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CFD Simulation to Study the Effect of Ambient Temperature on the Ventilation in a Metro Tunnel

Yousif Naif Almutai, Yajue Wu

Abstract**—**In larger cities worldwide, mass transportation systems, including underground systems, have grown to account for the majority of travel in those settings. Underground networks are vulnerable to fires, however, endangering travellers' safety, with various examples of fire outbreaks in this setting. This study aims to increase knowledge of the impacts of extreme climatic conditions on fires, including the role of the high ambient temperatures experienced in Middle Eastern countries and specifically in Saudi Arabia. This is an element that is not always included when assessments of fire safety are made (considering visibility, temperatures, and flows of smoke). This paper focuses on a tunnel within Riyadh's underground system as a case study and includes simulations based on computational fluid dynamics using ANSYS Fluent, which investigates the impact of various ventilation systems while identifying smoke density, speed, pressure and temperatures within this tunnel.

Keywords**—**Fire, subway tunnel, CFD, ventilation, smoke concentration, harsh weather.

I. INTRODUCTION AND LITERATURE REVIEW

EFFICIENT ventilation is recognized as an essential factor within underground transport systems, and its performance plays a basic role in the way in which certain events unfold, such as in the case of fire, or biological/chemical attack, with large numbers of people being injured or killed in previously-documented events of this type [1]. Tunnel fires have the potential to cause far more severe outcomes compared to fires occurring outdoors, due to the restricted space to move and increased smoke density.

From statistical evidence, 85% of injuries in underground transport system fires are caused by heat and smoke toxicity [2]. The outbreak of fire leads to the production of strong heat and toxic gases which can cause harm to those unable to exit from the tunnel. Globally, various serious fires and other incidents have taken place in transportation tunnels.

The most severe case of a tunnel fire was recorded in 1995 in Azerbaijan's capital city, Baku. This incident led to the death of 558 people, with a further 269 suffering injury. Another fire, in South Korea, at Daegu's Jungangno Station, caused 200 deaths and 150 injuries within a very short space of time [3].

Underground fires have been investigated extensively in the literature, both experimentally and based on numerical approaches [4]. Fires and their impacts on the environment in tunnels require management and this is generally done through ventilation systems and the way in which the tunnel is designed. Approaches to ventilation in fires vary by country, aiming at the minimum to prevent backlayering of smoke at the stage at which the tunnel is self-evacuated [5]. Critical velocity is the key factor in achieving this, and represents the lowest velocity needed to stop the spread of smoke against ventilated air flowing longitudinally in the case of a fire in the tunnel [6]. Critical velocity is dependent upon the size of the fire, and therefore the rate at which it releases heat, slope, and the geometrical dimensions of the relevant section of the tunnel and is applied in defining the specifications for the inlet fan to manage backlayering smoke which might arise from a fire and thus maintain safe conditions in the evacuation pathway [7].

Experimental work demonstrated that critical velocity occurs in direct proportion to one-third power of the Heat Release Rate (HRR) [8]. In the work by Wu and Bakar, critical velocity was investigated in five sections of tunnel of identical heights but varying widths, though experimental work and numerical simulations, and suggested that geometric form and critical velocity were correlated, allowing for prediction of critical velocity [9].

Inappropriate ventilation systems lead to less effective management of smoke spreading from a fire. A commonly utilized design approach for underground tunnels currently is Pull-Push Ventilation, utilising fans at each tunnel end, operating at the same time to introduce fresh air into the tunnel's inlet, and remove smoke through the outlet at the other end [10].

Fire safety in tunnels has been much researched globally. Ingason [11] conducted four large experimental investigations within an unoccupied Norwegian tunnel, measuring concentration of CO_2 and CO, as well as radiation, air speeds and temperatures. Experiments in full-scale tunnels are rare however, because of the significant cost incurred, as well as challenges in the organizing and gaining approval for such tests [12].

A more recent technique which is increasingly applied uses Computational Fluid Dynamics (CFD) to assess ventilation approaches in various built settings such as office buildings, healthcare facilities, museum buildings and residential buildings, for example [13].

A recent experimental investigation [3] looked at impacts from ventilation on flows of smoke for fires in tunnels and identified significant influence on smoke distribution from both vertical ventilation and ambient temperatures. At decreased ambient temperatures, smoke spread at a faster rate and over a shorter period. External environmental conditions significantly

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impact the conditions for smoke to disperse within underground systems, with a stable connection between the air within the underground and external air being highly significant. Where the air externally is hotter than the internal atmosphere, occurring particularly in springtime and at the start of summer, temperature inversion means that the naturally-occurring internal-external air exchange is poor, with poor air flows within the network as a consequence. This allows gases to disperse only weakly [14].

As previously stated, existing work forms an extensive and useful theoretical basis for assessing mechanical ventilation systems, assisted by knowledge of the velocities needed to allow for effective evacuations. Most work previously conducted has investigated fires in cooler ambient conditions, such as those occurring in Eastern Asian or Western European continent [3], [11].

Parameters of climate, including harsh surrounding temperatures, are frequently not included in fire safety assessment. With the majority of research being conducted in the western world which consider a pleasant ambient temperature which often does not exceed 30 °C; therefore, there has been a comparatively small focus on those variables which might differ between the climates where research was conducted and those where it might be applied. The ambient temperatures found in more extreme climates could therefore be significant for the internal environment of a tunnel, meaning that safety is affected for travellers and firefighting teams.

Based on the above, this study investigates the impacts of extreme climate as presented in Saudi Arabia on tunnel ventilation, modelling this using ANSYS Fluent.

II. NUMERICAL MODELLING

A. Governing Equations

A 3D CFD simulation was done by ANSYS Fluent, using Reynolds Average Navier Stokes (RANS), turbulence model $(k-\epsilon)$ standard wall function to model the turbulence effects, and energy equation to predict the temperature distribution inside the tunnel.

Some assumptions were added to our model to simplify it as [15]:

- Incompressible flow because the compressibility effect can be neglected in the ventilation application.
- Using Boussinesq approximation to model the buoyancy-driven flow.
- Fire Source modeling by Volumetric Heat Source (VHS) with certain fire size, heat flux, and smoke generation rate.
- Neglecting the air leakage from the tunnel, and the viscous heating at the tunnel walls.

By using the previous assumptions, a closed system of equations for the mathematical model is shown as follows:

Continuity Equation (Conservation of mass)

$$\nabla.\vec{u} = 0 \qquad (1)$$

Momentum Equation (Conservation of momentum):

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \vec{u}.\nabla\vec{u}\right) = -\nabla p + \nabla.\left((\mu+\mu_t)(\nabla\vec{u} + (\nabla\vec{u})^T)\right) + \rho g(1-\beta(T-T_o)) \qquad (2)$$

Energy Equation (Conservation of energy):

$$\rho\left(\frac{\partial T}{\partial t} + (\vec{u}.\nabla)T\right) = \nabla.\left(\left(\frac{k_{th}}{c_p} + \frac{\mu_t}{\sigma_t}\right)\nabla T\right) \qquad (3)$$

Turbulence Model $(k-\epsilon)$:

$$\rho\left(\frac{\partial k}{\partial t} + \nabla.(\vec{u}k)\right) = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + P_k + G_b - \rho\epsilon \qquad (4)$$

$$\rho\left(\frac{\partial \epsilon}{\partial t} + \nabla.(\vec{u}\epsilon)\right) = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\nabla \epsilon\right] + C_{1\epsilon}\frac{\epsilon}{k}(P_k + G_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} \qquad (5)$$

where μ_t is the eddy or turbulent viscosity; k_{th} is the thermal conductivity of air; $\sigma_k, \sigma_\epsilon, C_{1\epsilon}, C_{2\epsilon}, C_\mu$ are the constant coefficients.

B. Buoyancy Driven Flow (Boussinesq Approximation) [16]

The Boussinesq approximation is a way to solve thermal flow with small change of temperature, such as natural convection problems, without having to solve for the full compressible formulation of the Navier-Stokes equations.

$$\rho g = (\rho_0 + \Delta\rho)g = \rho_0 g - \rho_0\beta(T - T_0)g \qquad (6)$$

where $\beta = -\frac{1}{\rho_o}\left(\frac{\partial\rho}{\partial T}\right)_P \approx -\frac{1}{\rho_o}\left(\frac{\rho-\rho_o}{T-T_o}\right)$ is thermal expansion coefficient; ρ_0 is reference density = $1.225\,kg/m^3$; T_0 is reference temperature = 25 °C.

C. Geometry Modelling

In this study, the subway tunnel distance to be analysed was 20 m long between two station buildings with height and width as H = 3 m, W = 3 m, with a heat source in the tunnel ground with dimensions 1 m X 2 m; this layout is shown in Fig. 1, which shows an overall diagram of the tunnel model and boundary conditions.

D. Boundary and Initial Conditions

Boundary Conditions (BCs) for the tunnel are:

- Inlet: velocity inlet with a normal direction and magnitude equals velocity critical to avoid the back-layering with weather conditions (summer or winter) ambient temperature.
- Outlet: pressure outlet with atmospheric pressure with weather conditions (summer or winter) ambient temperature.
- Tunnel walls are no-slip, stationary, and adiabatic walls.
- Stations walls are modelled as symmetry BCs.
- Fire Source (Heat Release Rate) equals 5 MW.
- Average Smoke Production Rate equals 0.5 kg/s.

Initial Conditions (ICs) are:

- No smoke or zero smoke concentration inside the tunnel.
- Initial temperature 293 K or 20 °C.
- Initial zero velocities inside the tunnel.
- Initial zero-gauge pressure.

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- Initial turbulent kinetic energy ($k = 0.016\ m^2/s^2$)
- Initial turbulent dissipation rate ($\epsilon = 0.362\ m^2/s^3$).

E. Mesh Generation

ANSYS Fluent meshing tool was used to generate the mesh for all cases with clustering mesh near walls to obtain the accurate values near walls due to the boundary layer effect, Tetrahedron element was used to enable us to create the mesh for the complex geometry.

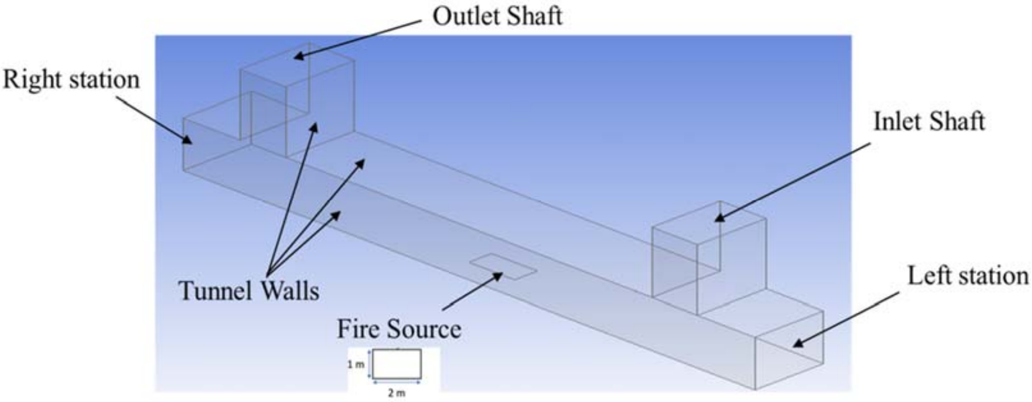

Fig. 1 Tunnel layout model

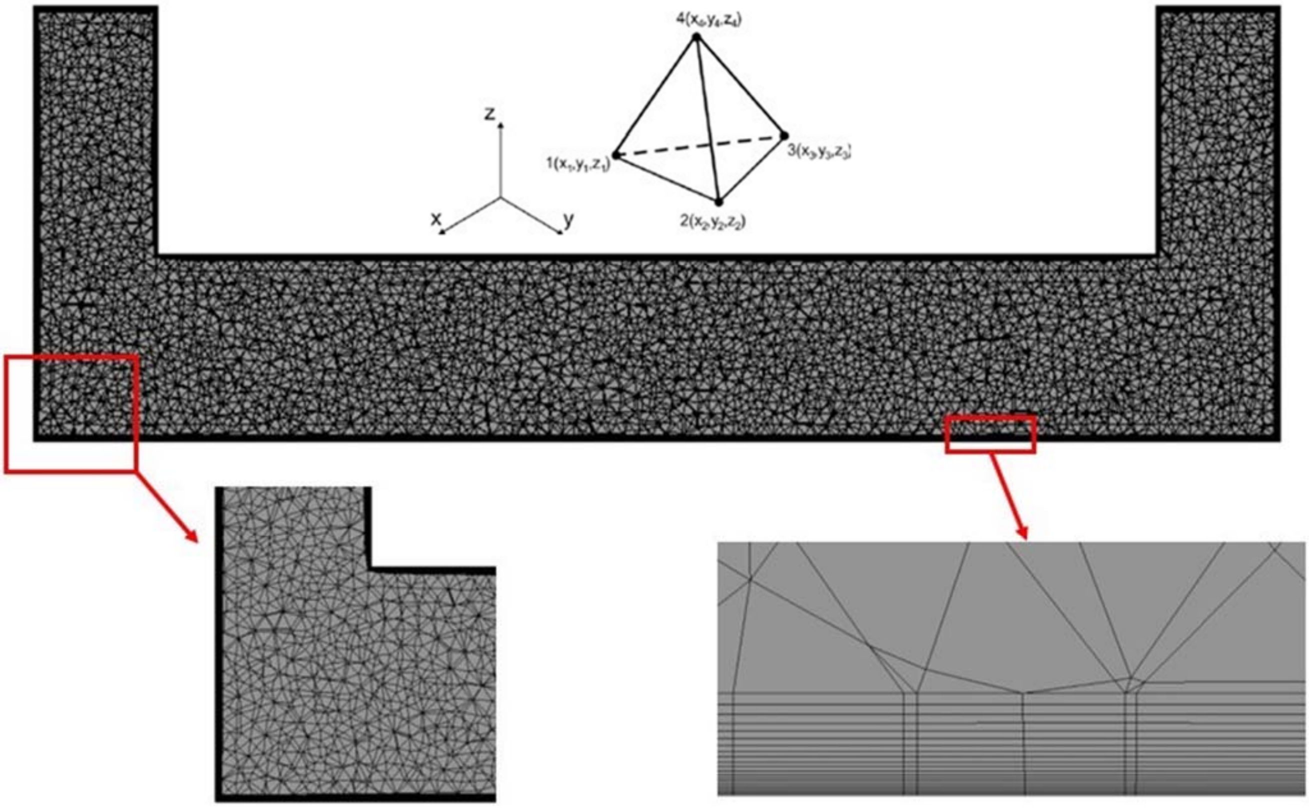

Fig. 2 Mesh generation with ANSYS meshing

F. Critical Velocity Calculation

A lot of experiments were done to study the effect of velocity critical on the smoke backlayering, some researchers used numerical methods to estimate the critical velocity by using FDS or ANSYS but also some used the experimental data to predict empirical relations [3].

$$V_c = K_1 K_g \left(\frac{gHQ}{\rho C_p A T_f}\right)^{\frac{1}{3}} \tag{7}$$

$$T_f = \left(\frac{Q}{\rho C_p A V_c}\right) + T \tag{8}$$

where V_c is the critical velocity (m/s); K_1 is the Froude number; K_g is the Grade Factor; g is the gravitational acceleration; H is

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the tunnel height; Q is the fire heat rate; ρ is the average density; C_p is the specific heat of air; A is the inlet duct area; T_f is the fire temperature; T is the ambient temperature.

K1 can be calculated from Table I. Kg can be calculated by graph shown in Fig. 3.

TABLE I
K1 RANGE WITH HEAT SOURCE VALUES [16]

Q (MW)	K_1
>100	0.606
90	0.62
70	0.64
50	0.68
30	0.74
<10	0.87

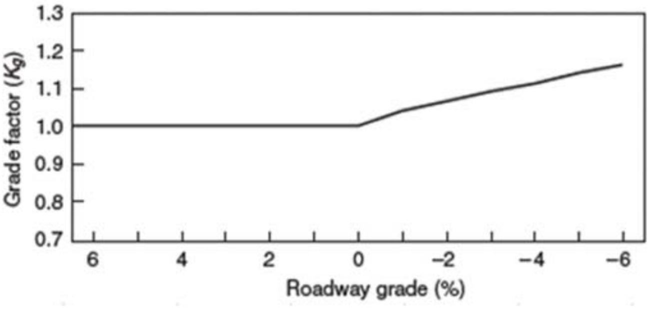

Fig. 3 Global factor Kg change with roadway grade (%) [16]

MATLAB was used to generate a code to estimate the critical velocity of which prevent the backlayering in this tunnel in both cases, summer and winter, as shown in Figs. 4 and 5. From these figures, after four iterations critical velocity and average fire temperature will be constants and did not change with values in Table II.

TABLE II
MATLAB CODE RESULTS FOR CRITICAL VELOCITY & AVERAGE FIRE TEMPERATURE (SUMMER AND WINTER)

Season	Winter (T_{amb} = 5°C)	Summer (T_{amb} = 50°C)
$v_c(m/s)$	2.35	2.35
T_f(°C)	120	185

ANSYS Fluent is used to check the critical velocity on smoke backlayering to make sure that critical velocity method accuracy.

Critical velocity has a large effect on the backlayering as in Fig. 6, the backlayering is clear, but in Fig. 7, the backlayering has vanished.

III. RESULTS

Distributions of smoke concertation, velocity, and temperature are studied in this research to predict the effect of summer and winter weather on the ventilation in the tunnel.

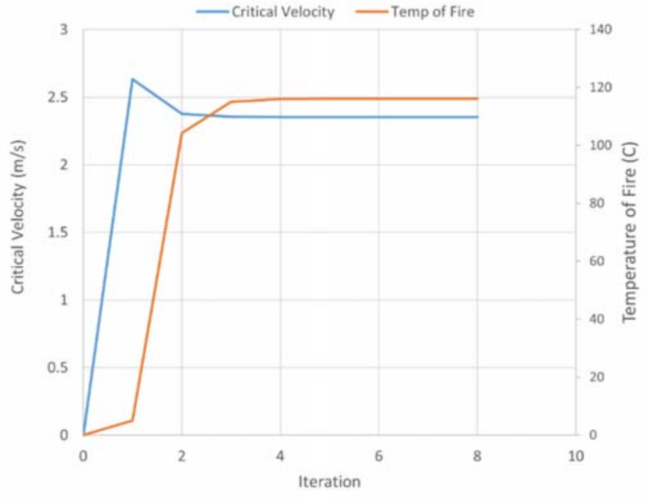

Fig. 4 Winter critical velocity and fire temperature change with iterations number

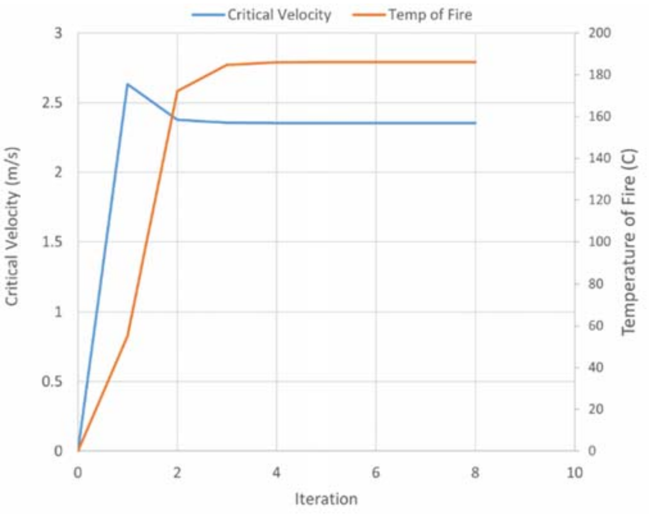

Fig. 5 Summer critical velocity and fire temperature change with iterations number

Three phases will be studied in this paper as:

A. First Case Results

1. Distribution of Smoke Concentration Inside Tunnel

Figs. 9 and 10 show the smoke concentration for case #1, where the ambient temperature has the only effect only on it, the summer case has the smother smoke concentration relative to the winter case.

2. Distribution of Temperature Contours inside Tunnel

From Figs. 11 and 12, it can be seen that the winter case has a lower average temperature inside the tunnel than the summer case.

3. Distribution of Velocity Contours inside Tunnel

From Figs. 13 and 14, it can be seen that winter fresh air has a significant effect on smoke particles motion than in the summer case.

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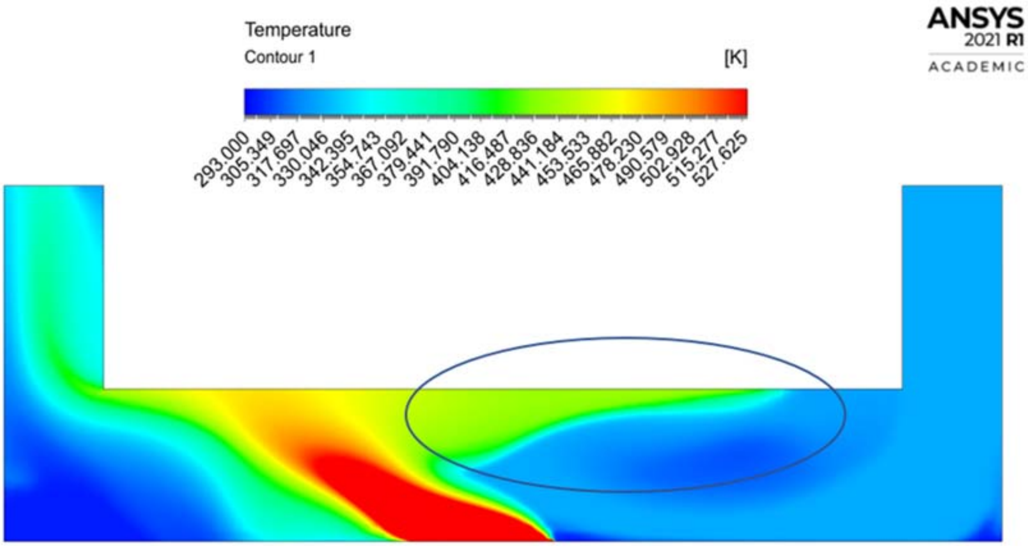


Fig. 6 Temperature contours with inlet fresh air velocity is less than critical velocity

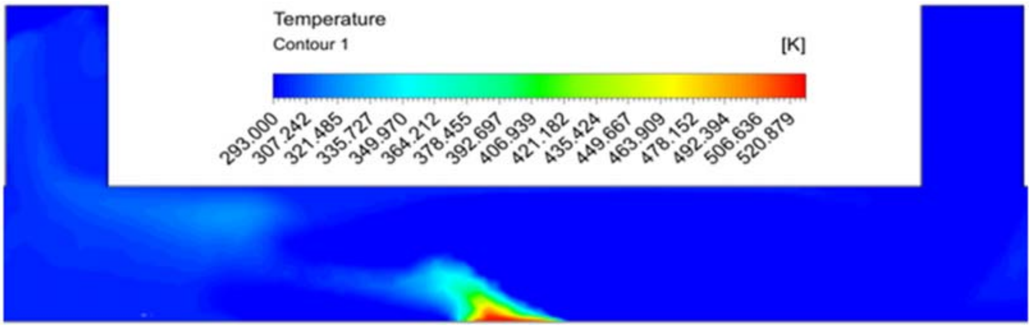
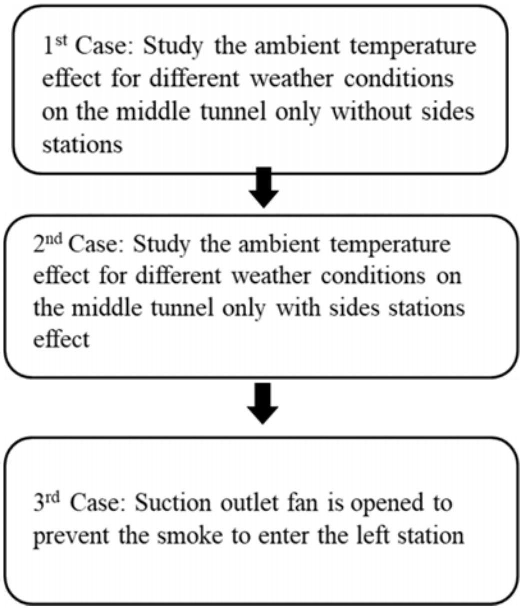


Fig. 7 Temperature contours with inlet fresh air velocity equals to critical velocity



1st Case: Study the ambient temperature effect for different weather conditions on the middle tunnel only without sides stations

2nd Case: Study the ambient temperature effect for different weather conditions on the middle tunnel only with sides stations effect

3rd Case: Suction outlet fan is opened to prevent the smoke to enter the left station

Fig. 8 Methodology of numerical simulation

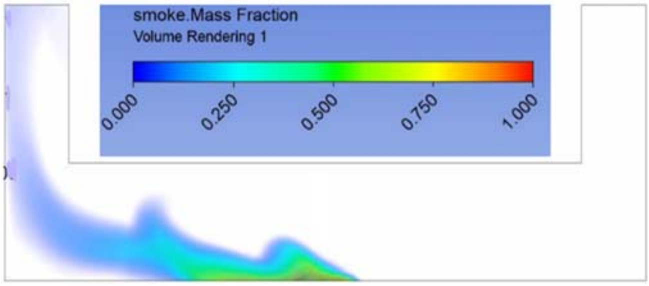


Fig. 9 Winter smoke concentration Case#1

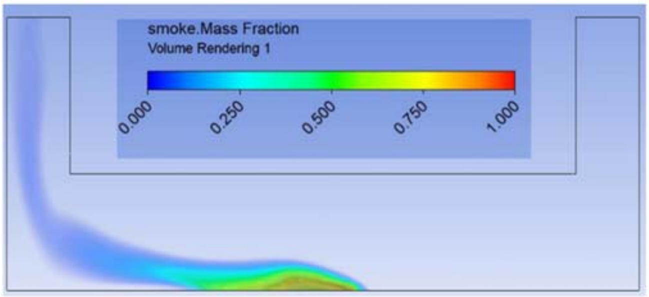


Fig. 10 Summer smoke concentration Case#1

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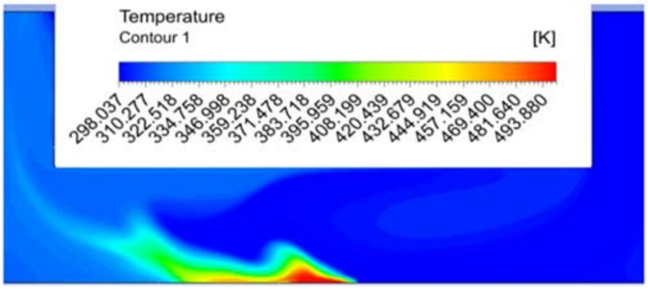

Fig. 11 Winter temperature contours Case#1

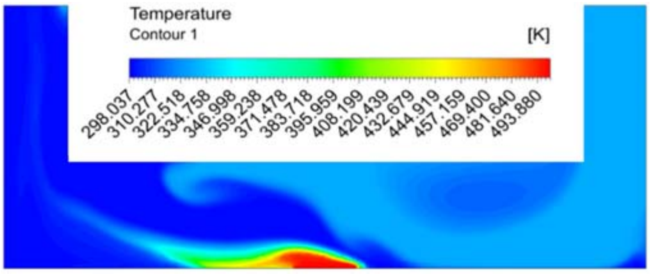

Fig. 12 Summer temperature contours Case#1

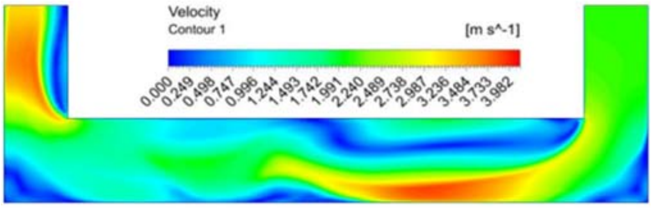

Fig. 13 Winter velocity contours Case#1

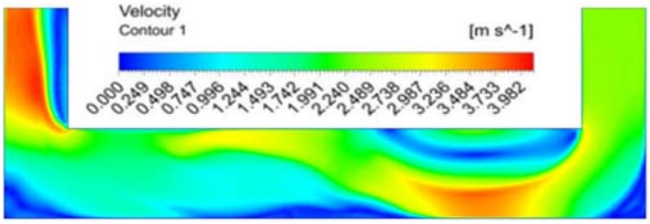

Fig. 14 Summer velocity contours Case#1

B. Second Case Results

1. Distribution of Smoke Concentration inside Tunnel

As shown in Figs. 15 and 16, smoke can enter the left station due to open stations without suction fan.

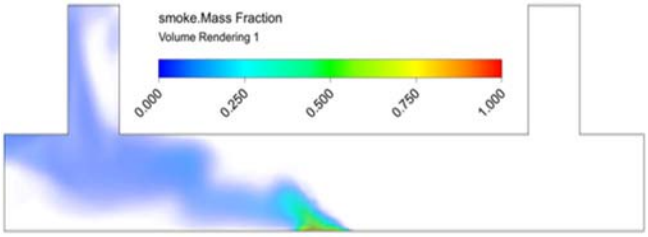

Fig. 15 Winter smoke concentration Case#2

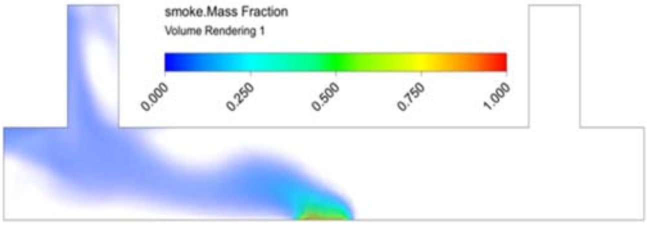

Fig. 16 Summer smoke concentration Case#2

2. Distribution of Temperature Contours inside Tunnel

From Figs. 17 and 18, it can be seen that the winter case has a lower average temperature inside the tunnel then the summer case, as in Case#1.

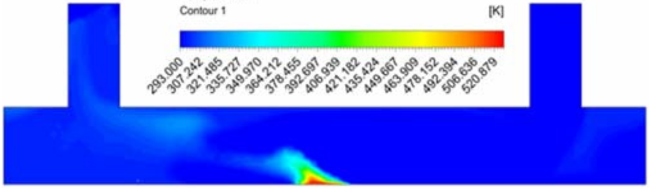

Fig. 17 Winter temperature contours Case#2

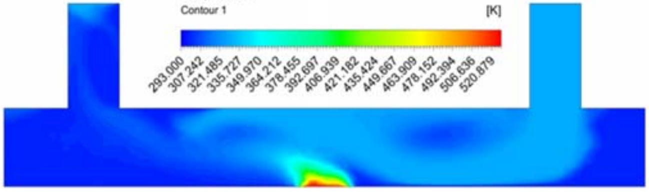

Fig. 18 Summer temperature contours Case#2

3. Distribution of Velocity Contours inside Tunnel

From Figs. 19 and 20, it can be seen that winter fresh air has a significant effect on smoke particles motion rather than in the summer case, as in Case#1.

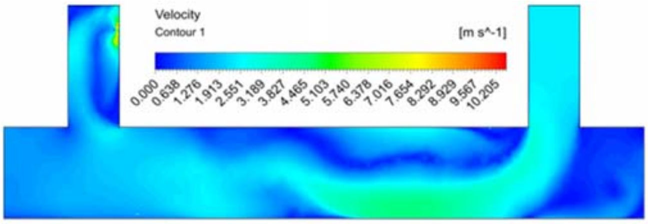

Fig. 19 Winter velocity contours Case#2

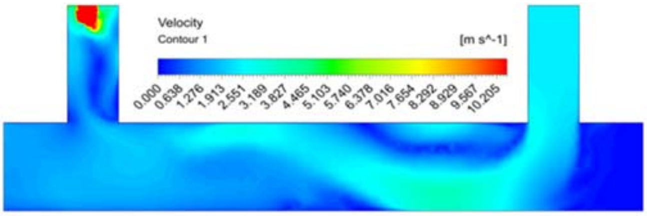

Fig. 20 Summer velocity contours Case#2

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C. Third Case Results

1. Distribution of Smoke Concentration inside Tunnel

As shown in Figs. 21 and 22, the smoke did not enter the left station due to the suction fan which is working to take the smoke outside the tunnel.

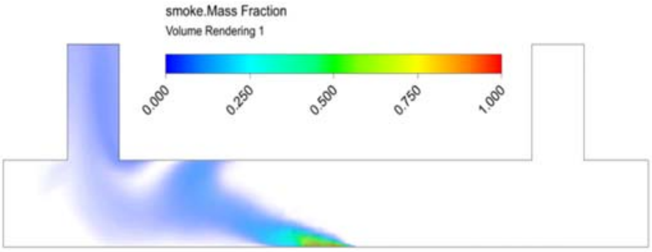

Fig. 21 Winter smoke concentration Case#3

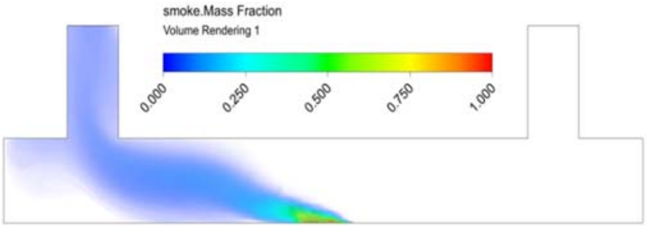

Fig. 22 Summer smoke concentration Case#3

2. Distribution of Temperature Distribution inside Tunnel

From Figs. 23 and 24, it can be seen that the winter case has a lower average temperature inside the tunnel then the summer case, as in Case#1 and Case#2.

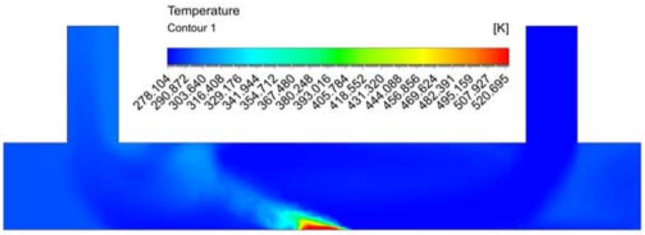

Fig. 23 Winter temperature contours Case#3

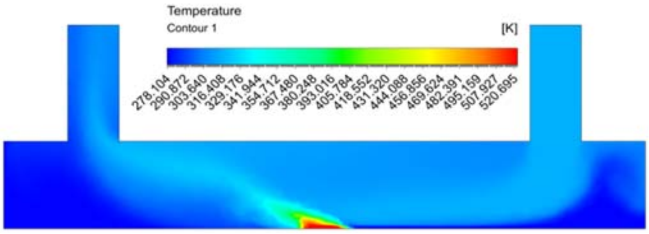

Fig. 24 Summer temperature contours Case#3

3. Distribution of Velocity Vectors inside Tunnel

Figs. 25 and 26 show that winter fresh air has a significant effect on smoke particles motion compared to the summer case, as in Case#1 and Case#2.

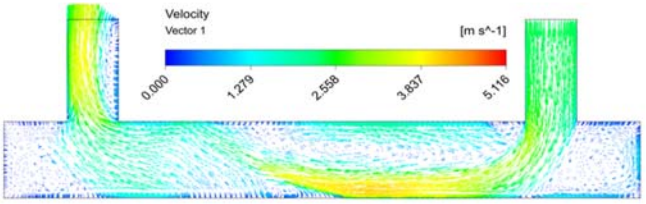

Fig. 25 Winter velocity vectors Case#3

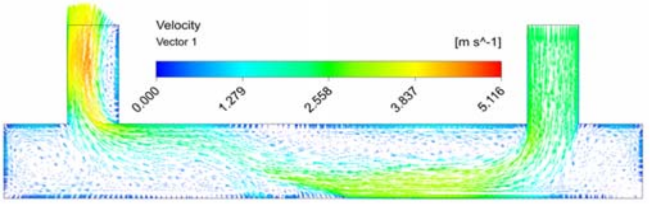

Fig. 26 Summer velocity vectors Case#3

IV. CONCLUSION

Ventilation in tunnels is the most challenging study in the ventilation field; as mentioned before, the main aim of this research is to improve our understanding of the effect of harsh weather in this field in the Middle East (ambient temperature), especially in Saudi Arabia.

Critical velocity has a significant effect on smoke backlayering in the tunnel with the effect of weather (summer and winter), smoke concentration is smoother in summer than in winter, winter has a lower average temperature in the tunnel than summer, also winter causes significant mixing for the flow field. Finally, the ambient temperature or weather has a significant effect on the ventilation and smoke concentration. The is result could help in providing accurate models of fire performance in academic and industrial spheres.

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