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# THERMAL COMFORT IN THE PASSENGER AREAS OF THE BUDAPEST METRO

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## Abstract

60,000 passengers travel by metro in Budapest day by day in the rush hours. It is very important that the passengers could be waiting – in the passenger areas of the metro – under agreeable conditions. In the last few years I have examined the questions of thermal comfort in the passenger areas of the metro, which are mostly influenced by ventilation.

This paper proposes to describe the main features of existing ventilation used in the Budapest metro, then presents the climatic conditions and thermal comfort in passenger and operative areas. Based on measurements and previous studies, our objective is to define a new economic main ventilation system and mode of operation complying with current technical requirements.

*Keywords:* ventilation, thermal comfort, normal comfort, measurement techniques, mechanical ventilation.

## 1. Introduction

Nowadays, the main ventilation fans of the thirty-year-old Budapest metro are out-of-date and should be replaced. The Budapest Transport Company has not up-to-date economical operation of the main ventilation system which is complying with the recent technical requirements. There is no existing national up-to-date planning method in respect of a possible new metro line (Dél-Buda-Rákospalota).

I tried to look for answers to the above mentioned basic problems. In the past five years I have measured the climatic parameters ($t$, $v$, $\mathrm{d}p$, $\varphi$) of the Budapest metro. I would like to create a new yearly main ventilation operation system with my measurements. The aim of my study is to make the ventilation system economical in such way that in the occupied zone a required thermal comfort can be maintained. Furthermore, I would like to develop a new calculation which can be used when calculating the heat load in the metro line. In this way the calculation could determine the necessary ventilation air flow.

This study is based on my earlier measurements.

## 2. Operation of the Metro in Budapest

Hungary is very proud of the fact that the first modern electric underground on the Continent (and in the world the fourth one) was built in Budapest in 1896 commemorating the Millennium of the establishment of the Hungarian state. The construction works of the 3696-meter long millennium underground-line have lasted two years and needed 2000 workers. To speed up the construction, the state-of-the-art building methods and machinery of that period were used.

Unfortunately, because of the two world wars and other reasons no other lines were built for about 50 years. The planning and construction of the first deep level metro line was begun after the 2nd World War in 1950, primarily based on Soviet experience and with the technical help of the Soviet Union. The entire length of the east-west line (M2) was opened in 1972. The line is 10.1 km long with eleven stations and average depth of 35 m. In 1972 the construction of a new, north-south line started (M3) and the complete line was finally opened in 1990. The line is 18.3 km long, the number of stops is 20 and the average depth of the deep level section is 25 m. In the 1990s the construction of a new fourth metro line was decided which was to be 7.3 km long with 10 stations and depth varying between 17 and 44 m [1], [2].

The construction of the Budapest deep level metro stations is very interesting. At the beginning the stations were constructed through three tunnels and a cast iron tübbing structure. Three parallel tunnels, each with a diameter of 8.5 m, were dug to form the station area. The two outside tunnels were used to receive the trains and create the platforms, while the middle tunnel formed the passenger area. Later the design was modified to the effect that instead of three tunnels, five tunnels were drilled next to each other (with a diameter of 5.1 m each) and the middle three tunnels gave room to the passenger area and the platforms.

The climatic conditions and the thermal comfort in the passenger and the operative areas of the metro are decisively influenced by ventilation. The climatic conditions of underground spaces are subject to several factors which have an impact on the public, the staff as well as the machinery.

The tunnels and the passenger areas of stations are ventilated by the main ventilation system, while the operative, service and sanitary areas are equipped with auxiliary ventilation – the latter will not be discussed in detail. The main ventilation is linear along the metro line. Main air shafts were designed to conduct the ventilation air underground and the exhaust air outside. The ventilation air carried underground from the surface must contain the least amount of pollutants (dust, soot, gas etc.) therefore the lower edge of the outside vent holes are placed 1–3 m above the ground. Noise reduction is provided both on the surface and towards the tunnel thus the noise coming from the main ventilation shaft should not exceed the limit set by the relevant regulations under the most favourable circumstances.

The main ventilation fans used in the east-west line were manufactured by *Szellőző Művek (Ventilation Works)* using the plans of the *Department of Fluid Mechanics of the Technical University of Budapest*. At the time of their design and manufacturing (1967–1972) these fans complied with the technical needs of that period. The main ventilation equipment consists of two-grade counter-rotating axial fans with an impeller of 1800 and 2000 mm in diameter and air flow capacity of 50,000–250,000 m$^3$/h. The blades of the impeller can be reset in a different angle, changing the volume and direction of ventilation air. The resetting of the blades, however, is complicated therefore the volume of ventilation air can only be modified periodically when the ventilation system is not operational. These out-of-date fans are scheduled to be replaced in the near future.

The main fans used on the north-south line were supplied by the English firm *Woods* in 1976. The one-grade axial fans have an impeller with a diameter of 1200–1600 mm and an air flow capacity of 140,000–180,000 m$^3$/h. Usually one main ventilation tunnel contains two fans of similar capacity. The fans are equipped with *KNH* silencers manufactured by *FŰTŐBER.* To regulate the performance, the angle of the impeller of the *Woods* fans can be pneumatically reset during operation. If the blades are taken off, turned by 180° and refitted, the air flow can be reversed. Without refitting the blades, the fans can carry 55% of the nominal ventilation volume flow through resetting the motor's direction of rotation. This mode may be necessary to use in extraordinary situations such as fire in the tunnel when the smoke-filled tunnel must be ventilated within a short time. It is our experience that the main fans used in the north-south line meet the operational requirements of the metro.

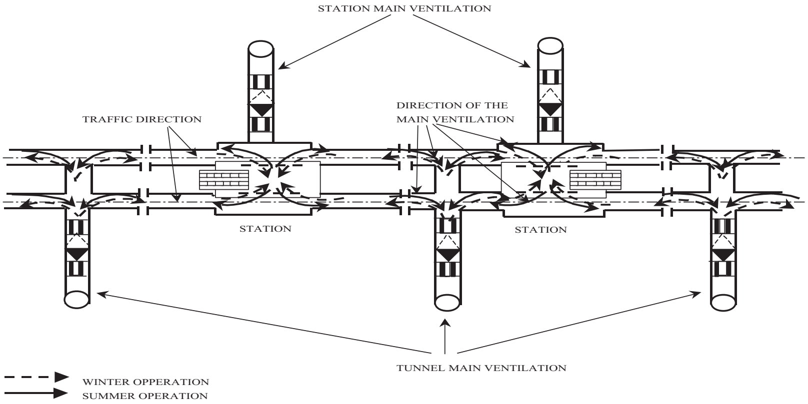

*Fig. 1.* Operation of the main ventilation system

The main ventilation equipment is a lift-and-force system, which has summer and winter modes operation (*Fig. 1*). In the summer mode the fresh air is carried through the station shaft and in the winter mode the main ventilation shaft. Exhaust air is conducted outside in a reversed direction. To change the mode of operation the blades must be taken off and refitted twice a year, which should be followed by the time-consuming dynamic balancing of rotating masses. Due to the lack of necessary conditions and appliances this could not be performed and the operating company, based on several years of experience of operation, decided to use only one-way ventilation. In this mode of operation, fresh air is sucked in through the main ventilation shafts at the stations and the exhaust air is carried out through the shafts on the line. This system has been adequately functioning for years. Experts of the *Budapest Transport Company* conducted a series of measurements for several years and found no overheating – in contrast, in 1988 the annual temperature fell by 1 °C compared to 1985.

From the perspective of dimensioning the extent of ventilation is determined by the volume of heat developed in the tunnels and the operative areas. 75% of the heat comes from traction power and 25% from the heat transmission of other electric equipment and passengers. The volume of heat generated per one meter of the pair of tunnels is 1.3–1.8 kWh depending on the size of the traffic. This means that the main ventilation e.g. on the east-west line must carry away a volume of heat that would be enough to heat 900 apartments. In practice this volume must be removed from the tunnels of the metro. On the north-south line during the main part of operation the ventilation system must make 5.2–6.7 million $m^3$ of air flow in the tunnels every hour to ensure ventilation and prevent the indoor temperature rising above the required figure.

This way the ventilation system ensures an appropriate level of temperature in passenger areas, the air pushed by the trains running in the tunnels, the so-called ‘piston effect’, however, has not been removed.

The volume and direction of ventilation air was defined in a way that the temperature cannot go below $+5\,^{\circ}$C in winter and $+30\,^{\circ}$C in summer at the stations. In winter the ventilation air reaches the station through the main ventilation shafts leading to the surface, which is built between the two stations where the air becomes slightly warmed up. Exhaust air is pumped to the outside by fans through the main ventilation shafts located at the stations, as described above.

No ventilation shafts were built in places where two stations were close or e.g. in tunnels under the Danube. In such cases the main ventilation equipment of the middle station operates as two main station ventilation systems connected in parallel.

Changes in outdoor temperature are set off by varying the volume of ventilation air. If the outdoor temperature is higher than 27 °C or lower than 0 °C, ventilation stops – natural ventilation is still provided. In the range between these two extreme temperatures the intensity of ventilation can be modified by adjusting the angle of the fan blades.

## 3. Measurement of Thermal Comfort in the Passenger Areas of the Budapest Metro

The previous section was devoted to the summary of general information about the Budapest metro lines. This section proposes to present a brief description of the measurements I carried out in the last few years (1994–2000) as well as previous data and measurements processed by the experts of the *Budapest Transport Company* and the *Technical University of Budapest*.

The objective of the measurements was to determine the parameters of thermal comfort in the occupied zone of the metro stations and to evaluate these parameters both for the summer and the winter.

The in-situ measurements for the summer status were conducted between August 4 and 8, 1997 and for the winter status between October 20 and 24, 1997. The locations were stations Déli pályaudvar, Moszkva tér and Batthyány tér on the east-west line and stations Ferenc körút and Klinikák on the north-south line as well as the connected tunnels.

The selected five metro stations are deep level stations (20–30 m deep down from the surface). The natural temperature of the ground is roughly 12–14 °C at such depth.

The following climatic parameters were measured at typical areas of the passenger areas:

- air temperature
- relative humidity of air
- air velocity in the occupied zones of the metro stations.

The occupied zones of metro stations were divided into three main areas: passenger sorting area, left and right platforms. Based on related climatic parameters measured in these locations, the thermal comfort of passengers can be determined.

It is assumed in case of thermal comfort indications calculated for the occupied zone that in the given place during the period of time (1–15 minutes) the inertia of the adaptability of the human body is negligible. It is not the case in reality: if a person is removed from a neutral environment into a cold or warm one, his/her thermal sensation becomes less favourable. If a person is put in a neutral environment from a cold or warm place, the neutral environment is obviously considered more favourable, even if the temperature of the body did not have enough time to change. Due to the lack of subjective indications of thermal comfort for short periods and varying temperatures, the indicators developed by P. O. FANGER (for long stays in permanent air temperatures) were used.

Currently this is the most widely used and accepted method for the calculation of thermal comfort. It was published by FANGER in the 70s who developed a calculating method for given points of a closed space. Using this method the *predicted mean vote* (PMV) and the *predicted percentage of dissatisfied* (PPD) can be determined provided the necessary parameters are known. The predicted mean vote in our case was calculated on the basis of the current metabolic heat generation, clothing and the available measured data [3], [4], [5].

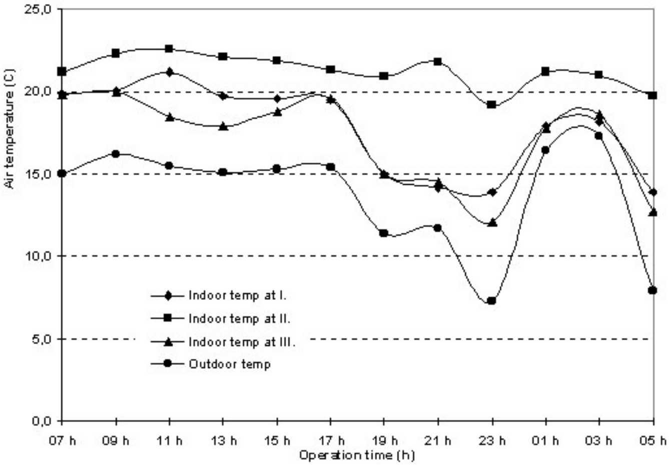

*Fig. 2.* Temperature diagram at Klinikák station (Winter pos.)

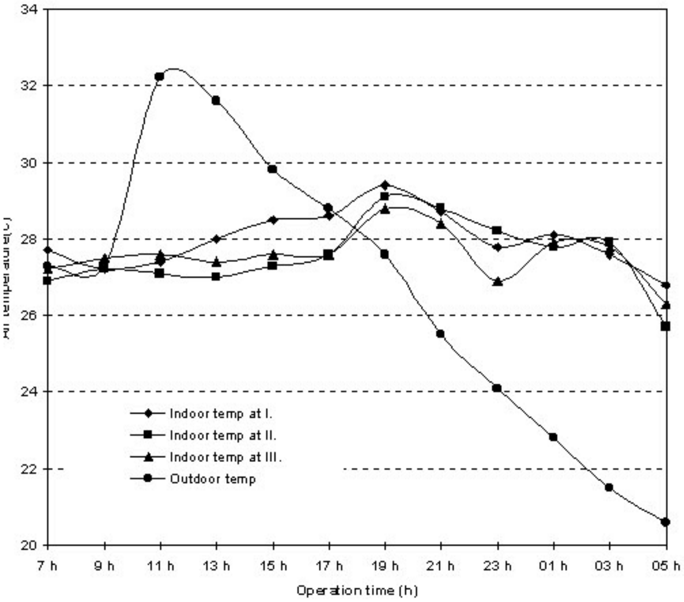

*Fig. 3.* Temperature diagram at the Déli pu. (Winter pos.)

Using the calculated PMV and PPD values it was possible to determine the thermal comfort in passenger areas in the operational Budapest metros and to predict the thermal comfort in the stations of Dél-Buda-Rákospalota fourth metro line (DBR metro).

The major observations at the stations where the in-situ measurements were carried out are as follows:

- in winter the predicted mean vote is slightly cool or cool ($-1.4 < PMV < 0$);
- in summer the predicted mean vote is slightly warm ($0 < PMV < 1.4$);
- the percentage of dissatisfied was between 5 and 30% at the measured stations. During the measurements, however, there was a case when the predicted percentage of dissatisfied went up to 80%. This figure can be explained by the so-called ‘piston effect’, the result of one or two trains arriving at a station, causing an air velocity of 6–8 m/s, and by the ‘small’ capacity of metro stations.
- In winter the ambient temperature in metro stations is always 5–10 °C higher than the outdoor temperature while in summer during the day it is roughly 5 °C lower. At dawn, in the cool early hours, the temperature in the tunnel is about 5 °C higher than outdoors, owing to the fact that the temperature of the tunnel walls changes roughly 11 °C annually whereas the outdoor air temperature fluctuates by 35–40 °C (see *Figs.* 2, 3). The walls of the tunnel therefore warm cold air up and cool hot air.
- According to earlier measurements the difference between the temperatures of the tunnel walls and the air is slight, around 1 °C [6].

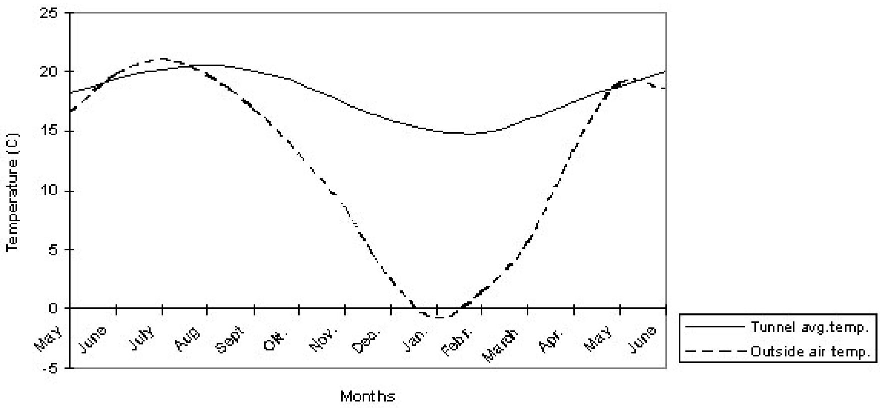

*Fig. 4.* Average temperature in the tunnel during the year

I would like to highlight some interesting measuring results from previous measurements.

- In case of peak thermal load the climatic parameters measured in metro trains show a very hot thermal sensation for a short period of time. The maximum predicted percentage of dissatisfied is 90% for a deep level metro, a realistic value since a large amount of heat is released when the train is slowed down through braking at its arrival in the station. The released heat flows to the passenger area through the open doors of the carriage. Another interesting issue is the air velocity in the metro carriage, which clearly depends on the motion of the carriage. In a stationary train the motion is practically zero: when the train moves, the open windows and the ventilation slits influence air velocity and the volume of air. Unfavourable thermal sensation is therefore experienced while the train stops at the stations for a short period of time. This shows that carriages, considered modern 25 years ago, now do not meet current requirements of thermal comfort.

- Previous measurements focused on the changes of air velocity in a larger area at the Nagyvárad tér station (north-south metro line). The measured values show that at the larger Nagyvárad tér station the velocities are more balanced and the piston effect of carriages is less significant. It is also supported by my measurements as in smaller stations greater permanent velocities are created.
- It is also important to study the deep level sections and the sections just below the surface. The temperature of the walls at deep level metro stations adjusts to the outdoor air temperature with a delay of 30 days (see *Fig. 4*) while at stations under the surface the temperature of walls follows the changes in the outdoor temperature without delay due to the proximity of the surface [7], [8], [9].

## 4. Conclusions

Both our own and the existing measurements point to the conclusion that thermal comfort at the stations of the new DBR metro line will be similar to that of the stations of the existing lines. This is supported by the selection of DBR's deep level line so the temperature of tunnel walls will follow the outdoor ambient temperature in a sine line with a delay of roughly one month.

It should be taken into account that the most modern trains are likely to be running on the DBR line with a considerably smaller heat transfer than the current carriages (e.g. trains with a regenerative brake system), therefore roughly 40% less heat well be generated during motion. This will significantly reduce indoor thermal load so a smaller ventilation equipment will be sufficient to efficiently ventilate the metro line.

From an architectural perspective the formation of stations will make the biggest difference. The DBR plans show stations with 80 meter-long platforms and stations 20–25 meters wide. Carriages will arrive in a larger space where the piston effect of air, useful in the tunnels, will be less powerful at the stations and passengers will have no sensation of the draught now occasionally observed at stations.

A more favourable thermal sensation is expected to be experienced in the passenger areas of the DBR metro than in the older metro lines, which will be the result of a better temperature in the tunnel, owing to a less strong draught and the minimisation of heat generation in the tunnels caused by the modern trains and main ventilation systems. Comparing these changed climatic parameters with the data previously measured it is easily seen that thermal comfort will be more agreeable in the passenger areas in the DBR line. It is also likely that the predicted percentage of dissatisfied will shrink and no extraordinary figures such as 80–90% PPD values in the current measurements will be found, thanks to the favourable climatic parameters and the new metro line, considered modern from every aspect.

## List of Notations

| | |
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| $t$ | Temperature |
| $v$ | Air velocity |
| $\mathrm{d}p$ | Pressure drop |
| $\varphi$ | Air humidity |
| $PMV$ | Predicted Mean Voted |
| $PPD$ | Predicted Percentage of Dissatisfied |

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