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Full scale measurements of the operation of fire ventilation in a road tunnel

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ABSTRACT

The main aim of the research performed was to check the operation of a ventilation system in a conventionally operated road tunnel in Southern Poland. The length of the examined tunnel is 678 m and it has a gradient of 4%. It includes longitudinal ventilation. The measurements of normal and reversed velocity of air flows (which were forced by the fans) were conducted at two cross-sectional profiles inside the tunnel. A set of fourteen thermal anemometers was applied there. In addition, at the intake and exit portals the wind direction, wind velocity and temperature were recorded during the tests. The fans worked according to the emergency operation pattern. The results were compared to estimated critical velocity and the correct functioning of the ventilation system was confirmed. The results showed a significant influence of the naturally caused airflows. Numerical simulations were performed to determine the air velocity resulting from this effect. CFD Ansys Fluent was used to solve the simplified model of the tunnel. The results confirmed that the combination of the stack effect and wind influence is crucial.

1. Introduction

Road tunnel ventilation must ensure an acceptable level of air contaminants as well as sufficient visibility. In the event of fire, it should initially permit safe evacuation and aid rescue action. The road tunnel ventilation system can either be natural or mechanical, depending on the length of the tunnel, the density of road traffic intensity and whether the traffic flow is unidirectional or bidirectional. In considering potential ventilation systems, real-world experiments are commonly performed on a small scale. Large scale experiments in actual road tunnels are rare because they are difficult to undertake (they require cooperation between many different services, such as using the police force to coordinate traffic diversion). Thus, large scale tests are the most interesting and they give important results that serve as the basis for further validation of numerical models. These systems are often tested with the application of computational fluid dynamics programs (CFD).

Currently, such tests are focused on different aspects of fire ventilations systems, although the Natural Stack Effect (NSE), which is also defined as the Natural Ventilating Pressure (NVP), and the backlayering effect are key among them. The effects mentioned above depend on various factors (wind, tunnel inclination, temperature distribution etc., airflow rate) and have an influence on the following:

– fire development,
– smoke and gas movement,
– critical velocity in the tunnel (minimal velocity assuring smoke clearance), and
– efficiency of ventilation system,
– evacuation time.

After reviewing the relevant literature (described briefly later in the text) it may be stated that a lot of scientists analyze air conditions during a fire without looking into the preliminary conditions outlined above, conditions which in fact strongly influence smoke movement at the initial stages of the fire. In terms of fire detection and tunnel evacuation, this stage is the most important and knowledge about airflows is crucial. Therefore, the results presented in the article make reference to the airflow produced in the tunnel by different modes of ventilation systems. Moreover, the results give reliable data for further validation of the CFD model.

The natural stack effect is present whenever heat transfer occurs in the subsurface or when there is a tunnel inclination which leads to a variation in air density. For example, if the rock is cooler than the air, then the NSE will apply in the reverse direction of the airflow (McPhearson, 1993). In the case of a geographical region where the diurnal or seasonal ranges of surface air temperature encompass the

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Nomenclature

A	area perpendicular to the flow (m^2)
C_p	specific heat of air (kJ/kg K)
D	effective diameter
H	height of tunnel at the fire site (m)
K_1	0.606 (Froude number factor)
K_g	grade factor (depending on the inclination of the tunnel)
Q	heat the fire is adding directly to air at the fire site (kW)
T	temperature of the incoming air (K)
T_f	average temperature of the fire site gases (K)
V_c	critical velocity (m/s)
g	acceleration caused by gravity (m/s^2)
h	height above reference level (m)
k	Boltzmann's constant (J/K)
p, p_0	pressure, reference pressure (Pa)
v	air flow velocity
λ	resistance coefficient (depends on Reynolds number, wall roughness and tunnel cross-section shape)
μ	air molecular weight (kg)
ρ	density of air (kg/m^3)

mean temperature of the strata in a naturally ventilated tunnel, then reversals of airflow can occur. Because of such instabilities, only short tunnels are now ventilated purely by natural ventilation. The NSE also influences the operation of fans in a tunnel and can lead to insufficiently high air velocity, even lower than the critical velocity, as is shown in chapter 5. Although the current studies relate to conducting experiments across different scales, the operation of ventilation systems is not commonly the subject of large scale real-world tests. Thus, there is a lack of authentic in situ data. For instance, Kashef et al. (2013) carried out tests only on a 1:15 model of a tunnel to ascertain the smoke temperature beneath the roof during smoke clearance by vertical ducts. He pointed out that smoke temperature determines the efficiency of this process. On the other hand, the same process (natural ventilation by vertical ducts) was the aim of comparison between large scale experimental results and numerical simulation data by Wang et al. (2016). He showed a high degree of similarity between them, although the comparison being made only referred to this particular type of ventilation. Zhong et al. (2013) performed a numerical analysis of smoke movement along an entire tunnel under the influence of buoyancy and longitudinal wind. However, the results were not validated. The influence of wind speed and direction on smoke clearance by roof vents was also the aim of other research (Tanaka et al., 2016; Jin et al., 2017). However, the experiments were carried out on 1:12 and 1:36 tunnel models. Jin pointed out that the number of vents and the speed of the cars does not influence the smoke direction near the vents. Other experiments (e.g. Wang et al., 2017; Mei et al., 2017) or numerical simulations (Ji et al., 2013; Fan et al., 2014) were focused on the plug-holing effect, where the shape of the vents or their distribution in a tunnel were under investigation. Musto and Rotondo (2014) carried out research into the dependence of critical velocity and temperature on tunnel inclination. He performed numerical simulations for four different angles of inclination and then proposed a Longitudinal Alternative Ventilation System (LAVS), which allows the tunnel to be protected against the backlayering effect. However, the results were not validated by *in-situ* measurements. Lin conducted numerical simulations into determining the efficiency of semi-transverse ventilation in a tunnel (Lin et al., 2014), using the Memorial Tunnel Fire Ventilation Test (1995) for validation. He demonstrated that semi-traverse ventilation is virtually impossible when the inclination of a tunnel exceeds 3%. He stated that this effect (intense smoke flow in the upper part of a tunnel) is caused by strong buoyancy and in order to avoid this the airflow rate should be increased by 10–20%. However, he did not perform the analysis into the physical aspects of buoyancy which lead to NSE, focusing instead solely on the consequences of this effect. Similar research was undertaken by MaoHua et al. (2016), Chow et al. (2015), Šulc et al. (2016). They examined wind (natural wind pressure – NWE), inclination and NSE as the reason for airflow variations in a tunnel. They stated that at the initial stages of the fire they are significant and can lead to dangerous disturbances in air velocity and consequently to a backlayering effect (smoke flow against airflow direction in longitudinal ventilation systems). Yao examined this effect using a 1:10 scaled tunnel (Yao et al., 2016) which was ventilated naturally. He stated that vertical ducts can reduce backlayering. Ko and Hadjisophocleous (2013) pointed out that even when air velocity is lower than the critical velocity, backlayering can be controlled when sprinklers are in use. Gannouni and Maad (2016) and Tang et al. (2016) examined this effect under different heat release rate (HRR) assumptions although they used model results.

Additional tests (referring to application of air curtains or air dilution) were carried out by Yu et al. (2016) and Vauquelin (2008), yet, in the same manner as mentioned previously, they were only validated by model tests.

The above examples show that current research requires, on the one hand, validation data (acquired during real large scale experiments) and, on the other hand, analysis of NSE, which determines airflow direction and its velocity at the initial stage of the fire. The need for *in-situ* data for further validation of CFD models was also pointed out by Betta et al. (2010), Barbato et al. (2014), Cascetta et al. (2016). Therefore, this article presents the results of *in-situ* tests performed in a real-world road tunnel ventilated by a longitudinal system. It includes examination of variations in air velocity in a tunnel under varying scenarios for fan activation. Additional factors were tested: wind speed and its direction and basic air parameters at both portals. The results were the basis for determination of the air velocity profiles, including the analysis of critical velocity. The data acquired were the basis for validation of the CFD model of the tunnel and for the examination into NSE.

2. Air velocity in the tunnel

The fans produce an airflow in a particular direction. The velocity of the airflow generated is crucial in the event of fire. In the initial growth phase of a fire, this velocity should be sufficient to ensure that both smoke and heat flow in the required direction. On the other hand, it should not disturb the natural stratification of smoke and air layers in the tunnel.

For every tunnel, the critical velocity should be estimated as the limit value ensuring that smoke flow will occur in the designated direction (according to longitudinal ventilation), (Klote et al., 2012). Smoke flow in the opposite direction is defined as backlayering. Backlayering can lead to complete fogging in a tunnel. The critical velocity (NFPA 502, 2011) can be determined by:

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

$$T_f = \left(\frac{Q}{\rho C_p A V_c}\right) + T \tag{1}$$

It should be noted that for tunnels with some degree of inclination the critical velocity must be corrected by K_g coefficient. K_g, can be taken from the diagram (NFPA 502, 2011). This correction can also be done analytically (Musto and Rotondo, 2014):

$$K_g = (1 + 0.0374|\min(grade,0)|^{0.8}) \tag{2}$$