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On the determination of the thermal comfort conditions of a metropolitan city underground railway

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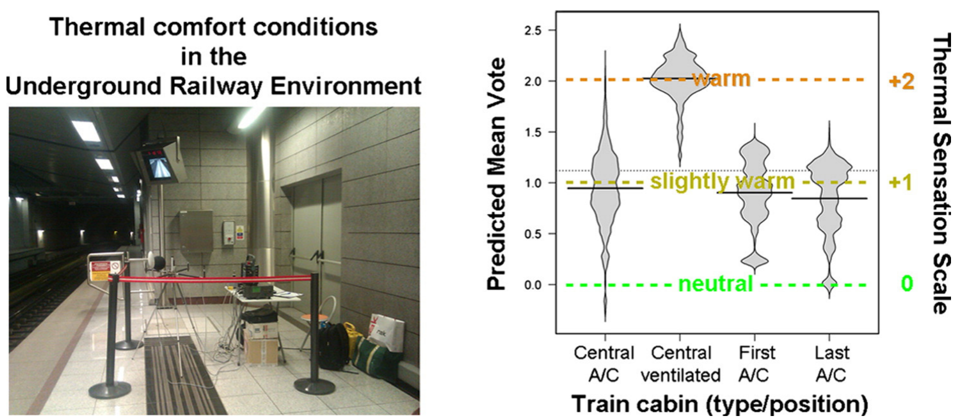
HIGHLIGHTS

- Limited thermal comfort studies in the underground railway environment.
- Field environmental measurements and passengers' data in Athens Metro.
- Slightly warm thermal environment in cabins with A/C and warm in ventilated cabins.
- Poor thermal comfort conditions on the platform of the station with small depth.
- Both depth and design of the stations seem to affect the thermal comfort conditions.

GRAPHICAL ABSTRACT



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ABSTRACT

Although the indoor thermal comfort concept has received increasing research attention, the vast majority of published work has been focused on the building environment, such as offices, residential and non-residential buildings. The present study aims to investigate the thermal comfort conditions in the unique and complex underground railway environment. Field measurements of air temperature, air humidity, air velocity, globe temperature and the number of passengers were conducted in the modern underground railway of Athens, Greece. Environmental monitoring was performed in the interior of two types of trains (air-conditioned and forced air ventilation cabins) and on selected platforms during the summer period. The thermal comfort was estimated using the PMV (predicted mean vote) and the PPD (predicted percentage dissatisfied) scales. The results reveal that the recommended thermal comfort requirements, although at relatively low percentages are met only in air-conditioned cabins. It is found that only 33% of the PPD values in air-conditioned cabins can be classified in the less restrictive comfort class C, as proposed by ISO-7730. The thermal environment is "slightly warm" in air-conditioned cabins and "warm" in forced air ventilation cabins. In addition, differences of the thermal comfort conditions on the platforms are shown to be associated with the depth and the design characteristics of the stations. The average PMV at the station with small depth is 0.9 scale points higher than that of the station with great depth. The number of passengers who are waiting at the platforms during daytime reveals a U-shaped pattern for a deep level station and an inverted course of PMV for a small depth station. Further, preliminary observations are made on the distribution of air velocity on the platforms and on the impact of air velocity on the thermal comfort conditions.

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1. Introduction

In recent years the underground railway network in the metropolitan city of Athens, Greece, also known as the Athens Metro, has become one of the most preferable transportation means since it is not influenced by the traffic congestion. About 480,000 passengers use the Athens Metro on a daily basis, sharing the thermal environmental conditions, inside the trains, the platforms and the other metro dwellings. The daily and annual ridership shows an upward tendency as a result of the construction of new stations and the extension of the existing lines.

Thermal comfort has received little research attention in the underground railway environment and it is mainly focused on other indoor settings, such as offices or residential and non-residential buildings. During recent years the studies in the subway environment have been performed targeting towards the assessment of air quality (Assimakopoulos et al., 2013; Johansson and Johansson, 2003; Kim et al., 2014; Kim et al., 2012; Kwon et al., 2008).

Worldwide the number of metro networks continues to grow and this increase has actually accelerated the last 30 years (UITP, 2014). Although passengers are exposed to underground railway environment for only a short time, the exposure can have dissatisfactory effects on their thermal sensation in poor conditions (Ye et al., 2010). Undoubtedly, in such a complex and special environment, the study of thermal comfort conditions as well as the definition of "acceptable" thermal comfort criteria is one of the rising concerns facing today the scientific community.

The complications and difficulties associated with defining "acceptable" thermal comfort criteria for the underground railway environment were thoroughly presented in the review article by Ampofo et al. (2004). According to this study, the predicted percentage of dissatisfied people in the space, also known as the PPD index which is incorporated in ISO-7730 (2005) and ASHRAE-55 (2013) standards, could be considered as acceptable for values between 40% and 50% for such an environment.

The passengers' areas of the Budapest metro were studied monitoring the environmental parameters and the results were analysed through the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) indices (Ordódy, 2000). The thermal comfort in Tehran metro stations and carriages was studied through field measurements and the results were analysed employing the relative warmth index (Abbaspour et al., 2008). A field study was carried out in Shanghai metro stations to evaluate the thermal environment using the thermal sensation vote and preferred environment vote with the questionnaire (Ye et al., 2010). A weak linear correlation between the air temperature and the number of passengers inside the cabins was found in the Korean subway during the rush hour (Kwon et al., 2008). Recently, Marzouk and Abdelaty (2014) presented an application that utilizes building information modelling in order to monitor thermal conditions and predict thermal comfort in subways. The thermal discomfort under future scenarios of climate change, and the potential number of passengers dissatisfied were studied in six lines of London underground (Jenkins et al., 2014).

In Athens Metro, the study by Assimakopoulos et al. (2013) focused on air quality in the interior of train coaches, while the study by Triandis et al. (2007) dealt with the environmental performance of underground railway stations as transitional spaces. Subjective evaluation experiments were carried out in underground stations of Athens Metro in order to produce a number of independent subjective factors for the thermal environment (Sotiropoulou, 2009). A statistically significant positive linear correlation between the number of passengers and the vapour pressure was found in naturally ventilated cabins of Athens Metro (Katavoutas et al., 2014).

The present work was designed to monitor simultaneously the air temperature, air humidity, air velocity, globe temperature and the number of passengers, using real time instrumentation placed in the interior of train carriages and on selected platforms in the modern underground railway of Athens.

The aim of this study is to evaluate the thermal environment and the thermal comfort conditions in the Athens Metro during the summer period of the year. The analysis was based on the PMV and PPD indices, since both indices are incorporated in ISO-7730 (2005) and ASHRAE-55 (2013) standards for moderate indoor thermal environments. The levels of thermal comfort were compared and analysed between different types of trains, those with air-conditioned cabins and those with forced air ventilation, as well as in the central cabin or simultaneously in the first and the last one. The variation of thermal comfort conditions per route, during the journey and during the day was also analysed, while the recommended thermal comfort requirements of ASHRAE-55 (2013) and ISO-7730 (2005) were tested in such an environment. Finally, the differences of the thermal comfort conditions on selected platforms are analysed and compared, while the impact of air velocity on the thermal comfort conditions is also investigated.

2. Materials and methods

2.1. Athens underground railway

The underground railway network of the metropolitan city of Athens, also known as the Athens Metro, was initially commissioned in 2000. The underground network consists of two lines, numbered 2 and 3, each color-coded (Fig. 1). Both lines are gradually extended while new stations were constructed later on. Nowadays, the total length of the underground network is 39 km and the network includes 36 stations. According to the World Metro Database, Athens Metro stands among the first 62 metros in the world regarding the network length, including the prior surface level Line 1 (Metrobits, 2015). The two metro lines are used for the transportation of about 480,000 passengers on a daily basis and combined with the daily ridership in Line 1, rank Athens Metro among the first 32 metros worldwide (Metrobits, 2015).

2.2. Experimental campaign

The experimental campaign took place along the underground section of Line 3 of the Athens Metro, from the terminal station of Egaleo, at that time, to Doukissis Plakentias station, which is 16.4 km long and includes 16 stations (Fig. 1). Doukissis Plakentias station is the terminal point for certain trains on Line 3, while others emerge at the surface level and using the network of Suburban Railway reach Eleftherios Venizelos International Airport. Therefore, the underground section of Line 3 is one of the busier routes of the network, since it connects the city centre with the Athens International Airport. The experiments were carried out during the summer period of the year, in June, July and August 2012, from 0700 to 1900 summer local time (SLT).

The experimental procedure involved continuous measurements inside the train carriages and on selected platforms. As far as the measurements inside the train carriages are concerned, two types of trains were involved, those with air-conditioned cabins and those with forced air ventilation. Furthermore, the measurements were conducted either in the central cabin or simultaneously in the first and the last one, so that a more accurate representation of the train environment would be achieved. On each experimental day, between 0700 and 1900 SLT, 10 routes on air-conditioned and 14 on forced air ventilated trains, were performed from Egaleo to Doukissis Plakentias station (E-D.P.) and vice versa. It is worth mentioning that Doukissis Plakentias station is the terminal point for the trains with forced air ventilation cabins whereas the terminal point for the trains with air-conditioned cabins is the station in the Athens International Airport.

It is worth noting that both types of trains have 6 carriages and each one has 4 doorways per side. The windows can be opened in both types,

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