Flow Regimes and Thermal Patterns in a Subway Station

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Abstract
The definition of a good indoor climate is important to the success of a passenger rail coach, not only because it will decide its energy consumption and thus influence its sustainability but also because good comfort for long journeys is essential. The intention is to use the results to optimize the control of the ventilation system to provide an indoor climate that passengers will find comfortable. The results of this study show that outdoor air ventilation, temperature, humidity and clothing are major factors that influence passengers' thermal comfort.

This paper primarily discusses and analyzes the simulation of the air flow and thermal patterns in a Subway station. Numerical simulation of a typical model is presented. The pre-processor Gambit is used to create the geometric model with parametric features.

Commercially available simulation software “Fluent 6.3” is incorporated to solve conservation of mass, momentum and energy in the processing of air distribution, and to analyze turbulence affection combined heat transfer on air distribution. In this thesis work, the so-called standard k-ε turbulence model, one of the most widespread turbulence models for industrial applications, was utilized. Basic parameters included in this work are air temperature, air velocity, relative humidity and turbulence parameters are used for numerical prediction of indoor air distribution.

Measurements of air velocity, and temperature were undertaken in a plane parallel to the supply diffuser and another plane in the vicinity of advertising lamp box. These values were then compared to the obtained results from the simulated cases.

The thermal comfort prediction through this work was based on the PMV (Predicted Mean Vote) model and the PPD (Percentage Predicted Dissatisfied) model, the PMV and PPD were estimated using Fanger’s model.

1. Introduction
Greater Cairo underground metro is considered one of the most important national projects executed in the Republic during the second half of the twentieth century. This project is included in the plan of urban transportation in the Greater Cairo Region. The project is consists of three lines linking the capital districts with the center of the city. This project will be operated integral with a group of the projects. The project aims to develop underground transportation system. The project has also secured parking areas, and multi-story garages for private parking at main squares to encourage the use of public transport. The Cairo Metro in Egypt is Africa's only full-fledged metro system. The system consists of two operational lines, with construction having begun on a third line in September 2008.

The two lines carry around 700 million passengers a year and on average 2 million per day. Line 1 opened in 1987 after the joining of two existing above-ground lines with a large underground section through the city center. The line runs a total of 43.5 km (27 miles) with 3 km (1.8 miles) underground, serves 33 stations, and has a 60,000 hourly passenger capacity per direction. Cairo's metro network was greatly expanded in the mid-1990s with the building of Line 2, from Shoubra to Cairo University, with an extension to Giza. Extending 21.5 kilometers (13 miles) with 20 stations, it is sometimes called the "Japanese-Built Line" and includes the first underground crossing of the Nile.[1].
1.1 Why Underground Metro?
Transport plays a great role in the development of a nation, economically and socially and it is considered to be a main base of the growth of any country, So Egyptian government had paid great attention to the development of the national transportation sector.

The current project of establishing lines of Underground Metro is not a newly planned project, but it had been a subject of about ten transportation studies carried out by International consultants from different countries over the last fifty years. These studies involved local consultants from the private sector or from the Egyptian universities.

These investigations show positive results and indicate that Cairo, likewise other Mega cities cannot solve its transport problems depending only on the surface transportation systems. Cairo needs a high-capacity Metro system to serve its people and provide a smooth, reliable and fast moving means of transport.

These studies produced a variety of solutions and recommendations to overcome the problems, which existed at the time of the Study.

For transportation development, the investment has been raised steadily from 11,000 Million EGP in the first five years plan starting in 1982 to 21,000 Million EGP during the current five year plan started on 1997. These amounts represent about 15-20% of the total sum of the governmental expenditure. One of the most essential and beneficial aspects of the transportation sector in Egypt is the construction of Greater Cairo underground Metro Network.

2. Subway station configuration
The station under investigation is a real subway station "Albohoos" Cairo Metro Line 2, which has main dimensions (length X width X height = 153.0 m (L) X 20.0 m (W) X 5.5 m (H)). Fig. 1 shows the case study picture generated using Autodesk 3ds Max 2010.

3. Experimental investigation
This investigation aims to validate the used computational fluid dynamics code, the results from both investigations, experimental and numerical, will be compared. Flow parameters like velocity and temperature have been measured at relatively important places on the platform in a plane perpendicular to a grill in the supply duct and in the vicinity of advertisement lamps mounted on a side wall. The measuring mechanism consists of a mobile carriage with a tower mounted perpendicularly on it with maximum height of 2.60 m from the floor. The measuring sensors are mounted on a plate moving by means of chain and sprockets all the height on the vertical tower. The eight-wheel mobile carriage powered by two 5-volts, DC-motors with a step down gearbox. The wheels motors and the sprockets motor are controlled by a 8-Relays circuit board connected to a personal computer using a 25-pins parallel port. The mechanism enables smooth movement of the temperature and air velocity sensor in a two dimensional mesh in order to get complete fields of mean temperature and mean velocity magnitude in a vertical plane.

The measurements of the mean velocity components were carried out using a hot-wire anemometer with time averaging (Testo 435). The hot-wire anemometer has the range of velocity between 0.0 m/s to 20.0 m/s, with accuracy of ± 1.0 digit (at 22
°C), ± (0.025 m/s ± 5% of m.v.) to 20 m/s. The hot-wire anemometer has a resolution of 0.01 m/s (at 0.0 to 10.0 m/s), and 0.1 m/s (at 10.0 to 20.0 m/s). This hot-wire anemometer depends on measurement readings averaging. The final result is average of the last 12 readings. The temperature measurements were carried out using a J type thermocouple. This thermocouple has a range between -20.0 °C to +70.0 °C, with accuracy of ± 0.5 °C to 50.0 °C. The thermocouple has a resolution 0.1 °C.

3.1 Measurements at a plane cutting the supply air grill

Temperature and vertical velocity component are measured at 18 lines spaced 0.3 m each has 25 points.

3.1.1 Temperature measurements

A 2-D contour plot for temperature profile shown in Fig. 2 is produced using Tecplot 360 by loading the measured temperature values at the selected points in this plane.

![3.1.1 Temperature measurements](image)

**Fig. 2.** Measured Temperature contours in the plane cutting the supply air grill

3.1.2 Velocity measurements

The measured air velocity contours are shown here in figure 3 at a plane through the supply air grill. The velocity contour demonstrated the jet drop and the lateral diffusion.

![3.1.2 Velocity measurements](image)

**Fig. 3.** Measured Velocity contours in the plane cutting the supply air grill

Velocities decrease from about 0.75 m/s at issuing jet to nearly 0.1 m/s at occupancy zone.

3.2 Measurements parallel to the advertising lamp box

The air properties such as the y-velocity component and temperature in a plane parallel to the advertisement lamp box were measured. The plane is 0.15 m away from this wall. Temperature and velocity were measured in 21 vertical lines spaced 0.5 m from each other.

![3.2 Measurements parallel to the advertising lamp box](image)
Fig. 4a. Measured Temperature contour in the plane parallel to the advertisement lamp box

It can be noticed from Fig. 4a that two green areas representing relatively lower temperature zones is formed vertically under the two existing supply grills at x= 44 m and 49 m.

Fig. 4b shows a 2D contour of the y-velocity component near the advertisement lamp box. The blue area represents the negative velocity under the supply grill, while the red area between them is due to buoyancy effect for the heated air near the hot plane affected by the heat flux emitted from the electric lamps.

Fig. 4b. Measured Velocity Profiles in vicinity of the advertisement lamp box

4. Numerical Investigation

The application of CFD simulation in the indoor environment is based on conservation equations of energy, mass and momentum of incompressible air. The turbulence model used in the numerical model is the widely used standard $k-\varepsilon$ model. Some researches [2] indicated that the $k-\varepsilon$ model of turbulence [3] was the most appropriate model for practical building airflow applications. Until today, it is still the most common turbulence model in use. However, due to its simplicity, its accuracy is limited, particularly when analyzing complex non-isothermal, three-dimensional flow in buildings [4,5] and it integrated the governing equation on the capital control volumes and discredited in the definite grids, at last simulated and computed with “Fluent 6.3” software.

The pre-processor GAMBIT was used in meshing the simulated model. The mesh dependency was examined by solving the flow field for five mesh configurations made of 705,000; 913,000; 1,096,000; 1,560,000 and 1,720,000 cells, respectively, and we compared the temperature and velocity profiles on a line for the five mesh configurations. Results showed that up to 3.7% difference in the maximum velocity existed between the coarser and finer mesh and less than 0.25% difference existed between the two finer meshes, which indicated that the finer mesh resulted in mesh-independent solutions.

4.1 Boundary Conditions

The following more important boundary conditions assumptions were made in the present investigations.

1- Wall temperature at various points were measured and found that all temperatures of enclosure are between 29°C and 31°C, there is little difference in all test positions, and the average temperature is 30°C.

2- Train heat generation was calculated using the equations first used by Ampofo et al [2] where, the heat load due to traction motor losses in the train is given by

$$Q_{brake} = Q_d + Q_{mr} + Q_{rl}$$

The train heat generation at station is calculated and found to be 132 w/m² after it's averaged on the entire area of the railway.

3- Supplied air conditions is set in the CFD code at values of 24°C, 60% RH, and 1.1 m/s inlet velocity based on measured data.

4- The body of the occupant is assumed to be as a volume of oval cylinder and the head to be as a small oval cylinder of 0.25 m height. As the skin temperature is a function of the metabolic rate in Met (1 Met = 58 W/m²) [7], and it has been assumed that the passengers' metabolic rate is 116 W/m² (2 Met), so the skin temperature is set to a value of 32.5 °C. The body is assumed to have zero diffusive flux.
The mass flow of expired air from the occupants is calculated as $2 \times 10^{-4}$ kg/s per occupant based on 20 times per minute [8], during normal activity.

4.2. Convergence and stability
The simultaneous and non-linear characteristics of the finite difference equations necessitate that special measures are employed to procure numerical stability (convergence); these include under relaxation of the solution of the momentum and turbulence equations by under relaxation factors which relate the old and the new values of $\Phi$ as follows:

$$\Phi = \gamma \Phi_{\text{new}} + (1 - \gamma) \Phi_{\text{old}}$$

Where, $\gamma$ is the under-relaxation factor. It was varied between 0.2 and 0.3 for the three velocity components as the number of iteration increases. For the turbulence quantities, $\gamma$ was taken between 0.2 and 0.4 and for other variables between 0.2 and 0.6.

The required iterations for convergence are based on the nature of the problem and the numerical conditions (grid nodes, under-relaxation factor, initial guess, etc.). So the time (on the computer processor) required to obtain the results is based on many factors. The computational number of iterative steps is selected according space cell (spatial difference) to yield converged solutions [9]. The validity of the present computational technique was assessed previously in the open literature, for example in references [10-15], where reference should be made for more detailed readings.

5. Simulation and discussion
The following Fig. 5 shows the vertical and horizontal planes selected to investigate the temperature and humidity patterns and velocity vectors in the subway station. The two $y$-$z$ planes were chosen to pass through supply grills and one of the setting people. The horizontal plane $x$-$z$ covers the whole area of the subway station at a height of 1.2 m.

![Fig. 5 Subway station isometric drawing showing dimensions and selected cutting planes](image)

The validity of the numerical model was further assessed for the present case by way of comparison with experimental results. These are shown in figure 6 at two locations of $z = -3.05$ m and $z = -3.65$ m.

![Fig.6a: Path Lines colored by velocity magnitude (m/s)](image)
PMV contours at studied planes

The Predicted Mean Vote (PMV) adopted by Fanger [16] is defined in FLUENT database using the custom field functions. The PMV contours, [17] at the studied planes are shown in Fig. 7 and 8. The PMV take values between 1 and 2 which are considered slightly warm and warm, respectively on Fanger's psycho-physical scale.

About 85% from the total volume of the subway station the predicted percentage of dissatisfied people will be between 45% to 65%.

6. Concluding Remarks

The present work presented preliminary experimental analyses of flow regimes and thermal patterns in a subway station in Cairo. Measurements were obtained with hotwire anemometer at various locations and were utilized to assess the validity of the numerical technique that was shown to demonstrate the various regimes in the platform area. Account was taken for the effect of the human presence, both as physical blocks in the air stream and as sources of heat and moisture as per the ASHRAE recommended values.

Fig.6b: Comparisons between measured and predicted air temperature profiles downstream the supply grill
Fig. 7 Contours of PMV at vertical plane X=27.6m

Fig. 8 Contours of PMV at vertical plane X=44.6m
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