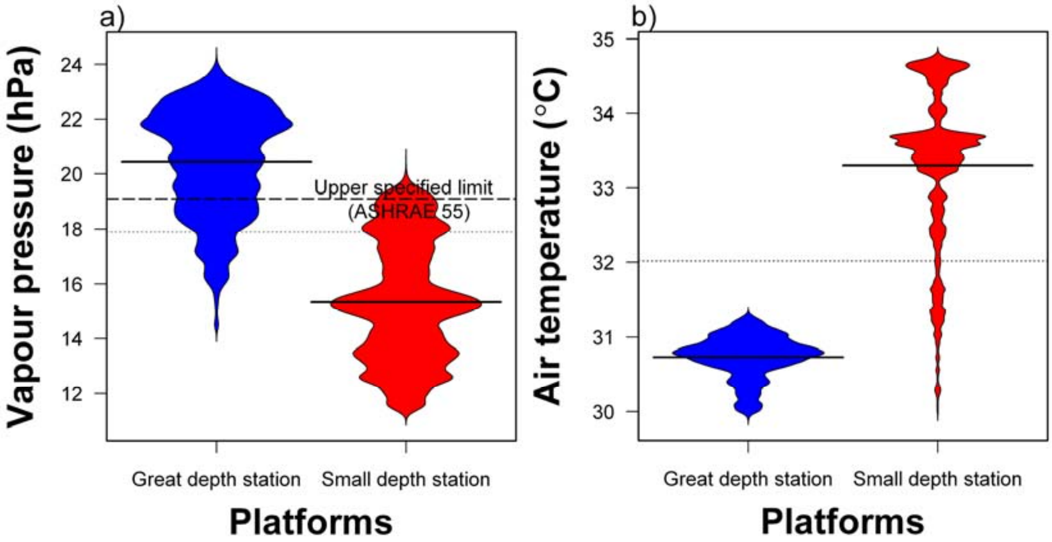

Fig. 1. Beanplots illustrate the distribution of (a) vapour pressure and (b) air temperature values on the platform space of the great depth station (Syntagma) and the small depth station (D. Plakentias). Each plot is represented by a dashed line, which is the overall average of the continuous variable on the y-axis. The average for each case is depicted by the thick black line.

For the case of the station with the greatest depth, the values of operative temperature are evenly distributed with relatively small dispersion (Fig. 2a). In particular, the values range from 30.2 ^{o}C to 33.2 ^{o}C, with an average value of 31.6 ^{o}C. On the other hand, for the case of the station with the smallest depth, the distribution of operative temperature reveals greater dispersion and higher values than that of the station with the greatest depth (Fig. 2a). The values range from 30.4 ^{o}C to 36.5 ^{o}C, with an average value of 34.2 ^{o}C. It is obvious that the results at both stations are far from the traditional still-air comfort zones. However, for the case of elevated air movement of 1.2 ms^{-1} and the assumption that the occupants have local control of air speed, 20.3% of the values at the station with the greatest depth do not exceed the upper limit (31.2 ^{o}C). The corresponding percentage for the station with the smallest depth is extremely low (1%).

The standard ISO-7730 [10] proposed three different classes of desirable indoor thermal environment for general comfort (Fig. 2b). The results reveal that the *PMV* values exceed these limits at both stations. More specifically at the station with the greatest depth, the lowest *PMV* value is 0.6 scale points higher from the limit of comfort class C, while the highest *PMV* value is 1.4 scale points higher from the same limit (Fig. 2b). The corresponding deviations from the limit of comfort class C at the station with the smallest depth are even greater and reach up to 2.4 scale points for the highest *PMV* value.

The scatter plots and the regression lines of air temperature and relative humidity between platform space and outdoor environment are presented in Figure 3. A positive linear relationship is observed between the outdoor air temperature and the air temperature on the platform for both stations (Fig. 3a). The relationship is quite strong (r=0.80) for the station with the smallest depth, whereas it is relatively moderate (r=0.54) for the station with the greatest depth. The R-square value reveals that 64% of the variation in the air temperature rate at the platform of the station with the smallest depth is increased by taking into account the outdoor air temperature. On the other hand, only 29% of the variation in the air temperature rate at the platform of the station with the greatest depth is increased by taking into account the outdoor air temperature.

A positive linear relationship is also observed between the outdoor relative humidity and the relative humidity on the platform for both stations (Fig. 3b). As in the case of air temperature, the relationship is quite strong (r=0.83) for the station with the smallest depth, whereas it is relatively moderate (r=0.46) for the station with the greatest depth. The R-square value reveals that 69% of the variation in the relative humidity rate at the platform of the station with the smallest depth is increased by taking into account the outdoor relative humidity. The corresponding percentage for the station with the greatest depth is far lower (21%).

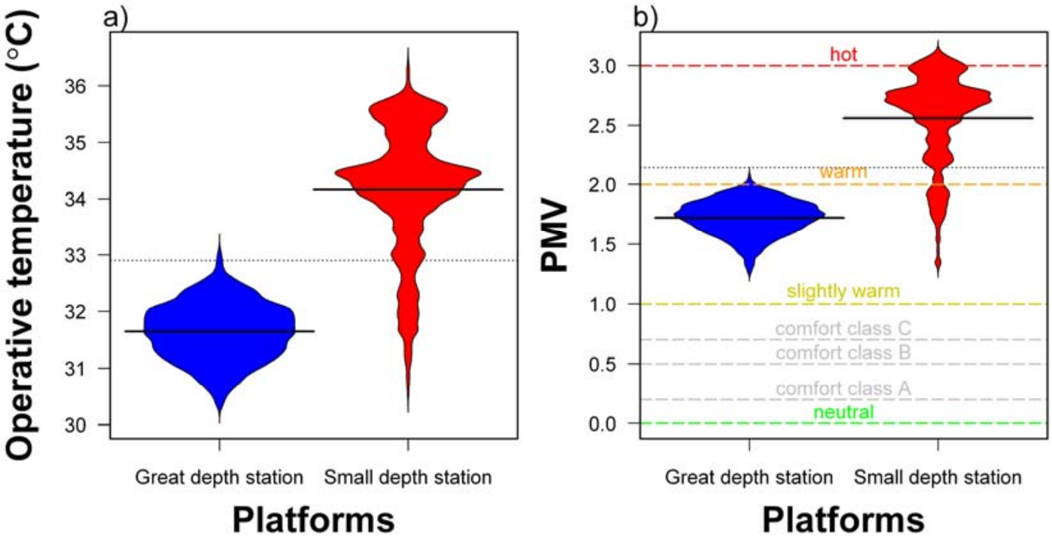

Fig. 2. Beanplots illustrate the distribution of (a) operative temperature and (b) *PMV* values on the platform space of the great depth station (Syntagma) and the small depth station (D. Plakentias). The comfort classes of acceptable thermal environment for general comfort [10] are also presented.

In parallel with the field measurements on the platforms, a similar experiment was conducted in the interior of air-conditioned train carriages. The average difference of air temperature and *PMV* between the platform and the air-conditioned carriage of the train that just have arrived at the platform and the doors are opening is presented in Figure 4. The results reveal that passengers experience an air temperature change that ranges between 0.4 °C and 2.7 °C at the station with the greatest depth, during their transition from the platform to the interior of the train and vice versa (Fig. 4a). This difference is even higher at the station with the smallest depth and ranges from 2.8 °C to 5.7 °C. The highest differences are observed during midday at the station with the smallest depth, probably due to the fact that the indoor air temperature seems to follow the diurnal variation of outdoor air temperature. On the other hand, for the case of the station with the greatest depth, highest differences are observed during the morning rush hours.

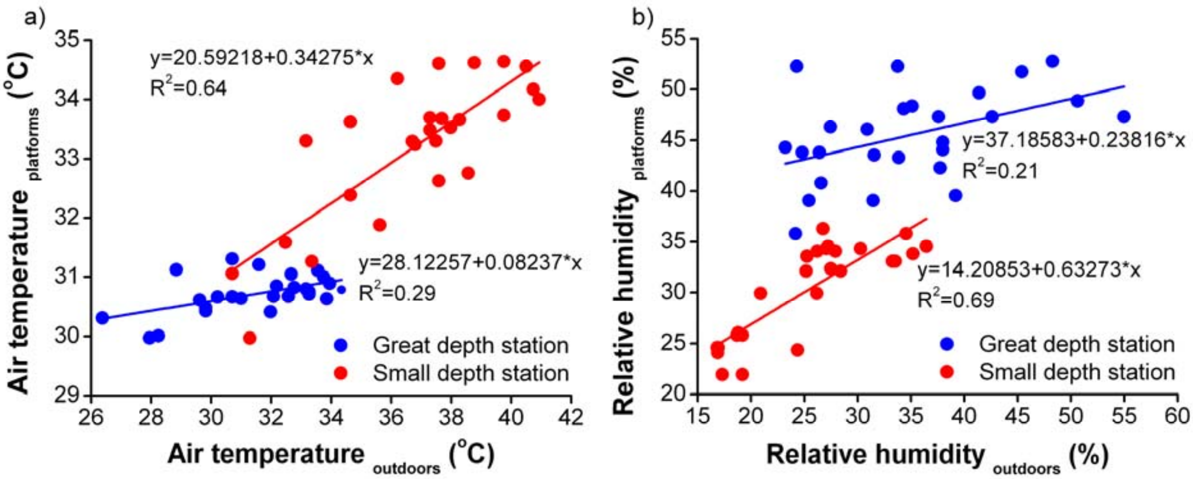

Fig. 3. Scatter plot of (a) air temperature and (b) relative humidity on platforms and outdoors for the great depth (Syntagma) and the small depth (D. Plakentias) station. The least squares regression line and the coefficient of determination (R^2) are also presented.

Further, passengers experience a PMV change that ranges between -0.1 and 0.8 scale points at the station with the greatest depth, during their transition from the platform to the interior of the train and vice versa (Fig. 4b). As in the case of air temperature, this difference is even higher at the station with the smallest depth and ranges from 0.8 to 1.9 scale points. In general, people experience sudden change in environmental conditions when they are moving from an indoor space to the outdoor environment and vice versa [23]. However, the above results reveal distinct thermal conditions in the underground railway environment. Consequently, passengers are exposed to transient thermal conditions, especially at the station with the smallest depth, when they are moving from the platform to the interior of air-conditioned train and vice versa.

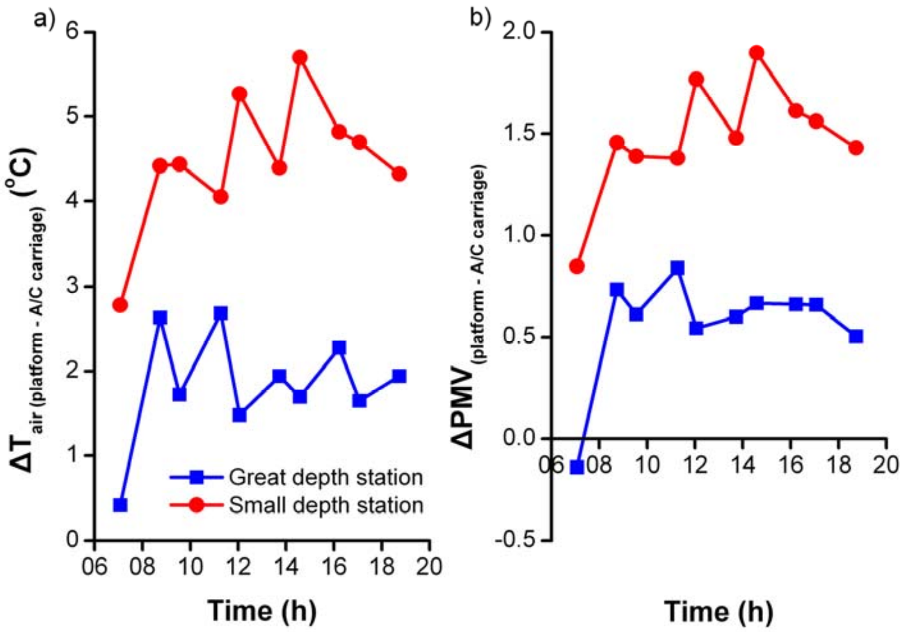

Fig. 4. Diurnal variation of average difference of (a) air temperature and (b) *PMV* between the platform and the air-conditioned carriage of the train that just have arrived at the platform and the doors are opening.

3. Concluding remarks

The main conclusions of the present work can be summarized as follows:

- The majority of vapour pressure values does not exceed the upper comfort limit at the station with the smallest depth. On the contrary, more than 73% of vapour pressure values exceed the upper comfort limit at the station with the greatest depth.
- The operative temperature at both stations is far from the traditional still-air comfort zones. However, for the case of elevated air movement of 1.2 ms^{-1} and the assumption that the occupants have local control of air speed, 20.3% of the values at the station with the greatest depth do not exceed the upper limit.
- The *PMV* values exceed the limits of the proposed classes for a desirable indoor thermal environment at both stations.
- 64% of the variation in air temperature at the platform of the station with the smallest depth is explained by outdoor air temperature, while the corresponding percentage for the station with the greatest depth is 29%. It is worth mentioning that the above result indicates the association and not the causation.
- Distinct thermal conditions between the platform and the air-conditioned trains that just have arrived at the platform are observed. Consequently, passengers experience sudden change of air temperature and *PMV*, especially at the station with the smallest depth, during their transition from the platform to the interior of air-conditioned train carriages and vice versa.

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