American Journal of Science, Engineering and Technology
2023; 8(4): 226-234
http://www.sciencepublishinggroup.com/j/ajset
doi: 10.11648/j.ajset.20230804.18
ISSN: 2578-8345 (Print); ISSN: 2578-8353 (Online)

CFD Application to Estimate Air Flow Rate for Normal Ventilation in Metro Trains and Stations

Mohamed Abuelkassem Mohamed, Elseman Ibrahim Abdelrasoul, Sayed Ramadan Hamed*

Department of Mining and Metallurgical Engineering, Engineering College, Assiut University, Assiut, Egypt

Email address:

Mohamabu2001@gmail.com (Mohamed Abuelkassem Mohamed), elseman@aun.edu.eg (Elseman Ibrahim Abdelrasoul), eng.sayed5060@gmail.com (Sayed Ramadan Hamed)

*Corresponding author

To cite this article:

Mohamed Abuelkassem Mohamed, Elseman Ibrahim Abdelrasoul, Sayed Ramadan Hamed. CFD Application to Estimate Air Flow Rate for Normal Ventilation in Metro Trains and Stations. *American Journal of Science, Engineering and Technology*. Vol. 8, No. 4, 2023, pp. 226-234. doi: 10.11648/j.ajset.20230804.18

Received: October 6, 2023; **Accepted**: November 6, 2023; **Published**: November 17, 2023

Abstract: Due to the problem of lacking enough fresh air for passengers in underground metro stations, increasing attention has been paid to improving ventilation in underground metro stations. In this paper, the distribution characteristics of airflow fields, geometry of the station, and the influence of airflow rate changes on passengers' ventilation conditions have been investigated and simulated according to computational fluid dynamics (CFD) theory. In addition, the volume of the stations was treated with a central air conditioning system, including several air handling units (AHU) connected to chilled water. Air flow for trains and stations has been calculated and compared with the actual data of the National Authority for Tunnels (NAT). It has been found that the highest air flow rate Q for Attaba station is 24.97 m^3/s at ticket hall level, and the lowest air flow rate is 5.23 m^3/s at platform level. Also, the required air flow rate is 111.02 m^3/s for trains has been calculated. This value is acceptable and suitable in comparison to the actual results from the NAT. This is to reduce the necessary heat and improve the air quality inside underground metro stations. It is concluded that, in cases where an air flow rate is required in stations, the efficiency of the fans must be superior to 70%. The rotation speed of the fans will range from 750 to 1480 revolutions per minute (r.p.m).

Keywords: Computational Fluid Dynamics (CFD), Air Flow Rate, Stations, Air Treatment and Improvement

1. Introduction

Nowadays, underground metro stations are very important to ease the transport of passengers away from the surface and reduce traffic problems. Without ventilation, no operations are possible at underground stations. Therefore, it is the most important single phase of subways [1]. Therefore, urban rail transit has become the primary mode of transportation for a large number of citizens. Among the different types of urban rail transit, urban underground metro stations take up the largest part, as stated by Ahn et al. [2, 3].

Previous studies have shown that if the condenser inlet air temperature is above 45°C, the air-conditioner is likely to face high-pressure failure. The failure of the air-conditioning in trains leads to heatstroke and syncope in passengers during the summer session. On this account, good control of the thermal environment in underground metro stations is of great importance and has drawn the attention of researchers [4, 5]. So, the purpose of the air treatment and improvement system is to maintain suitable ambient conditions throughout the stations [6].

This means that the maximum ambient air temperature at all levels of a station will be 3°C lower than the outside temperature. That means for a 38°C outside temperature, the following conditions shall be maintained in the station: a dry bulb temperature of 35°C and a relative humidity of 31%. The volume of the stations shall be treated with a central air conditioning system, including several air-handling units (AHU) connected to chilled water [6].

The primary air return and improvement system is a common form used in stations in most countries. As a result, a part of the air will be rehandled and chilled again after filtration and mixing with fresh air. About 50% of the spent air will be rehandled, and 50% of the minimum amount of fresh air will be added to the improved system in order to maintain suitable ambient conditions throughout the stations [7].

Also, Liu et al. [8] used the buoyancy shear stress transport

(SST) k-omega model to represent turbulent transport, component models for jet fans, and ventilation ducts for air flow distribution in underground metro stations. Zhang and Xiaofeng (2021) used a 3D airflow system model by using simulation (CFD) to represent turbulent transport, component models for jet fans, and ventilation ducts for air flow distribution in underground metro stations [9].

Calculating the air flow rate required in trains and underground metro stations is essential to improve distribution of speed and pressure. Hence, this paper covers the highlighted research gap, which is that researchers ignore the application of CFD modeling by using ANSYS FLUNT software and calculating the air flow rate required in trains and stations. Additional cooling for the train should be provided by cooling the tunnels within which they operate. So, the air flow rate required in normal ventilation (trains and stations) has been calculated to remove a certain amount of heat and improve air quality inside metro stations. The present case study would be in the tunnel of Cairo Metro number 3, with a length of 4.3 km, which extends from Attaba station to Abbassia station in Cairo.

Objectives of the work:

In this paper, it is intended to study a numerical simulation of air flow distribution in the tunnel of Cairo Metro Line No. 3 to improve the ventilation system, the following aims are:

Apply Computational Fluid Dynamics (CFD) modelling by using (ANSYS FLUENT) software to deal with airflow distribution in the underground metro stations.

Calculate the required air flow rate in normal ventilation (trains and stations) to remove a certain amount of heat and improve air quality inside metro stations.

Compare the calculated results with the actual data used by the National Authority for Tunnels (NAT).

2. Literature Review

Many studies have been conducted to calculate the required air flow rate for ventilating trains and stations normally.

Owais et al. (2021) calculated the air flow rate required in trains and the air flow required in stations to remove a certain amount of heat. They found an increase in fresh air for passengers inside the train and stations is needed. Also, they adjusted the way to distribute the required fresh air flow at the lowest possible cost [10].

Also, Liu et al. (2021) used the buoyancy shear stress transport (SST) k-omega model to represent the turbulent transport, component models for jet fans, and ventilation ducts of airflow distribution in underground metro stations. They found the model was able to reduce energy consumption and increase auxiliary ventilation system [8].

Wang et al. (2012) used computational fluid dynamics (CFD) to study the effects of the deflected angles of jet fans on the normal ventilation in a curved tunnel. They found that as the angle of inclination of the jet fans increases the amount of air flow increases. This means that curved tunnels require more ventilation than straight tunnels, which leads to improving the efficiency of the ventilation system [11].

Mohamed et al. (2020) have conducted a numerical study on the optimization of the air treatment and improvement systems of trains and stations. They found that before applying the numerical study, there was not enough fresh air for passengers inside the subway, while after applying the numerical study. Was enough fresh air for passengers inside the train and stationswas recommended [12]. Juraeva et al. (2013) developed a numerical model, the k-ε model, to reduce the necessary heat and improve the air quality inside the trains. He found that if the condenser inlet air temperature is above 45°C, the air conditioner is likely to face high-pressure failure. And the failure of the air conditioning in trains leads to heatstroke and syncope in passengers during the summer. So, the purpose of calculating the air flow rate is to maintain suitable ambient conditions throughout the stations [13].

3. Methodology

3.1. Model Description of Station

The studied length of Cairo Metro Line No. 3 extends from Attaba station to Abbassia station with a total length of 4.3 km and comprises five underground stations (Attaba-BabEl-Sharia -El-Geish -Abdou Pasha- Abbassia) as shown in Figure 1. In this paper, the ventilation design is limited to 4.3km length of the tunnel for the five stations (Attaba station to Abbassia station) as shown in Figure 2. In addition, the ventilation rate system and numerical simulation of airflow distribution inside the stations can be designed and calculated under the following tunnel conditions: dry bulb temperature of 35°C - 38°C, relative humidity o 31%, and specific volume of 0.90 m^3/kg.

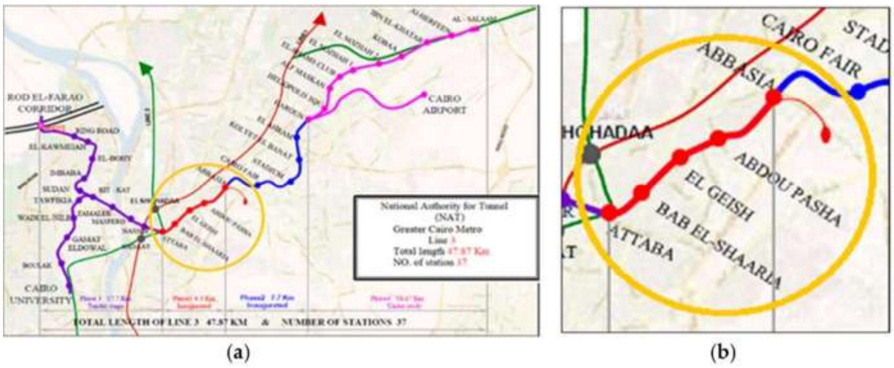

Figure 1. *General layout of Greater Cairo Metro Line No. 3 (phase No. 1) (b) The part under study [6].*

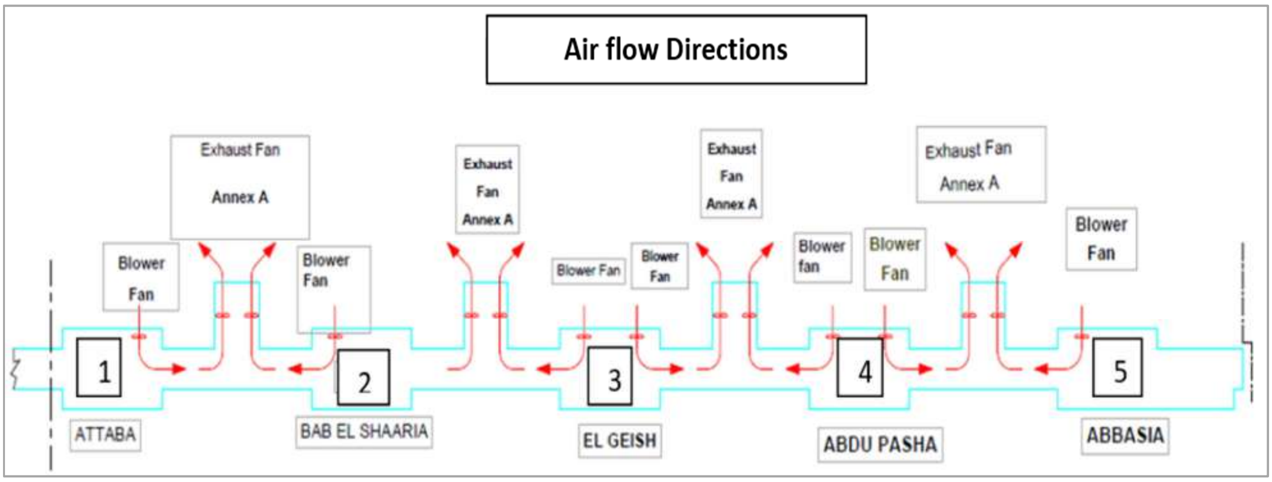

Figure 2. *A side section of the tunnel and stations for the part under study.*

Figure 3 illustrates the 3D model geometry of the tunnel and stations, as described below:

1) Three levels (platform, intermediate, and ticket)
2) A ticket window
3) Stairs with three levels
4) Exit door

The air flow rate in this study has been calculated to investigate the time needed in case there is not enough fresh air for passengers inside the station. The average number of passengers was assumed to be 1000, divided into two trains [6].

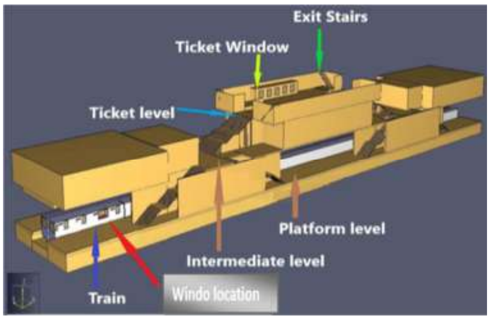

Figure 3. *3D model geometry of a train and station.*

3.2. Air Treatment and Improvement System of Train and Stations

The estimation of the air improvement system will have to be realized according to design criteria and the following technical specifications: Inside the tunnel, the maximum ambient air temperature will be 5°C higher than the outside temperature due to the required airflows and cooling capacity. The volume of the stations shall be treated with a central air conditioning system, including several air-handling units (AHU) connected to chilled water units [6]. The air treatment of ventilation systems and stations is explained below.

3.2.1. Ventilation Systems

In Cairo Metro Line No. 3, the ventilation system in the trains is by means of fans that pump fresh air (a blower fan) inside the tunnel. Fresh air is drawn directly through the air conditioning inside the train. An auxiliary fan may be used in a short duct to increase the air velocity near the face and improve cleaning efficiency. The contaminated air is drawn out by an exhaust fan [6, 14].

The different air flow directions when trains enter and leave the station are shown in Figure 4. When the train is moving, positive pressure is realized at the front by pushing air, and negative pressure is felt at the rear due to the lack of air. When the train enters the station, air in the tunnel will be pushed into the station, and when it leaves the station, air in the station will be sucked into the tunnels to fill the vacuum zone behind trains [15, 16].

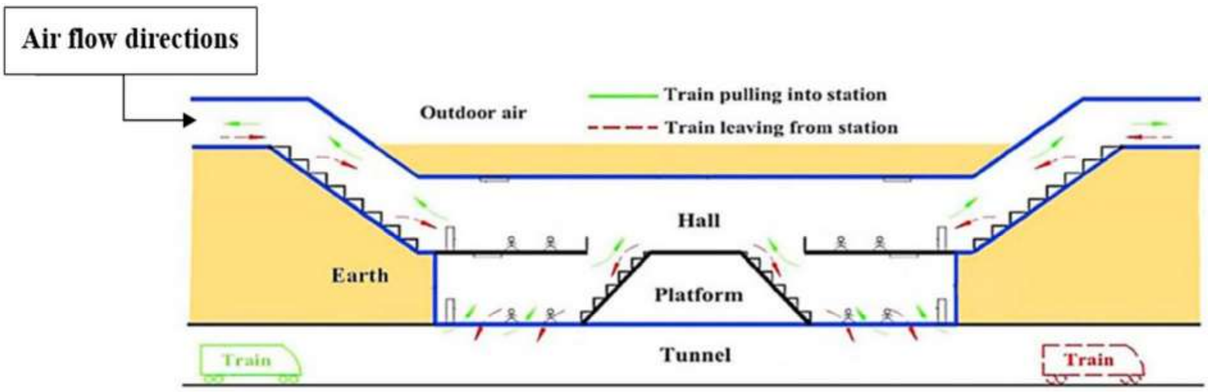

Figure 4. *Air flow directions schematic of the piston effect in Cairo metro line No.3 station.*

3.2.2. Ventilation Systems in Stations

The purpose of the air treatment and improvement system is to maintain suitable ambient conditions throughout the stations. The volume of the stations shall be treated with a central air conditioning system, including several air handling units (AHU) connected to chilled water units [6].

The central air-conditioning system is done by two methods. The first method is chilled water production units. The chilled water production units cool the water to a temperature of 7°C. It is pushed into air handling units and fan cooling units through pumps, and the network is connected to the insulated pipes. The second method is air handling units (AHU) and fan cooling units (FCU) by heat exchange between chilled water and air, as shown in Figure 5.

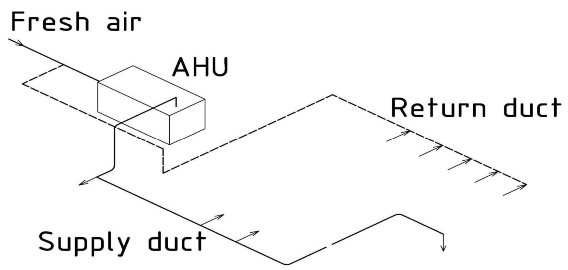

Figure 5. *Air direction network for a stations.*

From Figure 5, it can be noticed that the air is cooled in air handling units (AHU) and fan cooling units (FCU) by heat exchange between chilled water and air. The air is distributed through a duct network to the places where the passengers and the technical rooms are located. The ventilation of the ticket hall level is covered by two air handling units (AHU). After intermediate-level ventilation is covered by two air handling units (AHU), platform-level ventilation is covered by four air handling units (AHU). A part of the air will be rehandled and chilled again after filtration and mixing with outside new air (50% of the spent air will be rehandled and 50 % of the outside new air will be re-handled).

The primary air return and improvement system is a common form used in stations in most countries and is illustrated in Figure 6. [17]. There are some significant difficulties that can impact the energy efficiency of these systems when used in underground metro stations (UMSs): 1) the effect of train-induced airflow on heating, ventilation, and air conditioning HVAC loads; 2) a high percentage of energy consumption on moving mediums, including both air and water, in the system as a result of the large volume of stations; and 3) potential influential factors, such as the outdoor environment and occupancy level, affecting the system's performance.

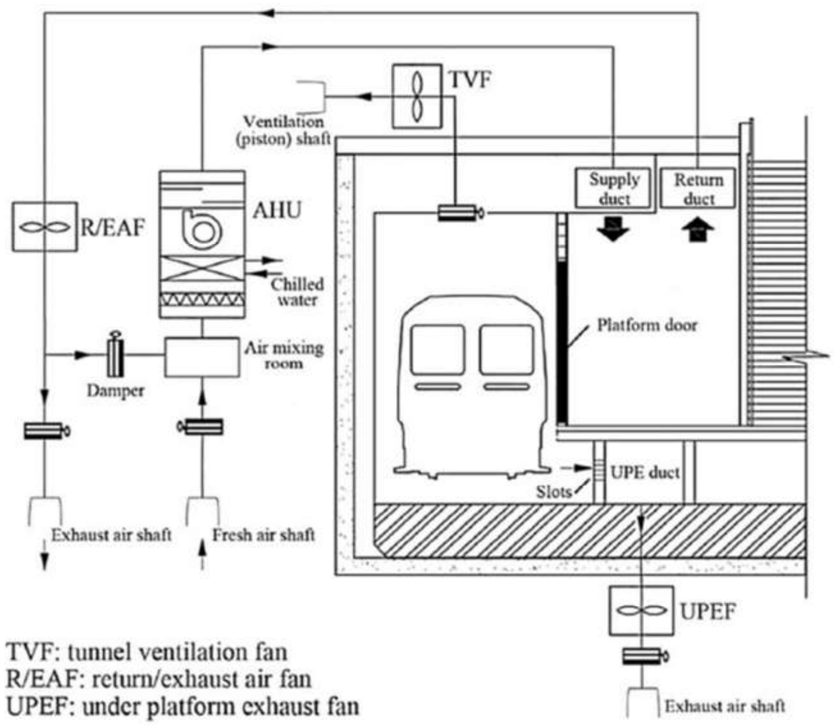

Figure 6. *Schematic diagram of a typical heating, ventilation, and air conditioning system in underground metro stations [17].*

From Figure 6, it can be seen that returning the hot air back to the station through cooling reduces the process of excess heat in the station through the cooling system of the outside air. There are factors that can affect the air entering the station that are overcome by the cooling and air conditioning systems in the primary air return and improvement system.

4. Results and Discussions

The ventilation rate is calculated to remove a certain amount of heat and improve air quality inside metro stations. The air flow rate in the stations is drawn from the atmosphere by blowing fans. The efficiency of the fans has to be superior to 70% in the normal running direction. The rotation speed of the fans shall range from 750 to 1480 r.p.m. The diameter of fans has to range from 2 m to 2.6 m for air exhaust fans and tunnel air blowing fans [6].

4.1. Air Flow Rate Required for Trains

The condenser inlet air temperature is above 45°C, the air conditioner is likely to face high-pressure failure. The failure of the air conditioning in trains leads to heatstroke and syncope in passengers during the summer. So, the required air flow rate for trains to reduce the amount of heat can be calculated using Equation (1) affiliated with the Ansys Fluent program. The difference in enthalpy between air in its initial conditions and its final state, to calculate the air flow rate Q required in trains, is equal to (Δ_i 0.0019 kwh/m^3) [6, 13]. Also, the heat released D, kw by train, passengers, lighting, and solar heat gain in trains has been obtained from the data of the NAT. A comparison of the results of this investigation and the actual data used by the NAT to calculate the required air flow rate, Q, in trains is given in Table 1.

$$Q = \frac{D}{\Delta_i} \quad (1)$$

Table 1. *Air flow rate required in trains a comparison of the results with the actual data used by the NAT.*

Heat released (D), kw [6]	Results of this investigation for air flow rate (Q)		Actual data from the NAT for air flow rate (Q)	
	m^3/h	m^3/s	m^3/h	m^3/s
565	297368.42	82.6	300526.31	83.48
185	97368.42	27.04	98947.36	27.48
2.15	1131.57	0.31	1052.63	0.29
7.34	3863.15	1.07	3052.63	0.85
Total air flow rate	399731.56	111.02	403578.93	112.1

From Table 1, it is noticed that the air flow rate required resulting from the investigation, which has been calculated, is 111.02 m^3/s. This value is acceptable when compared with the actual data from the NAT for an air flow rate of 112.1 m^3/s. This quantity is suitable for providing enough fresh air for passengers inside the subway and relieving a certain amount of heat. The air flow rate in the trains is drawn from the atmosphere by blowing fans. Additionally, cooling for the train should be provided by cooling the tunnels within which it operates. Fresh air is drawn directly through the air conditioning inside the train.

Figure 7. illustrates the relation between heat released D, kw, and the required air flow rate (Q, m^3/s) in trains with a comparison of the data used by the NAT.

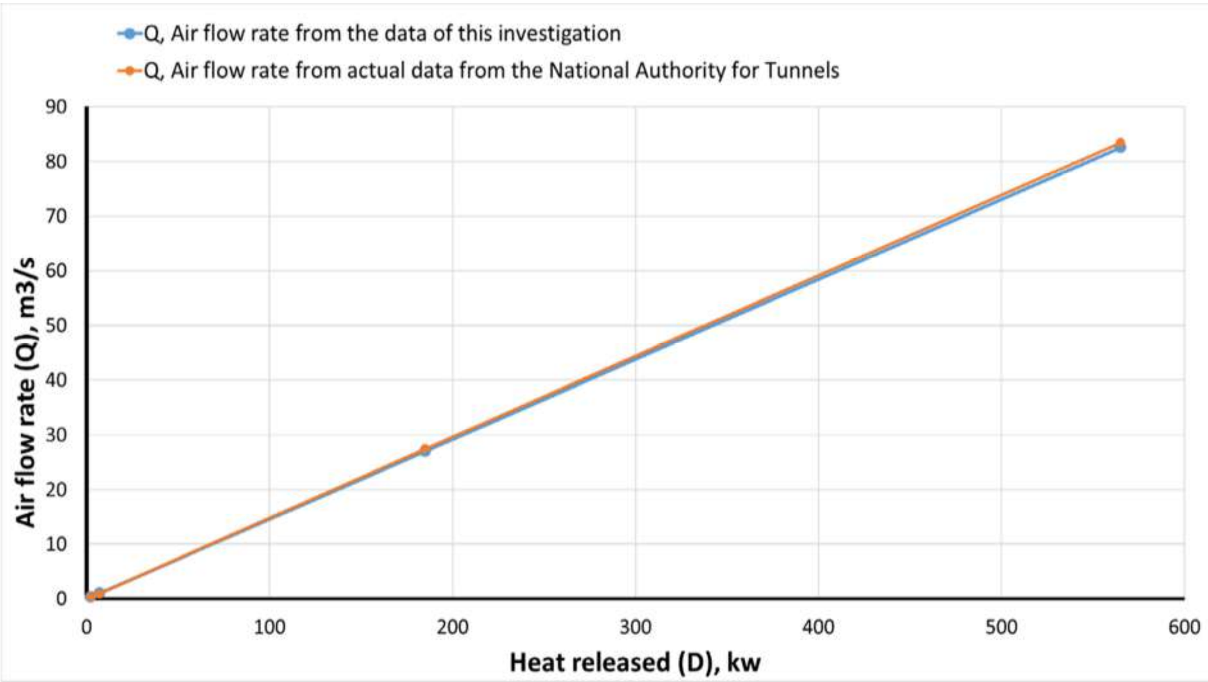

Figure 7. *Air flow rate in train of this investigation and the National Authority for Tunnels.*

From Figure 7, it is noticed that the values resulting from the current study to calculate the air flow rate required to ventilate the train are similar to the actual data from the NAT for air flow rate.

Air flow rate scenarios in the Cairo Metro at platform level. in the case of a train on the platform. Air conditioning equipment at the platform level is run, and ventilation fans at other station levels are run. Also, tunnel supply fans located at station ends are stopped. Fans in the intermediate shaft are operated in a "push-pull" mode (one side is in supply mode while the other is in exhaust mode), as represented in Figure 8.

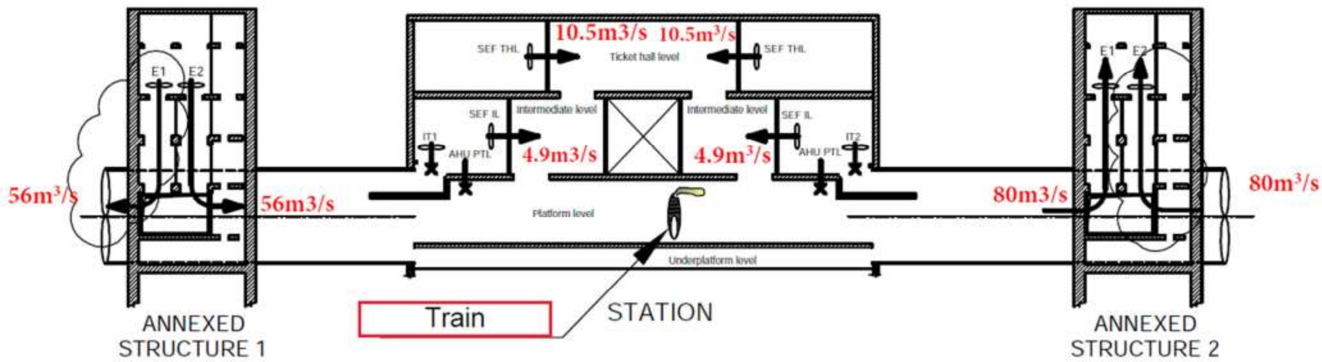

Figure 8. *Scenario of air flow rate scenarios in Cairo Metro at platform level.*

From Figure 8, it is noticed that when there is a train on the platform, fans on the intermediate shaft are operated in the "push-pull" mode (one side in the supply mode and the other in the exhaust mode). The tunnel supply fans at the ends of the station are also stopped to save energy and air quantities. An air flow rate of 80 m^3/s is pumped by pumping fans inside the station. In addition, there is air flow at intermediate level at 4.9 m^3/s and at ticket hall level at 10.5 m^3/s.

4.2. Air Flow Rate Required for Stations

The required air flow rate Q at stations on Cairo Metro Line No.3 can be calculated using Equation (1). The difference in enthalpy between air in its initial conditions and its final state has been used to calculate the air flow rate Q required in stations. It is equal to (Δ_i, 4.84 kcal/m^3 which corresponds to 0.005627575 kwh/m^3) [6, 13]. Also, the heat released (D, kw) was obtained from the data of the NAT at ticket hall level, intermediate level, and platform level. It is used to calculate the air flow rate required from Attaba station to Abbassia station, with a total length of 4.3km.

Table 2 gives a comparison of the air flow rate (Q, m^3/s) results of this investigation and the actual data used by the NAT. Cairo Metro Line No.3, from Attaba station to Abbassia station, has a total length of 4.3 km and comprises 5 underground stations (Attaba-Bab El-Sharia -El-Geish -Abdou Pasha- Abbassia). In this table, distinctions are made between the air flow of each station.

Table 2. *Calculated air flow rate and the actual data used by the NAT to calculate for stations.*

Stations		**Heat released (D), kw [6]**	**Results of this investigation for air flow rate (Q)**		**Actual data from NAT for air flow rate (Q)**	
			m^3/h	**m^3/s**	**m^3/h**	**m^3/s**
Attaba	At ticket hall level	106	18835.82	5.23	27035	7.5
	Intermediate level	191	33940.01	9.42	42638	11.84
	Platform level	506	89914.39	24.97	92930	25.81
Bab El-Shaaria	At ticket hall level	131	23278.23	6.46	29277	8.13
	Intermediate level	122	21678.96	6.02	27378	7.605
	Platform level	445	79074.91	21.96	81736	22.70
El Geish	At ticket hall level	123	21856.66	6.07	27855	7.73
	Intermediate level	124	22034.35	6.12	27733	7.7
	Platform level	460	81740.35	22.7	84934	23.59
Abdou-Pasha	At ticket hall level	146	25943.67	7.20	31942	8.87
	Intermediate level	142	25232.89	7.00	30931	8.59
	Platform level	470	83517.32	23.19	86888	24.13
Abbassia	At ticket hall level	229	40693.02	11.30	52690	14.63
	Intermediate level	162	28786.82	7.99	36785	10.21
	Platform level	445	79074.91	21.96	82269	22.85

From Table 2, it is found that the highest air flow rate Q for Attaba station is 24.97m^3/s at ticket hall level, and the lowest air flow rate is 5.23 m^3/s at platform level. This value is acceptable in comparison to the actual data from the NAT for an air flow rate of 25.81 m^3/s at ticket hall level, and the lowest air flow rate is 7.5 m^3/s at platform level. These quantities are suitable for removing a certain amount of heat and improve air quality inside metro stations. The air flow rate in the stations is drawn from the atmosphere by blowing fans. Therefore, a CFD program was applied to predict the appropriate amounts of air to reduce the heat. In addition, lower energy consumption and high fan efficiency reduce the energy consumed by the fans and reduce the calculation time in the solution.

Figure 9. illustrates the relation between heat released D, kw, and the required air flow rate Q, m^3/s for the five stations

from Attaba to Abbassia. The figure compares the results of the current study with the data used by the NAT. The compared data of the five stations include the three levels: Ticket Hall level, Intermediate level, and Platform level.

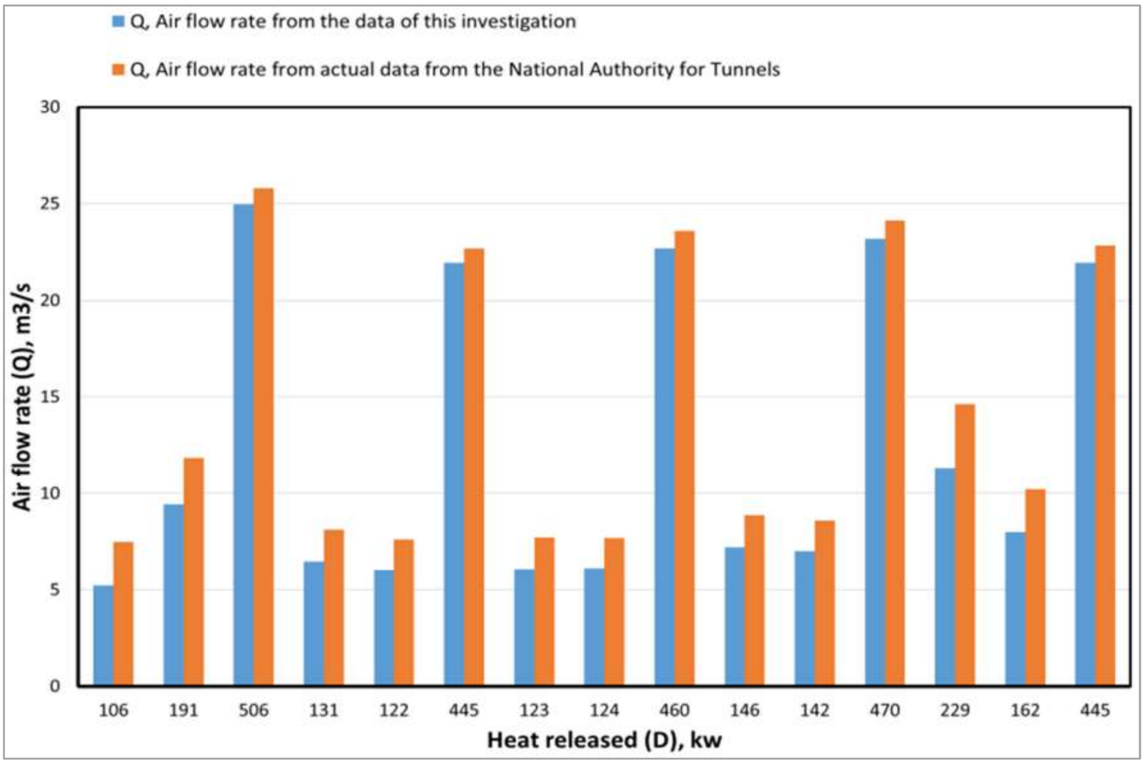

Figure 9. *Air flow rate required in stations from the results of this investigation and the data of National Authority for Tunnels.*

From Figure 9, it can be seen that the values resulting from the current study to calculate the air flow rate required to ventilate the stations are similar to the actual data from the NAT. Therefore, it follows that this calculation method can be applied to different ventilation conditions and different dimensions of an underground mine or tunnel. Also, this calculation can be used to predict the ventilation rate required to remove and mitigate a certain amount of heat and supply enough fresh air for passengers inside the subway.

4.3. The Required Air Flow Rate in Shopping Centers at Attaba and Abbassia Stations

The required air flow rate Q can be calculated using the same Equation (1), as seen in (section 4.1). The difference in enthalpy between air in its initial conditions and its final state has been used to calculate the air flow rate Q required in stations. This difference is equal to (Δ_i, 4.84 kcal/m^3 which corresponds to 0.005627575 kwh/m^3) [6]. Also, the heat released (D, kw) was obtained from the data of the NAT for people at base ticket hall level, escalators, lighting, and people staying in shopping center in stations for Attaba station and Abbassia station.

Table 3 gives the results of the air flow rate, Q, required in shopping centers on Cairo Metro Line No. 3 for Attaba station and Abbassia station.

Table 3. *Air flow rate required in shopping centers in Attaba and Abbassia.*

Station	Shopping center	Heat load in station, kw [6]	Results of this investigation for air flow rate (Q)	
			m^3/h	m^3/s
Attaba	People calories load base ticket hall level	70	12438.76	3.45
	Escalators	40	7107.86	1.97
	Lightings	22	3909.32	1.08
	People staying in shopping center	59	10484.09	2.92
Total		191	33940.03	9.42
Abbassia	People calories load base ticket hall level	29	5153.20	1.43
	Heat gained by hot air movement	72	12794.15	3.55
	Escalators	24	4264.71	1.18
	Lightings	24	4264.71	1.18
	People staying in shopping center	80	14215.72	3.94
Total		229	40692.49	11.28

From Table 3, it can be noticed that the required air flow in the shopping centers at Attaba and Abbassia stations is enough for passengers. Also, the total air flow rate for staff rooms and technical rooms ranges between 5153.2 m^3/h (1.43 m^3/s) and 7107.86 m^3/h (1.97 m^3/s) for ticket hall level and 4264.71 m^3/h (1.18 m^3/s) and 10484.09 m^3/h (2.92 m^3/s) for intermediate level. The efficiency of the fans has to be superior to 70% in the normal running direction. The rotation speed of the fans shall range from 750 to 1480 r.p.m.

5. Conclusions

From the present study, the followings can be concluded:

1) The CFD program has been applied to predict the appropriate amounts of air to reduce heat. In addition, lower energy consumption and high fan efficiency reduce the energy consumed by the fans and reduce the calculation time in the solution.
2) Fans on the intermediate shaft are operated in the "push-pull" mode (one side in the supply mode and the other in the exhaust mode) when there is a train on the platform. The tunnel supply fans at the ends of the station are also stopped to save energy and air quantities. An air flow rate of 80 m^3/s is pumped by a blower fan inside the station. In addition, there is air flow at intermediate level at 4.9 m^3/s and at ticket hall level at 10.5 m^3/s.
3) The required air flow rate, Q, in trains resulting from the investigation, which has been calculated, is 111.02 m^3/s. Also, the highest air flow rate for Attaba station is 24.97 m^3/s at ticket hall level, and the lowest air flow rate is 5.23 m^3/s at platform level.
4) The calculated values of the air flow rate required to ventilate the train and stations are similar to the actual data from the NAT. Therefore, the used program can be applied on different ventilation conditions and different dimensions of an underground mine or tunnel. Also, the calculation method can be applied to predict the ventilation rate required to remove and mitigate a certain amount of heat and supply enough fresh air for passengers inside the subway.
5) The predicted value using the program is almost the same as that from the NAT.

Nomenclature

Q: Is the air flow rate in m^3/s

D: Is heat released in kw

Δ_i, Is the difference in enthalpy between air its initial conditions and it is final state to calculate the air flow rate Q required in trains, is equal to 0.0019 kwh/m^3

Δ_i: The difference in enthalpy between air in its initial conditions and its final state, to calculate the air flow rate Q required in stations, is equal to (Δ_i, 4.84Kcal/ m^3 which corresponds to 0.005627575 kwh/m^3

AHU: Air Handling Unit

UMSs: Underground metro stations

HVAC: Heating, ventilation, and air conditioning

FCU: Fan Cooling Unit

SEF: THL, IL, PL, Smoke Exhaust Fan, Ticket Hall Level, Intermediate level, Platform Level

NAT: National Authority for Tunnels

SST: Shear stress transport

r.p.m: Revolutions per minute

ORCID

Sayed Ramadan Hamed: https://orcid.org/0000-0001-9526-9480

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

The authors would like to express their sincere gratitude to the National Authority of Cairo Metro Tunnels for their assistance and cooperation to complete this work.

References

[1] Kurnia, J. C., Sasmito, A. P., and A. S. Mujumdar. Simulation of a novel intermittent ventilation system for underground mines. Tunnelling and Underground Space Technology, 2014. 42: pp. 206-215.

[2] Ahn, J., Cho, S., and D. H. Chung. Development of a statistical analysis model to benchmark the energy use intensity of subway stations. Applied Energy, 2016. 179: pp. 488-496.

[3] Pan, S., Liu, Y., Xie, L., Wang, X., Yuan, Y., and X., Jia. A thermal comfort field study on subway passengers during air-conditioning season in Beijing. Sustainable Cities and Society, 2020. 61: pp. 102-218.

[4] Bogdanovská, G., Molnar, V., and G. Fedorko. Failure analysis of condensing units for refrigerators with refrigerant R134a, R404A. International Journal of Refrigeration, 2019. 100: pp. 208-219.

[5] Ampofo, F., Maidment, G., and J. Missenden. Underground railway environment in the UK Part 2: Investigation of heat load. Applied Thermal Engineering, 2004. 24 (5-6): pp. 633-645.

[6] National Authority for Tunnel. Tunnel from Attaba to Geish Shaft Monitoring Measurements. Contract N 49/Metro, Phase 1. National Authority for Tunnel: Cairo, Eqypt, 2010; pp. 270–271.

[7] Wang, F., Wang, M., He, S., Zhang, J., and Y. Deng. Computational study of effects of jet fans on the ventilation of a highway curved tunnel. Tunnelling and underground space technology, 2010. 25 (4): pp. 382-390.

[8] Liu, Z., Chen, G., Zhou, D., Wang, Z., and Z. Guo. Numerical investigation of the pressure and friction resistance of a high-speed subway train based on an overset mesh method. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2021. 235 (5): pp. 598-615.

[9] Zhang, Y. and Xiaofeng. Li. Numerical analysis on the condenser inlet air temperature of train-mounted air conditioner when a train stops in subway station tunnel. Sustainable Cities and Society, 2021. 69: pp. 10-79.

[10] Owais, M., Ahmed, A. S., Moussa, G. S., and A. A. Khalil. Integrating underground line design with existing public transportation systems to increase transit network connectivity: Case study in Greater Cairo. Expert Systems with Applications, 2021. 167: pp. 114-183.

[11] Wang, F., Wang, M., and Q. Wang. Numerical study of effects of deflected angles of jet fans on the normal ventilation in a curved tunnel. Tunnelling and Underground Space Technology, 2012. 31: pp. 80-85.

[12] Mohamed M. K., Mohamed S. H., and M. A. Ismail. NUMERICAL STUDY ON THE OPTIMIZATION OF SMOKE VENTILATION IN A SITUATION OF A TRAIN FIRE AT A SUBWAY STATION. Engineering Research Journal, 2020. 166: pp. 350-365.

[13] Juraeva, M., Ryu, K. J., Jeong, S. H., and D. J. Song. Influence of mechanical ventilation-shaft connecting location on subway tunnel ventilation performance. Journal of Wind Engineering and Industrial Aerodynamics, 2013. 119: pp. 114-120.

[14] Hartman, H. L., Mutmansky, J. M., Ramani, R. V., and Y. J. Wang. Mine ventilation and air conditioning. 2012: John Wiley & Sons. p. 752.

[15] Jiangyan, M., Zhang, X. in., Angui, L. i., Baoshun, D., Wenchao, L. v., Yongzhen, Guo., Wenrong, Z., and Lin. Huang. Analyses of the improvement of subway station thermal environment in northern severe cold regions. Building and environment, 2018. 143: pp. 579-590.

[16] Pan, S., Liu, J., Xie, J., Sun, Y., Cui, N., Zhang, L., and B. Zheng. A review of the piston effect in subway stations. Advances in Mechanical Engineering, 2013. 5: pp. 95-205.

[17] Yu, Y., You, S., Zhang, H., Ye, T., Wang, Y., and S. Wei. A review on available energy saving strategies for heating, ventilation and air conditioning in underground metro stations. Renewable and Sustainable Energy Reviews, 2021. 141: pp. 110-788.