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Flow Regimes and Thermal Patterns in a Subway Station

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Abstract As underground railway systems can generate enough heat from their operations to raise station and vehicle temperatures substantially[1,2]. This may lead to passenger discomfort and complain in warm weather conditions if the underground railway environment is not cooled. This paper presents modifications that can be made on air conditioning systems in subway stations by discussing and analyzing air flow and thermal patterns in a typical one. As CFD is now a popular design tool for engineers from different disciplines for pursuing an optimum design due to the high cost, complexity, and limited information obtained from experimental methods[3-5]. 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 paper 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. The CFD model was validated by comparing the simulation results with measurements of air velocity, and in a plane perpendicular to the supply diffuser and another plane in the vicinity of the advertisement lamp box. Thermal comfort was used in this paper to judge the impact of any modification. 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.

Keywords CFD, Thermal Comfort, Subway Station, Task-ambient, Platform Screen Doors

1. Introduction

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 consists of three lines linking the capital districts with the centre of the city. This project will be operated integral with a group of the projects. The project aims to develop the 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 two lines carry around 700 million passengers a year. Line 1 opened in 1987 after the joining of two existing above-ground lines with a large underground section through the city centre. The line runs a total of 43.5 km with 3 kilometres underground, serves 33 stations, and has a 60,000 hourly passenger capacity per direction.[6]

Why Underground Metro?

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Transport plays a significant 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 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, as well other huge cities cannot solve its transportation 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. 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)). "Figure. 1" shows the case study picture generated using Autodesk 3ds Max 2012.

Figure 1. Subway station configuration

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. Measuring mechanism consists of a mobile carriage with a tower mounted perpendicularly on it with maximum height of 2.60 m from the floor. 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 is 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-pin 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 reading. The temperature measurements were carried out using a J type thermocouple. This thermocouple has a range from -20.0℃ to +70.0℃; with accuracy of ± 0.5℃ to 50.0℃. 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.

Temperature measurements

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

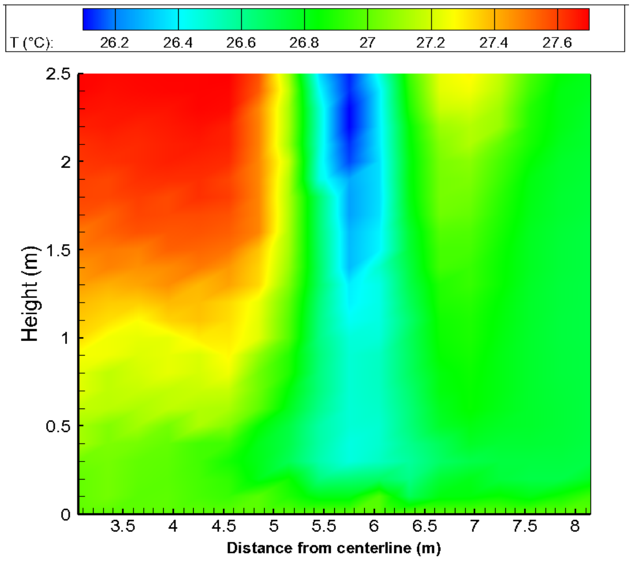


Figure 2. Measured Temperature contours in the plane cutting the supply air grill

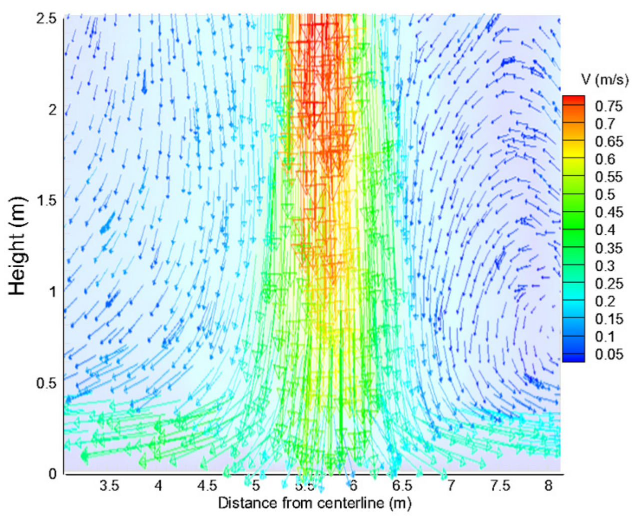


Figure 3. Measured Velocity vectors in the plane cutting the supply air grill

Velocity measurements

The measured air velocity vectors are shown here in "Figure. 3" at a plane through the supply air grill. The velocity vectors demonstrated the jet drop and the lateral diffusion.

As shown in figure Air 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 Advertisement 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.

"Figure. 4" shows two green areas representing relatively lower temperature zones is formed vertically under the two existing supply grills at x= 44 m and 49 m.

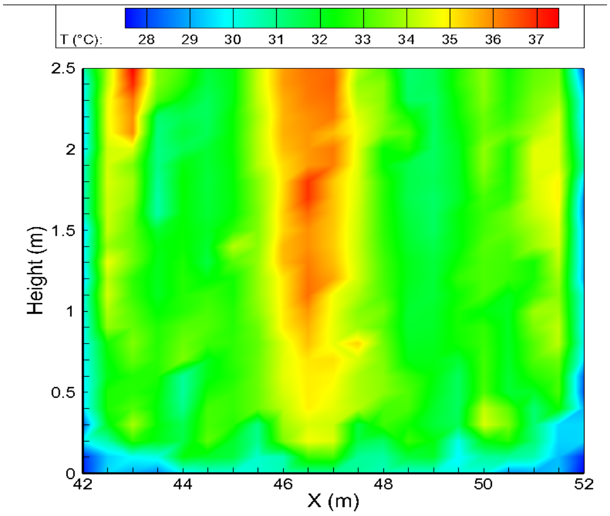


Figure 4. Measured Temperature contour in the plane parallel to the advertisement lamp box

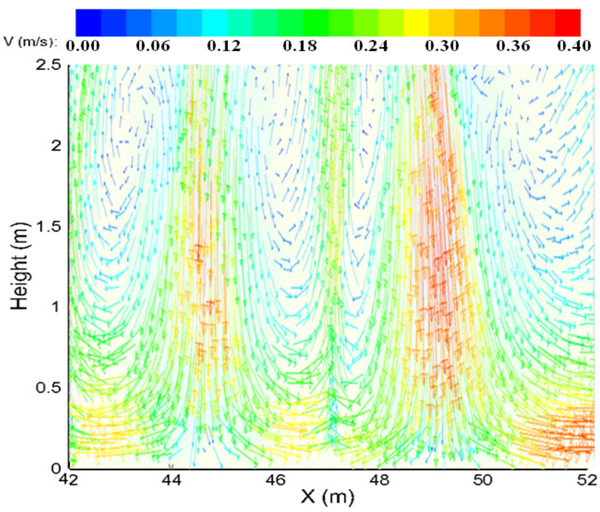


Figure 5. Measured Velocity vectors in vicinity of the advertisement lamp box

"Figure. 5" 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.

4. Numerical Investigation

Earlier CFD simulations of tunnel ventilation system mainly focus on emergency situation as fire condition[7-9]. Many scientists and research workers[10-12] have done much work on this. The ventilation of subway is crucial that the passengers should have fresh and high quality air[13].

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-ε model. Some researchers[14] indicated that the k-ε model of turbulence[15] 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[16,17] 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.

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℃ and 31℃, there is little difference in all test positions, and the average temperature is 30℃.

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/m^2 averaged on the entire area of the railway.

3- Supplied air conditions is set in the CFD code at values of 24℃, 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/m^2)[18], and it has been assumed that the passengers' metabolic rate is 116 W/m^2 (2 Met), so the skin temperature is set to a value of 32.5℃. The body is assumed to have zero diffusive flux.

5- The faces of the passengers are treated as a species source due to the presence of the CO_2 in the expired air of the respiratory system of the occupants. The volume fractions of the gases in dry expired air under standard conditions are:

74.5% N_2, 15.7% O_2, 3.6% CO_2 and 6.2% H_2O. The mass flow of expired air from the occupants is calculated as $2*10^{-4}$ kg/s per occupant based on 20 times per minute, during normal activity[19].

5. Simulation and Discussion

The following "Figure. 6" 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 1.2m.

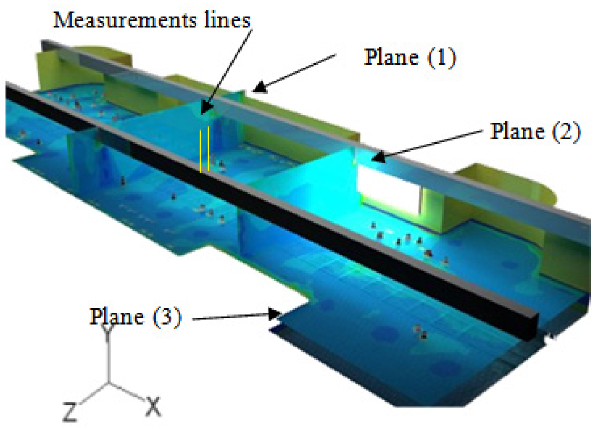
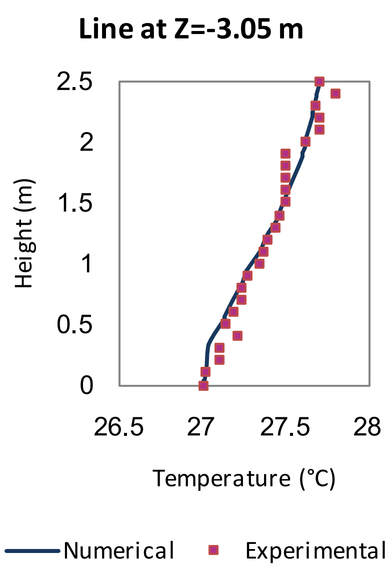


Figure 6. Subway station isometric drawing showing dimensions and selected cutting planes



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. 7" at two locations of (x,z)=(27.6,- 3.05) m and (x,z)=(27.6,-3.65) m. Both lines locations are shown in figure 6.

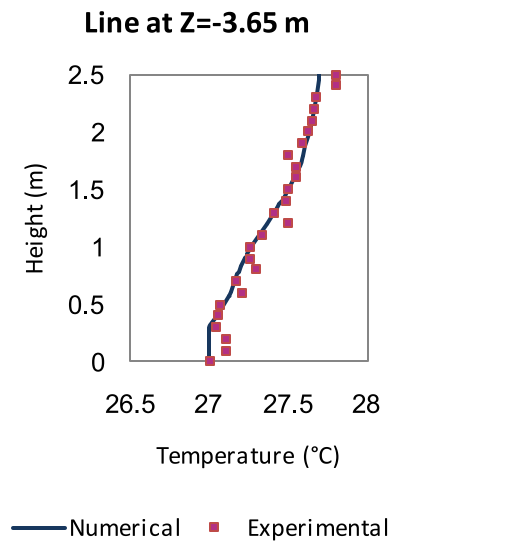


Figure 7. Comparisons between measured and predicted air temperature profiles downstream the supply grill

5.1. PMV Contours at Studied Planes

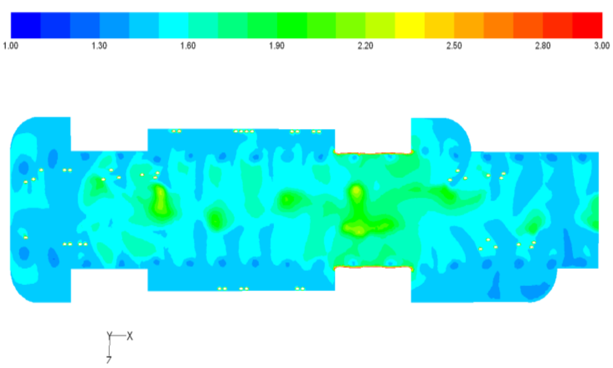


Figure 8. Contours of PMV at horizontal plane y=1.2m

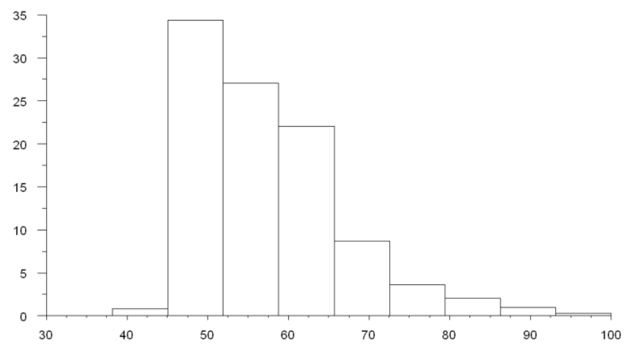


Figure 9. The predicted percentage of dissatisfied (PPD) histogram

The Predicted Mean Vote (PMV) adopted by Fanger[20] is defined in FLUENT database using the custom field functions. The PMV contour at a horizontal plane covering the whole station area is shown in "Figure. 8". The PMV index takes values between 1 and 2 which are considered slightly warm and warm, respectively on Fanger's psycho-physical scale.

"Figure. 9" shows the existed case with the actual station conditions. Nearly 85% from the total volume of the subway station the predicted percentage of dissatisfied people will be between 45% to 65%..

5.2. Modifications that can be made

5.2.1. Task-Ambient air-conditioning.

Task-ambient (TA) air-conditioning systems selectively control local microclimates in 'task' areas where users are present, while loosely controlling those in 'ambient'. This control method is aimed at decreasing air-conditioning loads while simultaneously maintaining the thermal comfort of occupants[21].

The Predicted Mean Vote (PMV) shown in "Figure. 10" takes values between 0 and 0.9 which are considered neutral and slightly warm, respectively on Fanger's psycho-physical scale. These values are lower than the case before by at least one unit on this scale, which clearly demonstrates the effect of Task ambient air-conditioning (TAC) on the thermal comfort of the subway stations.

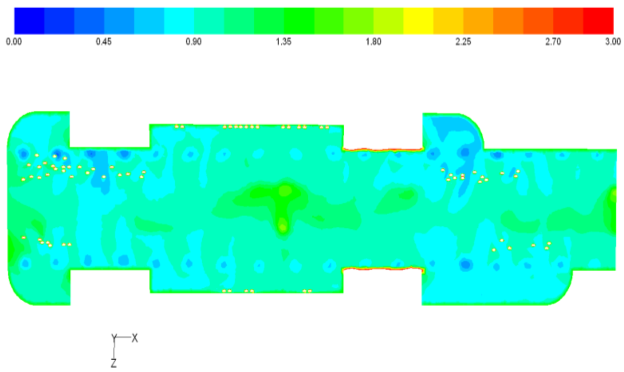


Figure 10. Contours of PMV at horizontal plane y=1.2m

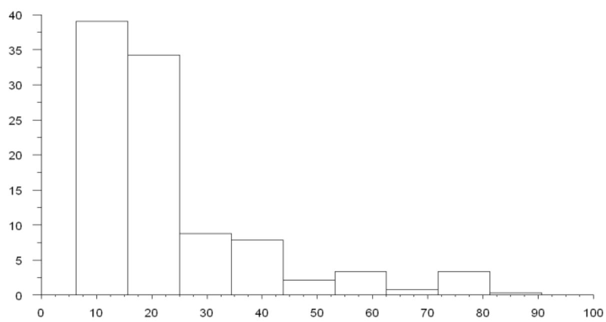


Figure 11. The predicted percentage of dissatisfied (PPD) histogram

"Figure. 11" shows that for about 80% of the volume of surrounding passengers in crowded areas will PPD between 5% and 25%. This means that less than 20% of the people in the station will be dissatisfied.[22]

5.2.2. Platform Screen Doors (PSD)

Platform screen doors (PSDs) and platform edge doors (PEDs) at train or subway stations screen the platform from the train. They are a relatively new addition to many metro systems around the world, with some platform doors retrofitted rather than installed with the metro system itself.

As shown from "Figure. 12, 13" the PMV take values between 0 and 0.7 which are considered neutral and slightly warm.

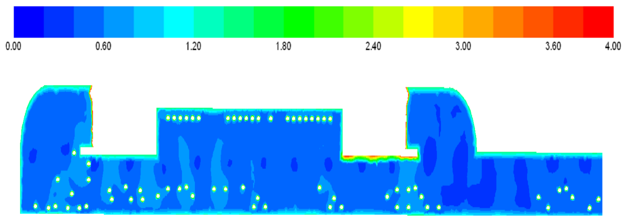


Figure 12. Contours of PMV at horizontal plane y=1.2m

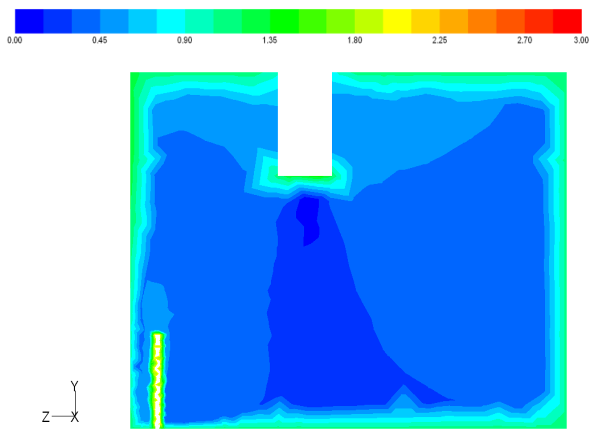


Figure 13. Contours of PMV at vertical plane X=53m

"Figure. 14" shows that for about 80% from the total volume of the subway station the predicted percentage of dissatisfied people will be between 10% to 20%, meaning that less than 20% of the people in the station will be dissatisfied.[22]

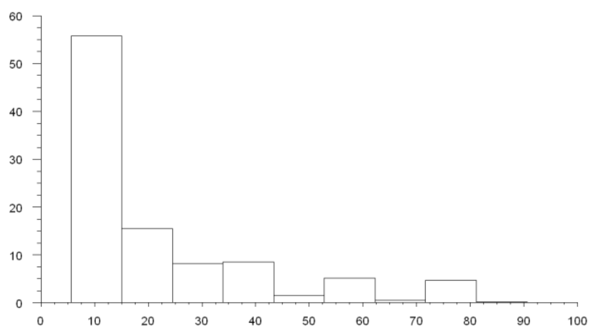


Figure 14. The predicted percentage of dissatisfied (PPD) histogram

Table 1. Required Cooling Load for Each Case

Case	Description	Cooling load (KW)
1	Actual case 90 person	156
2	Task-Ambient Air-Conditioning	292
3	Using Platform Screen Doors	162

6. Conclusions

The present work presented preliminary experimental analysis of flow regimes and thermal patterns in a subway station in Cairo. Measurements were obtained with hot-wire anemometer at various locations and were utilized to assess the validity of the numerical technique that was shown to demonstrate the distinct 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. In order to modify the supplied air conditions, it was found that the cooling load should be increased from 175 KW to 424 KW for the same air outlets distribution. The cooling load is then decreased by using the task ambient air conditioning to 292 KW while maintaining the same thermal comfort level.

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