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Research Article

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF TEMPERATURE CHANGE DURING TUNNEL FIRES ON A MODEL

Ali Serdar GÜLTEK[1]*, Zeynep Düriye BİLGE[2]

[1]*Istanbul University, Vocational School of Technical Sciences, ISTANBUL;* ORCID:0000-0003-2869-086X
[2]*Yıldız Technical University, Department of Mechanical Engineering, ISTANBUL;* ORCID:0000-0003-0456-6573

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ABSTRACT

Fire incidents occur in the tunnels of various countries of the world. Depending on the tunnel geometry, traffic structure, and fire defense equipment, a large fire may cause people to die and cause damage to the tunnel structure. Threshold values for heat and toxic gas emissions that people would be exposed to a fire are defined in standards. To examine the change of the heat flux values that are defined in the standards with the heat release rate of the fire and the viability of the tenable environment during an evacuation in a tunnel fire, a model was created by reducing the dimensions of a tunnel by 1/12. Experimental studies and numerical studies carried out with the model in order to determine the instant that evacuation operation will start to impede and hazardous conditions dominate the fire scene and it is observed that results of both studies are in harmony.

Keywords: Tunnel fire, evacuation, tenable environment, FDS.

1. INTRODUCTION

Fire incidents occur in the tunnels of various countries of the world. When these fire incidents are examined, human losses and damage are experienced in different levels. Depending on the tunnel geometry, traffic structure, and fire defense equipment, a large fire may cause people to die and cause damage to the tunnel structure. Also, like the St. Gotthard tunnel incident that happened in the year 2001, fires cause economic losses that have a significant impact because major transport channels remain closed for long periods of time. The high heat energy which spanned from the 6-hour fire to the tunnel structure made St. Gotthard Tunnel unsafe for transportation in the following months and years.

Despite technological advances, hot and poisonous fumes in a tunnel can still not be extracted quickly and safely. Due to this inability, the structural damage to the tunnel ceiling coating cannot be reduced in the case of fire. Fixed and automatic extinguishing systems are not operated economically. Research efforts to overcome these difficulties and obstacles are being conducted by various institutions and groups all over the world.

* Corresponding Author/Sorumlu Yazar: e-mail/e-ileti: sgultek@istanbul.edu.tr, tel: (212) 473 70 70 / 18536

Programs have been implemented in different countries to investigate tunnel fires. In 1965, various sizes of petroleum fires were tested in the Ofenegg tunnel in Switzerland to investigate natural, longitudi nal and transverse ventilation systems. In 1980, fires on public transportation vehicles such as passenger cars and buses have been examined in a long highway tunnel in Japan. In 1985, burning experiments in railway wagons were carried out in Finland. Tests were carried out in an 183 m long tunnel. Between 1993 and 1995, 98 tests were conducted in a real tunnel in the Memorial Tunnel Fire Ventilation Test Program project in West Virginia, USA; project budget was 4 million US Dollars. In the European Union's FIRETUN 499 Fire Protection in Traffic Tunnels study with a budget of 6,600,000 Euros, researchers from 10 European countries conducted full-scale tests in real tunnels between 1990 and 1996. In these tests, fire propagation speed, temperature propagation gradients, smoke formation and propagation, amount of energy released, effect of ventilation systems, heating of tunnel coating materials have been examined. In the study of European Union's 11,000,000 Euros budget "UPTUN: cost-effective, sustainable and innovative upgrading methods for fire safety in existing tunnels", researchers from all over Europe examined options to increase fire safety in tunnel design to ensure sustainable transport between 2000-2006. They have published 45 reports on fire protection, fire detection, mitigation measures, human behavior, effects of fire to tunnel structure, improvement of existing tunnels, and reduction of socioeconomic damages. In 2003, heavy good vehicle (HGV) fires were investigated in the Runehamar tunnel in Norway. Heat release rates ranging from 70 MW to 200 MW were reached in the experiments. [1], [2]

Experimental investigation of tunnel fires is very costly and dangerous. Due to these two reasons, all around the world research and data collection activities are being carried out primarily through reduced scale tunnel models. This has led to the conduct of research activities both on the development of an efficient tunnel model and on the verification of data obtained from existing tunnel models.

H. Ingason [3] conducted experiments using a 1/10 scale model to obtain the data to calculate the heat release rate in a train compartment. The heat release rate and mass are scaled using the Froude number. Thermal inertia and radiation effects of the material were ignored and fire behavior on the surfaces of different materials was investigated by using fireproof gypsum panel, chipboard panel, and corrugated panel. JS Choi et al. [4] examined smoke propagation in the tunnel as a function of heat release rate of the fire, the change of the fire position in the tunnel. Experiments were conducted in a 1/20 scale tunnel. Lee and Ryou [5] studied the effect of different height-width ratios on fire smoke movement in different tunnels, although they have the same hydraulic diameter. The measurements made on the rectangular geometry test device of 1/20 scale and the comparisons of the calculations made with the "Fire Dynamics Simulator (FDS)" software. Roh et al. [6] investigated the effect of longitudinal ventilation on the rate of combustion and heat release rate in a tunnel environment. Experiments were conducted using n-heptane fuel in a 1/20 scale tunnel-shaped experimental setup. H. Xue et al. [7] carried out experiments in a 1/20 scale model tunnel with a height of 0.3 meters and a width of 0.9 meters in the laboratory environment and the gases generated from fires that had heat release rates of 3.15 kW and 4.75 kW. The air velocity in the tunnel were between 0.13 m/s to 0.61 m/s this change in velocity had occurred by changing the tunnel slope.

Research articles on tunnel safety from all around the world indicate that the selected scale for experimental modeling is concentrated between 1/10 and 1/20. Studies conducted on scales smaller than 1/20 tend to be more prone to inconsistency. [8], [9]

Ensuring safe evacuation of people during tunnel fires and preserving the structural integrity of the tunnel are the priorities of safe design of a tunnel. Therefore, threshold values of exposed heat and toxic gas are pointed out at tunneling standards The main objectives of the legal regulation in the tunnel fire are to prevent fire damage to the tunnel construction and to the existing equipment in the tunnel, to ensure that the users in the tunnel have sufficient time to evacuate and to protect the fire responders. Determination of tenable conditions is very important for these purposes.

NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways - 2014 version, provision 7.16.2 of the standard states that a tunnel fire must provide a tenable environment during evacuation [10]. As regards to this provision, in Appendix B of the same standard, the tenable environment is defined together with the heat, as well as the air quality. As stated in the standard, exposure to heat th reatens a person's life with hyperthermia, skin burns that form on the body surface and in the deep burns that occur in the respiratory system. This standard states values such as temperature rise resulting to acute psychological problems resulting from hyperthermia exposure, inability to move and inability to perform evacuation. These values can be used to model the effect of exposure to heat in the fire. As the humidity level in the breathing air goes below 10% injuries to respiratory system starts to occur. When the air temperature is 60 ^oC and is saturated with water vapor burns ay occur at the respiratory airways. The threshold value of human body skin that can withstand to radiant heat flux is in the order of 2.5 kW/m ^{2}. If the radiated heat flux is below this value, the skin may tolerate this exposure for more than 30 minutes. In this case, the effect on the time required for evacuation is limited. If the heat flux value exceeds the specified value, the minimum time required for skin burns to occur is reduced rapidly, depending on the following equation.

$$t = _{Irad} 4q^{(-1.36)} \quad (1)$$

In equation (1), (t_{Irad}) represents formation time of thermal burns to the skin that will result from radiation-induced heat (minute), and (q) is the radiant heat flux value in (kW/m^2).

The time-dependent exposure of a person exposed to radiation can be defined as a dosage. Equivalent dose (FED) (fractional equivalent dose) is valued as the heat flux exposure rate in a minute that will result as burns on the skin of the exposed person and is directly related with t_{Irad}. Radiation occurs with temperature. The level of radiation depends on the temperature and emissivities of smoke. Radiation is caused by both the smoke and the flame itself. The radiant heat tends to move in a certain direction so that warming still happens on parts of the body that are in contact with hot air even they are relatively low in temperature. The heat flux value of 2.5 kW/m ^{2} corresponds to the irradiation values of radiation source surface temperature that is about 200 ^oC. Radiation in the area near to the fire occurs with the flame itself, and the surrounding hot smoke contributes to this radiation. As you move away from the fire source, only the temperature of the smoke layer becomes the source of radiation hazard. In order to perform safe evacuation of all occupants, radiation level which leads to severe pain on the bare skin surface in a few minutes must be below the threshold value. This value is between 2 to 2.5 kW/m^2. Firefighters can withstand to heat flux value of 5 kW/m^2 for 7 minutes with their protective clothing. The time during which a firefighter intervenes by entering the enclosed space can carry out the operation is no longer than 30 minutes since it depends on the capacity of the air cylinder connected to the air breathing apparatus. Accordingly, a firefighter would perform only for 20 minutes as his or her breathing air capacity is limited, in this time restraint heat flux exposure value should not exceed 2 kW/m^2 so that responders would carry out their operations.

A model was created by reducing the dimensions of a tunnel by 1/12 scale to examine the change of the heat flux values defined in the standards with the heat release rate of the fire and the viability of the tenable environment during evacuation in a tunnel fire.

2. EXPERIMENTAL STUDY

An experimental setup and test process was designed to control and measure the temperature along the tunnel section according to the built model. The test setup consists of a 1/12 scale tunnel as shown in Figure 1 and a burner unit is mounted on this tunnel, 24 thermoresistors to measure temperature values, 1 gas analyzer, 1 pitot-pressure gauge, 1 weight-scale, 1 fan motor, 1 air velocity meter. Sensitivity values of the measuring instrument are listed in Table 1.

Table 1. Sensitivity values of measuring instruments that are used in test setup

Device	Sensitivity Range
Thermoresistor	± 1,3 °C
Gas analyzer	± 0,3 %
Pitot-pressure gauge	± 0,5 % Fs
Weight-scale	± 0,1% kg
Air velocity meter	± 0,2 m/s

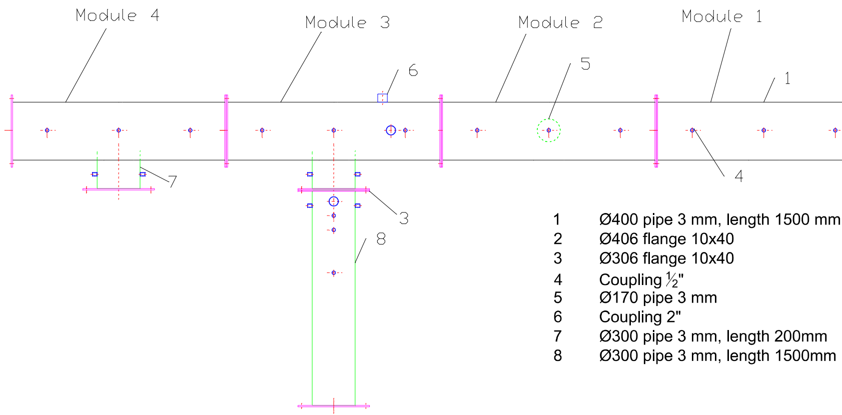


Figure 1. Top view of the assembly drawing of the tunnel model

Liquid petroleum gas (LPG) composed of 70% butane and 30% propane mixture was burned to obtain heat and combustion products. At the exit of the burner unit, the temperature versus time and temperature versus distance from fire center curves are obtained with temperature readings measured from 24 different locations such as tunnel evacuation entrance, midpoint of tunnel evacuation section. Experiments are finished as termination process initiated by cutting off gas flow when temperature value reaches 60 °C at a height that is equivalent of average human waist height at 1/12 scale.

3. NUMERICAL STUDY

Numerical studies have been performed in the Fire Dynamics Simulator software to be used for the Computational Fluid Dynamics (CFD) analysis to compare the data obtained from the experimental setup. In order to save computer time for CFD analysis, instead of using a single mesh for the atmospheric environment that defines the boundary conditions of the model and the tunnel model are designed as two separate zones. For this purpose, the model is divided into 9 separate meshes. Preliminary analysis was performed to determine the size of the cells to be placed in the mesh. For this analysis, a measure named as the characteristic diameter of the fire and shown in Eq. 2 was used [11].

$$D^* = \left(\frac{Q}{\rho_0 C_p T_0 \sqrt{g}}\right)^{2/5} \tag{2}$$

In this equation, ρ_0, C_p, T_0 are ambient air properties, Q is the heat release rate (kW), and g is acceleration of gravity(m/s^2). In the studies performed by other researchers, the selected mesh unit cell size was between 0.1D* to 0.12D*. It has also been observed that mesh cell size less than 0.075D* does not change the results. After the preliminary experiments, it was seen results would be consistent as less number of different peak values would occur if the unit cell size for the mesh area surrounding the model was 0.05 m and the unit cell size for the mesh surrounding outside the model was 0.1 m. Analyses were performed with a total of 49,325 cells.

The Froude number is defined as the ratio of the inertial forces to the gravitational forces and is shown in Equation 3. When the mechanism of fires on the surface of the flammable liquid and on the surface of the combustible solid is described, fuel vapor that has low momentum has been investigated instead of jet flames which generate turbulent flow. The number of Froude in fire dynamics is used to describe the relationship between gravity and inertia, which is the opposite of the lift force created by the density difference due to temperature. [12], [13]

$$Fr = U^2 / g.L \tag{3}$$

In this equation, the gas velocity U (m/s) is acting as fluid, L is the tunnel height which is defined as the characteristic measure of the tunnel and g is the acceleration of gravity. If the diameter of the fire area (D) is used instead of length (L) and density (ρ) and heat of combustion (ΔH_c) values of the fuel are known, through heat release rate calculation initial speed of the fuel vapor would be designated as shown in equation 4.

$$U = \frac{Q}{\Delta H_c \rho (\frac{\pi D^2}{4})} \tag{4}$$

When velocity components of Equation 2 and Equation 3 are compared it is seen that the Froude number is proportional with Q^2/D^5.

Depending on this ratio and Froude number, the heat release rate (Q) value of the fire, velocity of the gas layer along the tunnel section (U), time (t), and the mass of the combustible material consumed during combustion (m) can be used in the scale of the model as shown in the Table 2. Indices in the table are as follows: M denotes the quantity used in the model, T denotes the quantity used in the tunnel that is not scaled down.

Table 2. Rates derived with Froude number scaling [14]

Model Similarity Rates	
Heat Release Rate (Q) (kW)	$Q_M / Q_T = (L_M / L_T)^{5/2}$
Velocity (V) (m/s)	$V_M / V_T = (L_M / L_T)^{1/2}$
Time (s)	$t_M / t_T = (L_M / L_T)^{1/2}$
Mass (m) (kg)	$m_M / m_T = (L_M / L_T)^{3}$
Temperature (T) (K)	$T_M / T_T = 1$

The following equations are used to account for the radiation (E) that forms in the direction of the tunnel floor from the gas layer that accumulates in the tunnel ceiling and the heat flux (q '') that acts on the tunnel floor. In these equations, radiation emittance (5.a) radiation intensity (I) (5.b), heat flux on surface (A_1)is (q '') (5.c), view factor that affects the heat flux (ϕ), (5.d) are used.

$$E = \varepsilon \sigma T^4 \tag{5.a}$$

$$I = I_n.\cos\theta \quad (5.b)$$

$$q" = \phi E \quad (5.c)$$

$$\phi = \int_0^{A_1} \frac{\cos\theta_1 \cos\theta_2}{\pi r^2} dA_1 \quad (5.d)$$

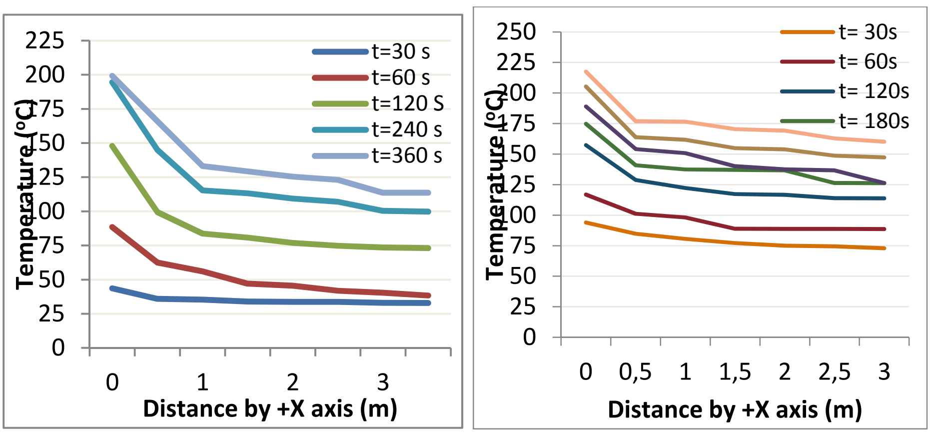
Since the hot gas accumulated in the ceiling is the combustion product resulting from the combustion reaction, the radiation values to be used when calculating the heat flux generated by the water vapor and the carbon monoxide in the gas layer, are given in Table 3.

Table 3. Carbon monoxide and water vapor, (ε) radiation values

Radiation (ε) of carbon monoxide gas							
Gas Temperature (K)	Partial pressure.beam length (atm.m)						
200	0.0015	0.003	0.005	0.009	0.1	0.15	0.2
300	0.0017	0.004	0.006	0.009	0.12	0.16	0.25
Radiation (ε) of water vapor							
Gas Temperature (K)	Partial pressure.beam length (atm.m)						
200	0.08	0.1	0.2	0.3	0.5	0.7	0.8
300	0.07	0.095	0.17	0.25	0.4	0.6	0.7

4. RESULTS

Thus, the temperature values obtained from the experiments and the heat flux calculations performed in the region defined as the fire source and the change of heat flux at different distances extending along the tunnel direction of this region are shown in Figure 2 below.



(a) (b)

Figure 2. a distance-dependent variation of the gas layer temperature in the ceiling in a tunnel at different points a) heat dissipation value HRR = 15 kW, b) heat emission value HRR = 20 kW

As the measured temperature increases in time, temperature of the gas layer also changes from the fire center as the gas layer extends along tunnel section. This change of temperature with distance from fire center is shown in graphs in Figure 2. As can be seen from the curves as time elapses at t=60 seconds at the distance of X= 1.25 m from the fire center, the ceiling gas layer temperature reaches 50 °C. At t=120 seconds at the distance of X= 2.25 m from the fire center, the ceiling gas layer temperature reaches 75 °C. It can be considered as a situation where people cannot approach fire center without personal protective equipment. When heat release rate of fire increases from 15 kW to 20 kW, at the distance of X= 2.0 m from the fire center both the temperature of breathable air and the radiant heat flux values due to radiation reaches dangerous levels as shown in Figure 2.b.

The temperature values obtained from the temperature gauges are integrated on the hemisphere between the floor and the gas layer, and the time-dependent variation of the heat flux values that can affect a person at different distances from the fire source is shown in Figure 3. In this experimental setup after a time changing between 2 minutes to 3 minutes after the start of the fire, the heat flux from the fire smoke layer to the tunnel floor reached a threshold level of 2.5 kW / m2 as defined in NFPA 502 standard and exceeded this value. This can be seen in Figure 3, in the curves of the variation of the heat flux depending on the distance, which acts on the floor from the gas layer in the tunnel. The heat release rates during the tests were 15 kW, 20 kW, 30 kW and 50 kW, respectively. In Figure 3.a and 3.b curves, threshold limit of 2.5 kW/m^2 that is dangerous to human skin decrease as gas layer move away from the fire source, and in the curves of Figure 3.c and Figure 3.d, at the distance X=1.5 meters, risk of skin burns and other hazards are likely to diminish. In the heat flux values below this level, people may be able to withstand compelling environmental conditions for some time, but when the threshold level is exceeded, people need to move farther away from the fire source. When examined in conjunction with Figure 2, it appears that the amount of time required to achieve this safety margin is very limited.

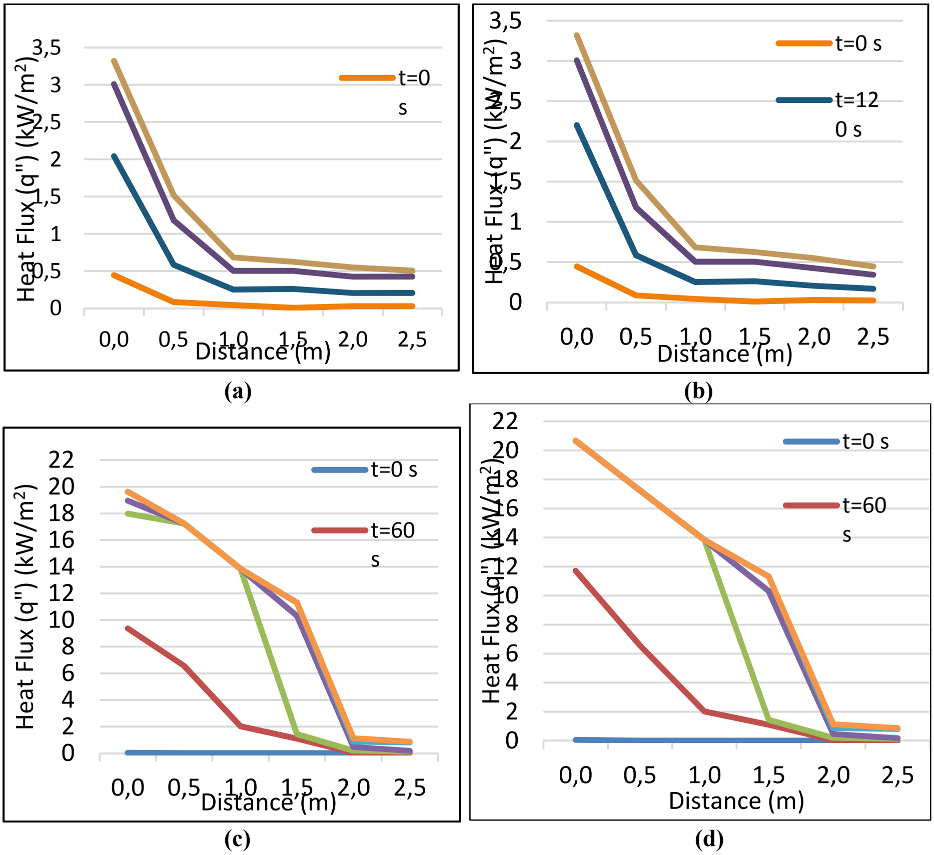


Figure 3. Distance-dependent variation of the heat flux effect to the floor from the gas layer in the ceiling in a tunnel a) heat release rate (HRR) = 15 kW, b) HRR = 20 kW, c) HRR = 30 kW, d) HRR = 50 kW

The experiments were carried out in numerical analysis as well as in experiments. An open-source source software named Fire Dynamics Simulator (FDS) that is focused on heat and smoke released from a fire, which analyzed Navier-Stokes equations using the Large Eddy Simulation (LES) form has been used to calculate thermal flows at low Mach speeds [15]. Some of the data obtained from experiments and numerical analysis studies are shown in the graphs in Figure 4. In numerical study, the maximum temperature values reached at the fire source were more than the values measured during experiment. The maximum temperature difference between numerical study and experimental values increases as the heat release rate of the fire increases. Although the increase in the energy generated by the burning of the fuel does not lead to the same degree of conduction loss in the surface and the resulting difference between generated heat and conduction loss is decreasing, this situation has been evaluated to occur.

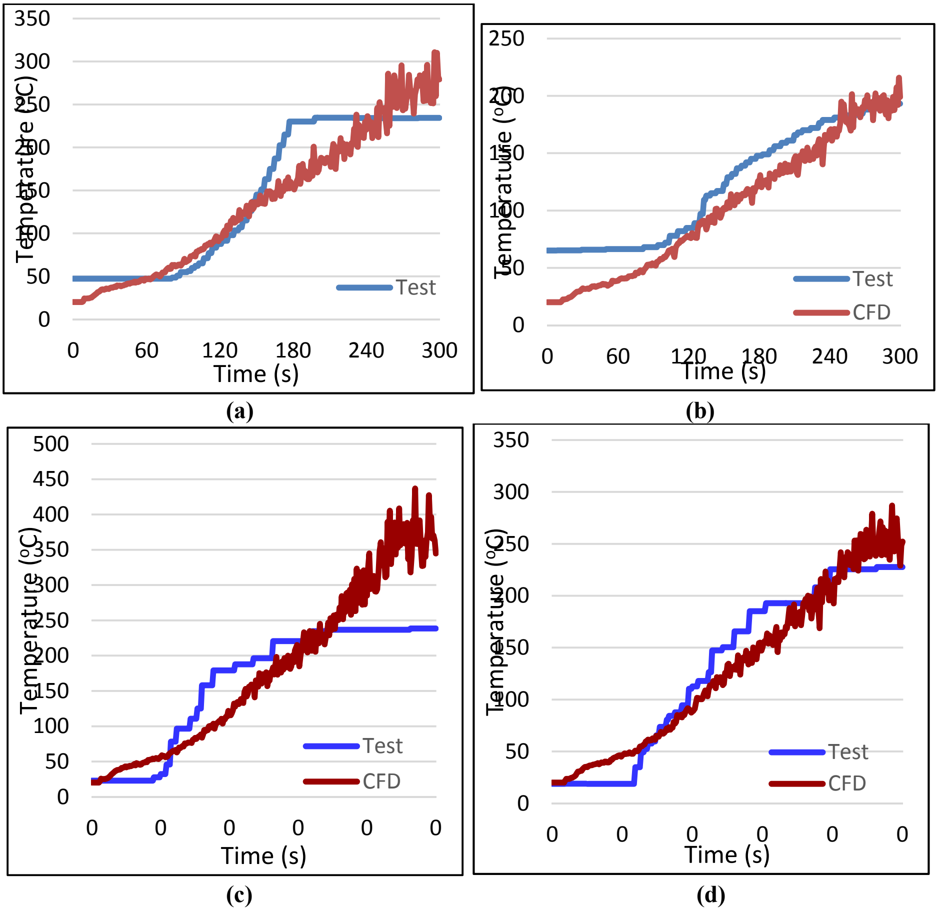


Figure 4. Tunnel comparative presentation of the results of CFD analysis of the gas temperature in the roof layer. A) Temperature at a distance of 0.25 m from the fire source, HRR = 30 kW, b) Temperature at X = 1.5 m distance from the fire source, HRR = 30 kW, c) Temperature at a distance of 0.25 m from the fire source, HRR = 50 kW, d) Temperature at the distance X = 1.5 m from the fire source, HRR = 50 kW

Comparison of experimental data and numerical analysis data on the change of heat flux with time, temperature and distance accordingly at the fire source and at the evacuation point is given in Figure 5. As the fire develops with time, concordant results were obtained in the experimental study and numerical study.

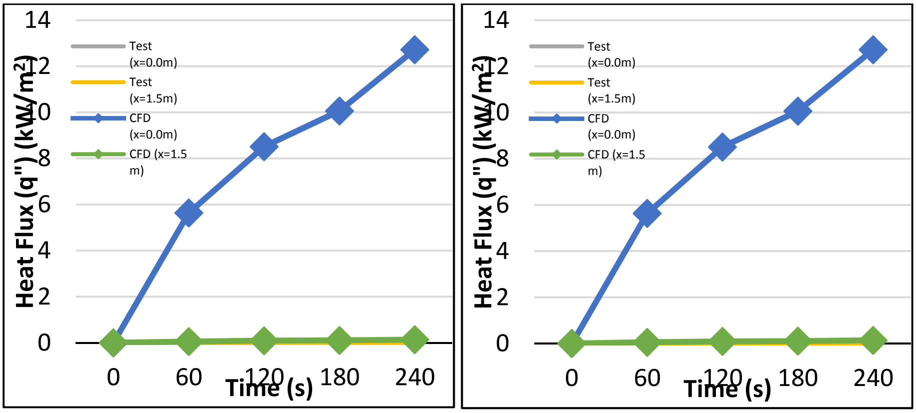


Figure 5. Comparison of experimental data and numerical analysis data on the change of heat flux with time, temperature and distance accordingly at the fire source and at the evacuation point a) HRR = 30 kW, b) HRR = 50 KW

5. CONCLUSION

A model has been developed to determine conditions that would obstruct to perform safe evacuation of occupants in a tunnel and endanger the life safety of the responders in the event of a fire. Experimental studies and numerical studies carried out in accordance with the model as the fire develops with time, compatible results were obtained in the experimental study and numerical study as shown in the curves in Figure 6 and Figure 7. The loss of conductive heat on the surface does not increase in the same level and the difference value between the two conditions is reduced, despite the increase in the energy generated by the combustion of the fuel. In case of high heat emission value, the maximum ceiling temperature calculated in numerical study is higher than the measured temperature values in experimental study as shown in Figure 6.b and Figure 7.b.

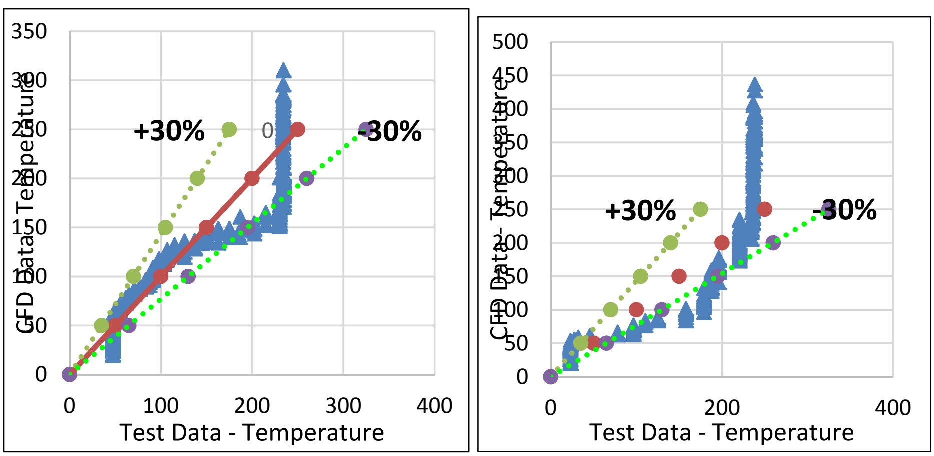
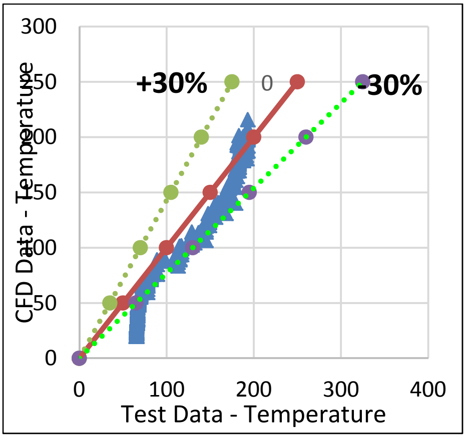
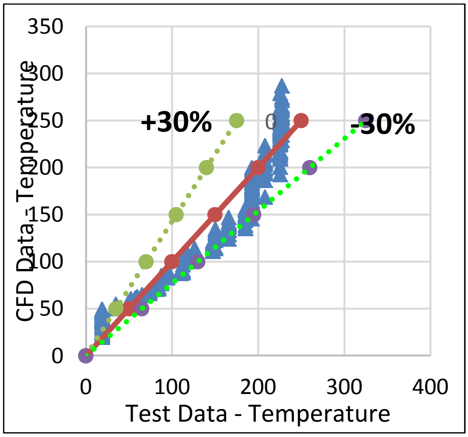


Figure 6. Tunnel fire source (x = 0.5 m) test data and comparison with the CFD analysis data a) HRR = 30 kW, b) HRR = 50 kW



(a)



(b)

Figure 7. Tunnel evacuation point (x = 1.5 m) test data and comparison with the CFD analysis data a) HRR = 30 kW, b) HRR = 50 kW

It is estimated that the fire area should be evacuated between 120 seconds and 180 seconds in case of a possible combustion in the studies carried out and the tenable environment defined in the standards cannot be provided after this point. Values examined in this study are consistent with the evacuation time determined in the reporting studies conducted after the actual tunnel fire incidents.

It is evaluated that the experimental model and the numerical model are compatible with each other. It is considered that the material constituting the boundary conditions of the experimental model, the development of temperature measurement points, dynamic control of air movements and calculation of heat losses in the tunnel model should be determined in accordance with the actual conditions for further studies.

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