

# PISTON EFFECT ON FIRE-INDUCED FLOW AND HUMAN CONFORT IN AN UNDERGROUND TRANSPORTATION SYSTEM STATION MODEL

ЕФЕКТ ОТ ВИЗПЛАМЕНЯВАНЕ НА ПОТОК И ЧОВЕШКОТО ЗДРАВЕ ЧРЕЗ МОДЕЛИРАНЕ НА ПОДЗЕМНА ТРАНСПОРТНА СИСТЕМА

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**Abstract:** In this study the effect of mechanical ventilation (train piston effect) on temperature distribution and emission characteristic for a fire induced flow is investigated experimentally. The main objective is to understand fire behaviors, experimentally in a scaled version of an underground burning 10 ml n-heptanes alcohol fuel in a fire pool with dimensions 5cm x 10cm x 4 mm at the center of 1/100 scaled underground station model. This study showed that, the train piston effect velocity is increased from 0 m/s to 1 m/s the maximum temperature in the station is found to be less for piston effect velocity of 1 m/s. The reason for these experimental result lies on the relative dominance of oxygen supply effect on cooling effect. Also the piston effect prevent the moving of hot smoke back layering on the ceiling zone of station. Since 1m/s piston effect create a ventilation velocity in the model station nearby close to critical ventilation velocity for a 2.3 kW n-heptanes fire.

**KEYWORDS:** TUNNEL FIRES, PISTON EFFECT, SMOKE VALUE

## 1. Introduction

Over the last 15 years there has been a great increase in the building of both road and rail tunnels, has been rapid. The new era's mega cities faces with problems of over population and most crowded traffic which leads to authorities to tend to use underground transportation systems. One type of transportation systems is subways. To overcome increase in traffic volume and centralization of city, the need for better and more efficient transport systems is increasing and construction of road and railway tunnel is on an increasing trend [Roh et al., 2007]. In last century there were dozens of catastrophic fires in under-ground transportation systems, like saint Gotthard tunnel in Switzerland in 2001, Hongjimun tunnel in Korea, Tauern tunnel in 1999 and king's cross in London in 1987 [Hu et al., 2005-2007]. The king's cross subway station fire is very important in fire analyze and fighting since the ditch effect is noticed. Another very important fire event in history is Daegu subway station fire (South Korea in 2003) which proved there is no way to be ready for a catastrophic fire even in the most modern subway stations. In this event 192 people lost their lives and hundreds of wounded by the smoke [Hu et al., 2007]. Another noticeable fire event is English Channel tunnel in 1996 which caused high cost damage in the structure. The fire events in the history attracted the effort of researchers to the fire experimentation, smoke discharging and subway ventilation. Olivier Vauquelin [2008] carried out experimental investigations on a small scale tunnel model to study the fire-induced smoke control by longitudinal and transverse ventilation system. The main objective of that model was to represent, as well as make possible, the duality between inertia forces (due to ventilation) and buoyant forces. The critical velocity is defined as the minimum air velocity required suppressing the smoke spreading against the longitudinal ventilation flow during tunnel fire situations. Wu and Bakar [2000] investigated the relationship between the critical velocity and heat release rate of the fire and the effect of the tunnel cross-sectional geometry to the critical ventilation velocity both experimentally and numerically. Li and Chow [2003] studied different tunnel fire scenarios, numerically. The tunnel concerned was simplified as a very long rectangular tube. Fire size, ventilation system and heat capacity were considered as parameters. Based on the results, performance of different safety systems are evaluated and compared. In ventilated tunnel fires, smoke and hot combustion products may form a layer near the ceiling and flow in the direction opposite to the ventilation stream. There was many numerical studies made about smoke movement [9-10].

In this study, the longitudinal ventilation represents train piston effect or mechanical ventilation. In experiments, the ventilation effects are inspected. The affects mechanical ventilation to the temperature distribution and the emission characteristics in the scaled subway station is inspected and analyzed.

## 2. Experimental setup and method

The difficulty of full scale simulations, have forced the model to scale. The similarity rules are rather useful approximation. The similarity rules adapted for this experimental simulation impose strict conservation of Froude number.

$$Fr = \frac{u^2}{gL} = \frac{\text{inertial forces}}{\text{buoyancy forces}}$$

Where  $u$ -air velocity,  $L$ -tunnel length and  $g$ -gravitation. Thomas [1968] expressed that the critical ventilation as a function of the Heat Release Rate (HRR) by

$$V_c \approx \left( \frac{g D_h Q}{\rho_o T_o C_p A} \right)^{1/3}$$

Where  $D_h$  (m) mean hydraulic diameter of tunnel,  $Q$  (W) is heat release rate,  $A$  (m<sup>2</sup>) is the station cross section area  $\rho_o$  (kg/m<sup>3</sup>) and  $T_o$  (°C) are ambient air density and temperature, respectively.  $C_p$  (J/kgK) is the specific heat capacity of air.  $D_h=0.262$ m,  $\rho_o=1.225$  kg/m<sup>3</sup>,  $T_o= 21$  °C,  $C_p=1006$  J/kgK,  $Q=2300$  W. The critical velocity in the station is calculated  $V_c=1.47$  m/s for  $Q=2300$  W.

### 2.1. Installation of test tunnel.

A 1/100 scaled heat resistant half subway station model was produced by the assumption of a real station is symmetrical in the longitudinal axis. Both tunnels are 1m long with a rectangular cross section. The model station dimensions are 90cmx24cmx32cm respectively. The symmetry plane is closed by a heat resistant glass in order to inspect the inside of the model while during the fire experiments in the scaled station. The upstream end of tunnel is connected with a blow-off type fan which is placed at the entrance of the inlet tunnel, to represents train piston effect A schematic layout of the test model is shown in Fig.1.

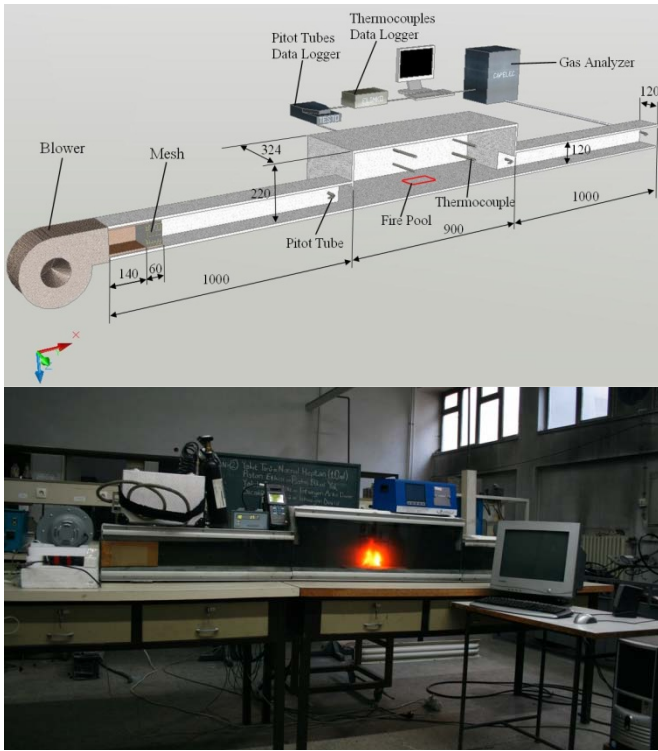


Fig.1. A schematic layout and image of the tested model tunnel.

### 2.2. Experimental methods

Experiments are performed with n-heptane ( $C_7H_{16}$ ) burned in fire-proof pools to investigate the effect of piston effect on fire temperature distribution and emission value in the station. For the fire experimentations, 10ml of n-heptane is burned in fire pools which dimensions are 10x5x0.4cm. In experiments, the location of the whole experiment was recorded from heat resistant glass window via a digital video recorder and a digital camera. The temperature distribution is detected using K-type stainless steel thermocouples. To measure the mean velocity vane probe and the gauge pressures, pitot tubes were used. All data were saved by using data loggers. A sketch of the arrangement of thermocouples and the pitot tubes is shown in Fig.2.

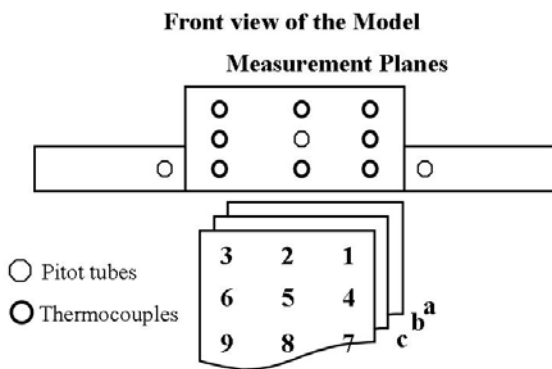


Fig.2. Arrangement thermocouples and the pitot tubes

### 3. Results and discussion

In this experiment, a fire in the middle of the passenger platform of subway station was inspected. During the experiment, 10ml n-heptanes was burned in a fire pool which was located in the centre of the station ground without piston effect. During the fire, fire column have reached and hit to the ceiling. Also flame spread out equally in a circular shape (although the fire pool is rectangular). The flames can be described as robust and stable. Thanks to the  $O_2$

rates in the station. The temperature measurements along time and positions are presented as follows; Fig.3.a,b,c. respectively.

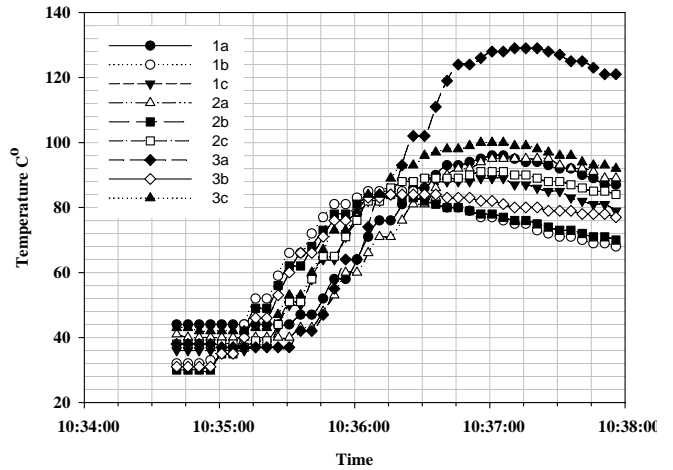


Fig.1. Temperature distribution on ceiling zone with no P.E.

Figure.6.a. shows that still buoyancy forces are dominant and hot air, reaction (fire) products rises quickly to the ceiling. In this position, the vaporization bubble cannot get bigger and fire reaction starts just a little above the fire pool.

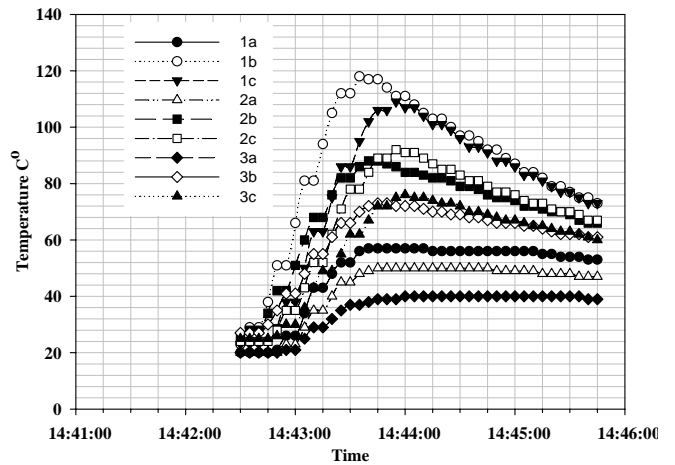


Fig.1. Temperature distribution on ceiling zone with 1m/s P.E.

The temperature distributions show that the entrance side ceiling zone has reached to the 72 °C degrees while the exit side ceiling zone reached to 120 °C degree temperature. Ceiling and Floor temperature distributions for the fire scenario at the centre of the station model are represented in Fig.11.b. and Fig.11.c.

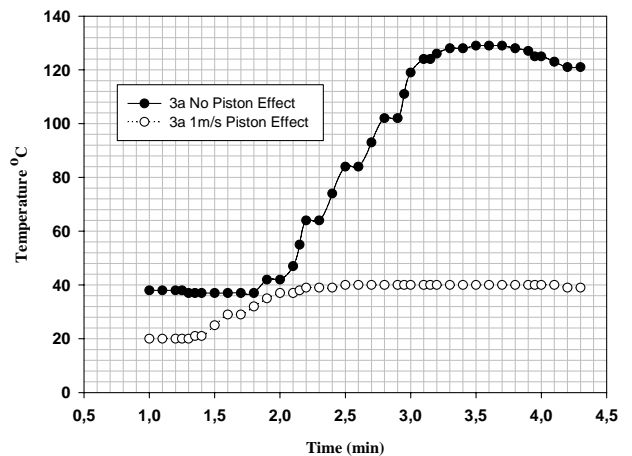


Fig.1. Piston effect on high temperature smoke Backflow layer.

The nearest thermocouple to the pool surface measured the temperature around 400 °C and the temperatures show that the whole flame block is around same temperature. The hot air and burning reaction products just rose and hit to the ceiling and spread out through the station walls.

measurement results from exit tunnel are; 57 ppm mean HC, %14.4 O<sub>2</sub>, %3.9 CO<sub>2</sub> and %0.082CO.

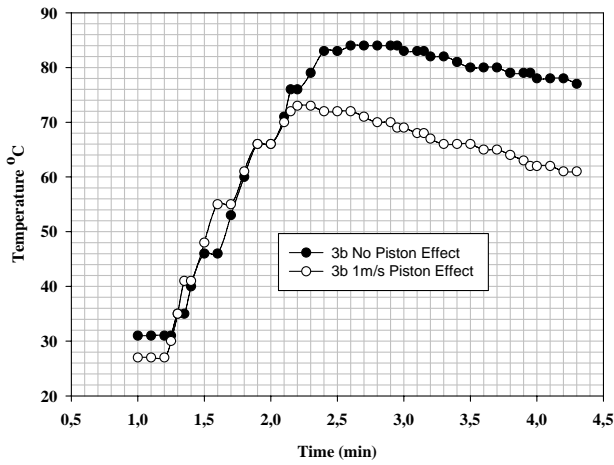


Fig.1. Piston effect on high temperature smoke Backflow layer.

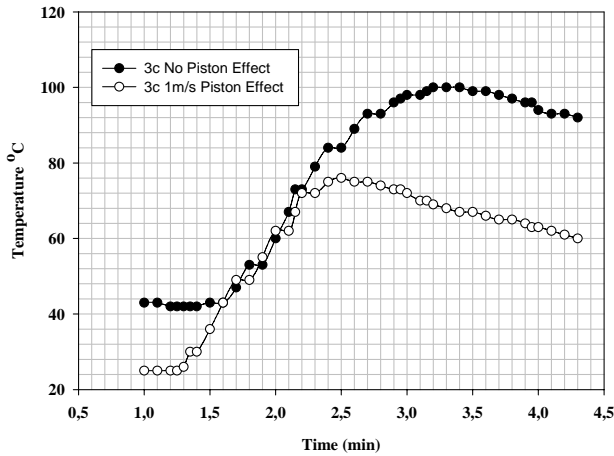


Fig.1. Piston effect on high temperature smoke Backflow layer.

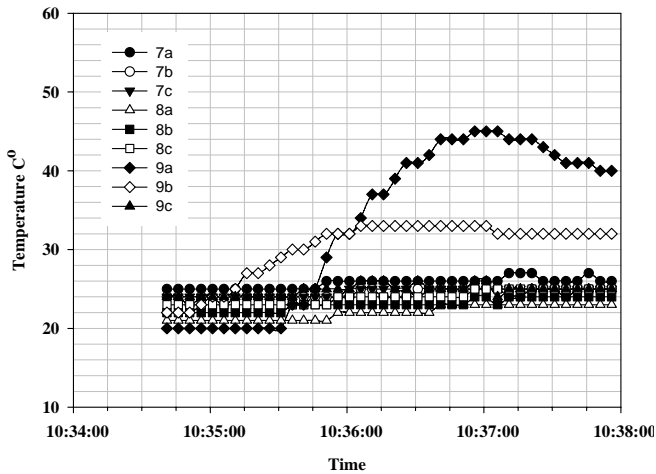


Fig.1. Temperature distribution on passenger zone with no P.E.

The temperatures along the ceiling were measured around 100-140 °C when the temperature measurements above the passenger platform stayed around 30°C. Also the temperature in the exit tunnel increased slightly and reached about 20 °C. The emission

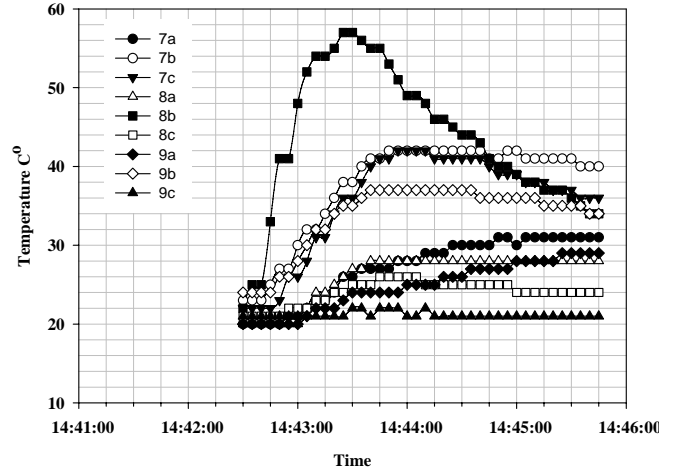


Fig.1. Temperature distribution on passenger zone with 1m/s P.E.

In Fig.11. b, the temperature distribution reveals the temperature rise around ceiling. Air stream prevents hot gas accumulation in specific zones so there are no more homogeneous temperature distribution layers. Fig.11.c is also confirms the state; only the behind-fire zones takes the heat. Also cooling is much faster.

The same experimental methods were applied in the centre of station fire scenario. The images related to the experiment sets are presented below;

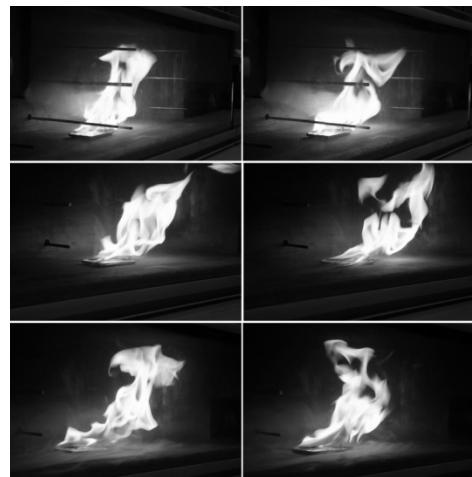


Fig.1. Temperature distribution on passenger zone with 1m/s P.E.

As seen from figure.10, flame tilted by the air stream and not only it affect the fire pool area, also it affect the backwards of the fire pool. The flame tips turned towards the entrance side of the station because of the flow regime characteristics existed the upper sides of the station model. The temperature distributions along the time for all points are presented in Fig.11.

**4.Conclusion**

Fire scenarios were inspected for no-piston effect and 1m/s piston effect condition. According to the emission measurements of exit tunnel and in station, it was understood that the oxygen rates drops dramatically right after the burning reaction started in no-piston effect case. The train exit tunnel mean oxygen levels were measured as ~%17 while in-station oxygen rates were obtained as ~%12. In some of the experiments, it was noticed that the local oxygen rates can be lower then %10, especially near the flame zone. According to Louisville University Department of Public Safety, the air has to contain %21 oxygen molecule for normal respiration. If oxygen rate

drops below %17 in the environment, mental insufficiency, deficiency in coordination and incompetence of muscle control can occur. This symptom affects fire victims and prevents them to escape. If oxygen rate drops even below %11, the victims respiration stops and death happens around in 6 minutes. In the no-piston effect case, oxygen is only supplied by natural ventilation and also the smoke discharge. The oxygen supplied by natural ventilation is not capable of fully feed the burning reaction, so in some experiments fire extinguished by itself while there was still some fuel in the fire pool. Although the flames were much weaker when compared to the fire scenarios for 1 m/s piston effect, the measured temperatures in the station was much higher. Another important fact is, the heat generated by the fire diffuses to the all station volume as waves. In the piston effect cases, the flow characteristics were dominated by piston effect but also the buoyancy effects were also visible. The smoke and heat generated by the fire, carried through train exit tunnel by air stream. In the experiments, it was noticed that the front side fire pools stay cool but the back side of the flames take the heat. Not only the back side of the fire was affected, also temperature rises were recorded inside of the exit tunnel. The oxygen supplied by piston effect fill the station volume by fresh air so burning reaction continues constantly and stable till fuel runs out of. The emission measurements and temperature distributions showed that, without the piston effect the station volume is not being suitable for respiration; both the temperatures and emissions are exceeding life conditions. This study is a part of experimental and numerical fire simulation project so it is still being evolved.

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