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Analysis of critical air velocity in a road tunnel fire

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Subject review

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A critical air velocity analysis was performed using a numerical model adapted for the eastern tunnel tube of the Kastelec road tunnel in Slovenia. This allowed the efficiency of the fans to be tested, which is required to maintain appropriate traffic conditions and prescribed safety in the tunnel. At the critical air velocity, that is, at an air velocity lower than the prescribed one, where the spread of smoke can still be effectively controlled to ensure time for a safe evacuation of passengers from a fire-endangered tunnel tube, special attention was paid to the phenomena of smoke backlayering and layered spread of smoke under the tunnel ceiling (so-called "stratification"). Simulations of the longitudinal ventilation system with single point extractions were conducted.

Key words:
road tunnel, fire, ventilation, critical air velocity, smoke backlayering, stratification

Pregledni rad

Ivan Kenda, Jakob Likar

Analiza kritične brzine zraka u požaru cestovnog tunela

Analiza kritične brzine zraka provedena je pomoću numeričkog modela prilagođenog za istočnu cijev cestovnog tunela Kastelec u Sloveniji. Time je omogućeno ispitivanje učinkovitosti ventilatora koja je potrebna za održavanje odgovarajućih prometnih uvjeta i propisane sigurnosti u tunelu. Pri kritičnoj brzini strujanja zraka, odnosno pri brzini strujanja zraka nižoj od propisane, gdje se još uvijek može učinkovito kontrolirati širenje dima kako bi se osiguralo potrebno vrijeme za sigurnu evakuaciju putnika iz požarom ugrožene cijevi tunela, posebna je pozornost posvećena fenomenima povratnog strujanja dima i slojevitog širenja dima ispod stropa tunela (tzv. "stratifikacija"). Provedene su simulacije uzdužnog ventilacijskog sustava s odsisima u jednoj točki.

Ključne riječi:
cestovni tunel, požar, ventilacija, kritična brzina zraka, povratno strujanje dima, stratifikacija

1. Introduction

The determination of the critical air velocity in longitudinal ventilation of road tunnels is a fundamental but challenging scientific problems. This is necessary to prevent the formation of turbulence or the rapid mixing of fresh cold air with hot smoke in the event of a road tunnel fire. When a fire breaks out in the tunnel, along with the lack of fresh air, large amounts of smoke are generated, preventing visibility and the ability of the vehicles and people to move around. There is a strong flow of flue gases moving in all directions. If the air flow is slow, the smoke will stay under the ceiling in the form of a layer for a long time, allowing traffic participants to evacuate along predetermined routes to a safe area. Experts' interpretations of the possibility of response in the event of backflow of air in a tunnel tube are not unanimous. Some recommend immediate forced ventilation of the tunnel, which often results in a rapid release of smoke, allowing for a very short time for people to evacuate. Smoke descends more slowly to the floor when there is no ventilation. A large number of studies have been conducted in this field in recent years to get as close as possible to the concrete application of complex numerical methods for simulating the determination of air velocity limits in the longitudinal ventilation of road tunnels.

Yan et al. [1] utilised numerical analyses to examine the possibility of smoke control in the event of a tunnel fire. In addition to temperature and smoke, he considered the minimum visibility and concentration of carbon monoxide (CO) for the simulation of three fire scenarios with 5 MW, 20 MW, and 50 MW for different fire locations. The dimensions of the smoke vents, as well as the smoke velocity, are critical. The results showed that the size of the clear cross-section of the tunnel tube is an essential parameter and that the exhaust opening perpendicular to the longitudinal direction of the tunnel is better suited for smoke control, particularly in areas further from the fire source. This is related to the rate of smoke extraction, so a higher level of extraction enhances the effectiveness of smoke control in the tunnel environment.

Furthermore, Tang et al. [2] utilised Froude's law of similarity to develop a model of a small tunnel (1/14) and investigate the critical air velocities in tunnels. A series of experiments were conducted to investigate the critical air velocity under various experimental conditions by varying the rate of fire heat release, ambient temperature, operating pressure, and nozzle arrangement. The test analyses the influence of fixed firefighting systems with water mist on the amount of critical air flow velocity. The spray-free tests revealed that ambient temperature had little influence on critical air velocity. The dimensionless analysis was also used to develop a new correlation for forecasting critical air velocities in a tunnel lacking a fixed water spray-based fire extinguishing systems. The accuracy of the correlation was compared to the results of the tests and other tests published by other researchers. After analysing 60 water mist tests, it was discovered that when the water nozzle is activated, the critical air velocity is significantly reduced. The maximum critical speed reduction was approximately 31% of face value. Furthermore, it was discovered that the reduction of critical air velocity is highly dependent on the number, positions, and working pressures of the water in the nozzles. The cooling effect of water droplets in water mist on contact with hot gas is by no means the only one, but it is an important mechanism for reducing critical air velocity caused by water mist.

Chen et al. [3] extensively investigated the effect of thermal buoyancy, which causes the return flow of smoke generated by a fire in a tunnel and is extremely harmful to the effective evacuation of people. The effect of the distance between the exhaust (opening) in the ceiling and the heat source on the flow length of stratified smoke under the ceiling in the tunnel, in combination with the effect of longitudinal ventilation, is addressed in the study. The experiments were conducted in a reduced-volume tunnel tube with the following dimensions: length = 72 m, width = 1.5 m, and height = 1.3 m. A porous gas burner was used to provide a constant source of heat. Its relative distance from the ceiling drain (opening) was different. It was discovered that as the distance between the heat source and ceiling increases, so does the heat flow of the air, allowing the smoke to escape. The new model was theoretically developed to forecast the length of the smoke lag current, including the heat source removal (opening) factor, taking into account the energy loss due to extraction, calculated on the basis of an estimate of the local longitudinal temperature profile. It was also discovered that the predictions of the proposed model agreed well with the experimental results.

A few examples of fire analyses in road tunnels are presented to demonstrate the importance of this type of analysis, which has a direct and indirect effect on properly selected scenarios for different fires in road tunnels.

2. Equations for determining the critical air velocity

According to PIARC's [4] recommendations, in the event of a fire, a one-way tunnel must have air velocities of up to 1.50 m/s, preferably in the positive direction. This speed is found to be the average speed of air movement prior to the outbreak of fire. When a fire starts, the speed at the site of the fire increases significantly (due to continuity) due to the generation of smoke. Because the average speed is typically lower than the critical one, there is frequently a return movement of smoke. Simulations revealed that the return movement does not present problems at air velocities of up to 3.00 m/s because the smoke is still in the return (negative) zone beneath the ceiling during the initial stages of the rescue. When the fans are turned on, all of the smoke (both before and after the fire) begins to move towards the outlet, that is, in a positive direction, and the smoke stratification gradually disintegrates. In the event of a fire, the most unfavourable speed is 3.00 to 6.00 m/s. The intense air movement at higher speeds reduces the combustion temperature.

So far, the critical velocity for various tunnels has been calculated primarily using sets of equations derived from the Froude number conservation in conjunction with experimental data. The Froude number is defined as the ratio of inertia to gravitational force:

$$F_r = \frac{v^2}{g \times D} \times \left(\frac{T_f - T_0}{T_f} \right) \tag{1}$$

Thomas and others [5] used the Froude number conservation technique to study the effect of ventilation rate on the spread of fire in underground tunnels and to account for the general concept of critical air velocity in a tunnel, assuming that the Froude number is the same.

The critical air velocity is defined in the study as the longitudinal velocity required to eliminate the return layer of hot flue gases. Table 1 lists the most commonly used equations (models) for calculating critical air velocity that are the result of research and are developed from the most basic forms:

1) Danziger and Kennedy (R_{ic}):

$$v_{crit} = \left(\frac{gHQ}{\rho c_p A T_0 R_{ic}} \right)^{\frac{1}{3}} \tag{2}$$

Danziger and Kennedy presented the formulas for calculating the critical air velocity versus heat transfer rate using the Subway Environmental Simulation (SES) method in 1982, [6, 7]. Kennedy developed a critical speed formula that was applied the same year in the Metro project, an environmental simulation by the U.S. Department of Transportation.

2) Thomas and Froude (T_f):

$$v_{crit} = K_g K \left(\frac{gHQ}{\rho c_p A T_f} \right)^{\frac{1}{3}} \tag{3}$$

$$T_f = \frac{Q}{\rho c_p A V_{crit}} + T_0 \tag{4}$$

Thomas was the first to calculate the critical air velocity to heat release rate ratio using Froude's number. Thomas presented the critical Froude number for predicting critical velocity, according to [5]. When the critical Froude number was set to 1, the backlayering phenomenon disappeared, and a critical air velocity prediction model was obtained._

3) Froude (according Kennedy) (F_{rm}):

$$v_{crit} = \left(\frac{gHQ}{\rho c_p A T_f F_{rm}} \right)^{\frac{1}{3}} \tag{5}$$

$$T_f = \frac{Qc}{\rho c_p A V_{crit}} + T \tag{6}$$

$$F_{rm} = 4,5 \times \left(1 + 0,0374 \times \left| \min(grade, 0) \right|^{0,8} \right)^{-3} \tag{7}$$

This model explains the properties of smoke flow in the tunnel under a limited number of assumptions , according to [6]. Later, Danziger and Kennedy proposed an improved model with a Froude number of 4.5.

4) Kennedy (*Ken*):

In tunnels where the air flow is directed downwards (slope) due to colder fresh air, the critical air velocity may be higher than that calculated by equation (2). A new formula for critical air velocity combining the increase in temperature of hot gases with the rate of convective heat release Q from a fire was introduced by Kennedy [8], namely:

In the case of a slope (–2%), computational take 1 (for flat and downhill driving)

$$K_n = K_g = 1 + 0,0374 \cdot (\text{inclination})^{0,8} \tag{8}$$

If there is no inclination, $K_n = K_g = 1,00$

It was accepted that

$$v_{crit} = K_g K_1 \left(\frac{gHQ}{\rho c_p A T_f} \right)^{\frac{1}{3}} \tag{9}$$

Table 1. Errors in the equation-based calculations at a fire load of 30 MW

Fire	Bora	T	Smoke ε	Flow Q	V_{crit} [m/s]. equations (2), (3), (5), (9) **Error** [%]					Ric/IDA	T_f/IDA	F_{rm}/IDA	Ken/IDA
MW	Pa	°C	1/m	m³	Ric	T_f	F_{rm}	Ken	IDA	Ric	T_f	F_{rm}	Ken
30	100	159.17	34.40	144.5	2.220	2.188	2.219	2.321	2.208	0.54	-0.009	0.49	5.11
V_{air}	200*	204.10	45.75	-135.82	2.145	2.065	2.147	2.071	2.208	-2.81	-6.47	-2.76	-6.20
	300	106.29	23.11	-258.78	2.316	2.229	2.318	2.230	2.208	4.89	0.95	5.02	0.99
	400	81.63	17.17	-338.69	2.370	2.280	2.371	2.280	2.207	7.38	3.30	7.43	3.30
	500	69.37	14.20	-401.92	2.400	2.306	2.399	2.310	2.207	8.74	4.48	8.69	4.66
	600	61.73	12.34	-456.07	2.419	2.320	2.417	2.330	2.207	9.60	5.12	9.51	5.57
	700	56.41	11.05	-504.18	2.430	2.337	2.430	2.340	2.206	10.15	5.93	10.15	6.07
	800	52.44	10.09	-547.80	2.440	2.346	2.440	2.350	2.206	10.60	6.34	10.60	6.52
	900	49.33	9.33	-588.19	2.448	2.353	2.447	2.361	2.206	10.97	6.66	10.92	7.02
	1000	46.83	8.72	-625.67	2.455	2.359	2.454	2.367	2.206	11.28	6.93	11.24	7.29

* snažne promjene

In 1996, the results of fire tests in the Memorial Tunnel in the United States [9] revealed that the critical speed forecast using the above formula was 5–15% higher, which we also proved by comparing the calculations using equations 2, 3, 5, and 9 (models) with the simulation results in Table 1.

2.1. Kennedy's equation

The Kennedy equation was used to calculate the minimum constant limit velocity of the air supply moving toward the fire that was required to remove the smoke and prevent the return layer. The Kennedy equation is accurate, and the estimate is realistic, as shown by simulations and the numerical method, respectively. Simulations were run at limit values when investigating safety in road tunnels. Kennedy developed the critical velocity formula, which was used in a simulation of the space project Metro, a subway project of the United States Department of Transportation, in 1982:

$$V_c = K_g k \left(\frac{gHQ}{\rho c_p A T_f} \right)^{\frac{1}{3}} \tag{10}$$

$$T_f = \frac{Q}{\rho c_p AVc} + T_0 \tag{11}$$

A certain amount of normalisation in the rate of heat emission is anticipated in relation to the length of the fire along the tunnel. Accordingly, it is likely that the Kennedy equation will continue to be the best method for estimating the critical speed for road tunnel design in the near future (without an adjusted CFD).
Depending on the size and intensity of the fire; the characteristics and rate of combustion, the air/fire interaction, among others; and the tunnel geometry, this may call for a change in the calculation of the temperature at the fire site. Simulations and calculations reveal that the critical speed in the event of a fire is typically between 2.20 and 2.40 m/s.

3. Methods of research

Computer programme analysis has revealed that while there are many different programmes, most of them are incomplete. The IDA-RTV programme proved to be the most comprehensive at the moment. The IDA RTV programme includes numerical methods for a variety of scenarios.
The programme enables the analysis of air flows in the road tunnel in relation to vehicle emissions with the aim of calculating the concentrations of each harmful component in the tunnel: CO, NO_X, smoke, and soot. Normal-hygienic and fire ventilation can both be studied. Longitudinal, semi-transverse, and transverse ventilation can be studied, with the option of one-way or two-way traffic. It is also possible to study the dynamics of traffic [10], such as regular traffic flows, congestion, and traffic jams. The IDA RTV programme includes a number of extra options, such as connection and branch analysis, sound attenuation analysis, tunnel dimensioning with semi-transverse or transverse ventilation, composite tunnels, and so on. It contains a set of fan data. It is unquestionably well suited to tunnel condition analysis, simulation, evaluation, and validation [11, 12].
The results of the simulation reveal the air pressure and temperature, volume and flow of the air, and concentrations of harmful substances along the tunnel tube. The geometry of the tunnel tube, including air flow friction, density and ratio of vehicles in traffic, quality or emission of vehicles, and hydrometeorological data at the tunnel location are all input data.
Simulations of various sizes were conducted in the eastern tube of the Kastelec tunnel. The tunnel tube has two lanes of one-way traffic in the Koper–Ljubljana direction.
Various data and parameters were used in the analysis of the data obtained by the computer simulation, but the critical (limit) air velocity in the tunnel, which depends on the speed of the Bora wind, was of particular interest. The critical speed was also calculated under various conditions and quantities. Different equations were simultaneously compared to determine this. The results are depicted in the tables 2 and 3.
The simulations were run to validate the parameters using Kennedy's equation under various conditions. These include changes in temperature, smoke concentration (visibility), toxic gases (CO, NO_X), air velocities and the resulting backflow phenomenon, and pressure changes.
The simulations with programme IDA RTV (Table 2) covered different values of the input Bora wind counter pressure, from 0 to 500 Pa, with a different number of included fans (12 or 14), at different fan speeds and thrust, at a different heat release rate (30 or 40 MW, which represents the trucks or buses on fire), different lengths of fires (5 or 10 m), and different locations of fires (600 or 1000 m).
As seen in Table 2, the critical speed value remains at 2.208 m/s despite variations in the number of fans, fan speeds, and distances between fires and the portal entry. Compared to Bora wind counter pressure at 200, 250, and 300 Pa, the speed of the air entering the tunnel tube ($V_{air\ entrance}$) changes and falls from 4.782 m/s to –5.95 m/s, with a change in the sign of the air flow speed at –0.0131 m/s. At a wind counter pressure of 250 Pa, 14 pulse fans and the piston effect of vehicles in traffic travelling at a speed of 50 km/h reverse the air flow. The critical velocity (V_{crit}) is reduced by the length of the fire, increased fire load, and associated fire pressure drop (P_{drop}). The Bora's increasing speed redirects the air flow and creates a dangerous area, especially during the rescue.
Therefore, it is necessary to provide appropriate conditions, taking into account wind speed and fan operation, to ensure such conditions (stratification) and that (excessive) mixing of fresh air and smoke in the fire does not occur. This means that the hot flue gases stay under the ceiling for as long as possible, allowing most participants to safely retreat into the adjacent (western) tunnel tube.

Table 2. Simulations of various fire loads and wind speeds in the tunnel tube with the IDA RTV programme

FIRE	Unit	Bora4	Congestion6	Bora3	Congestion6	Congestion1	Congestion3	Bora2	Congestion0	Congestion	Congestion5	Bora5	Bora	Bora 1	Congestion4
Length of fire	m	5	5	5	10	10	5	5	10	10	10	5	5	5	10
Ventilation	-	longitud.	longitud.	longitud.	longitud.	longitud.	longitud.	longitud.	longitud.	longitud.	longitud.	longitud.	longitud.	longitud.	longitud.
Vehicle speed	km/h	50	50	50	50	50	50	50	50	50	50	50	50	50	50
V_{Bora}	Pa	0	100	200	250	300	300	320	400	400	410	500	500	500	500
Fans	n	12	12	14	14	14	14	14	14	14	12	12	14	14	14
Fire	m	600	600	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	600
fans	m/s	30	30	35	30	30	35	35	30	30	30	30	30	35	30
Jet fans	kW	437.2	438.7	494.6	486.5	486.6	499.3	569.3	444.5	440.4	379.80	422.7	494.6	559.3	381.9
P_{pad}****	Pa/MWW	0.1	0.1	0.1	4.0	4.0	0.1	0.1	4.0	4.0	0.1	0.1	0.1	0.1	0.1
$thrust_{fan}$	N/kW	30	30	36	30	30	35	36	30	30	30	30	30	36	30
T_{air}	^{0}C	10	10	10	10	10	10	10	10	10	10	10	10	10	10
$T_{wall\ max}$	^{0}C	626.60	644.10	646.2	604	1685	2295	683.5	598.80	578.9	544.20	706.7	621.20	628.80	451.60
$P_{1\ entrance}$	Pa	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$P_{2\ entrance}$	Pa	0	100	200	250	300	300	320	400	400	410	500	500	500	500
fANS*	n	12 F+PE-B	12 F+PE-B	14 F+PE-B	14 F+PE-B	14 F+PE-B	14 F+PE-B	14 F+PE-B	14 F+PE-B	14 F+PE-B	12 F+PE-B	12 F+PE-B	14 F+PE-B	14 F+PE-B	14 F+PE-B
$P_{l\ (Atm)}$	Pa	-57.45	-57.45	-57.45	-57.45	-57.45	-57.45	-57.45	-57.45	-57.45	-57.45	-57.45	-57.45	-57.45	-57.45
$P_{d\ (Atm)}$	Pa	-57.45	42.55	142.5	192.5	242.5	242.5	262.5	342.5	342.5	352.5	442.5	442.5	442.5	442.5
P FIRE	MW	30	30	30	40	40	30	30	40	40	40	40	30	30	30
$V_{ulaz\ zraka\ (PE)}$	m/s	4.426	2.838	2.674	-0.0131	-0.1293	-1.925	-1.307	-1.887	-2.445	-4.581	-5.275	-5.028	-4.205	-6.126
$V_{izlaz\ zraka}$**	m/s	-4.426	-2.835	-2.669	0.01307	0.129	1.919	1.303	1.88	2.435	4.563	5.25	5.004	4.185	6.096
V_{crit}	m/s	2.208	2.208	2.208	1.278	2.072	2.244	2.207	2.369	2.369	2.37	2.369	2.207	2.207	2.207
Q_{lijevo}	m^3/s	252.3	161.8	152.4	-0.7467	-7.373	-132.1	-78.38	-120.5	-158.9	-300	-337.2	-313.3	-262.8	-398.8
Q_{desno}	m^3/s	-264.2	-168	-162.4	0.7448	7.351	109.4	74.28	107.2	138.8	260.1	299.3	285.4	238.7	347.6
direction	capacity till 3900 vehicle, traffic density 103.10/km/drive line								capacity till 4650 vehicle, traffic density 103.10/km/drive line				capacity till 3900 vehicle, density 103.10/km/line		
composition***	1000 PC. 200 HGT. 40 HGT														
	Warning: No traffic allowed from 'Entry1' to 'Sect'. Entering traffic ignored.														
	Error: The simulation was terminated with a reduced fire heat release rate. This is most likely not a physically valid result.														

Where: *F-FAN, PE-piston effect, B–Bora; ** We ignore, ***PC-passenger cars, HGV-Trucks, HGT-tanks, ****Pressure drop due to fire [Pa/MW]

Table 3. Display of the quantities' calculated limit values for CO, NO_2, and turbidity of smoke flow according to Table 2.

FIRE	Unit	Bora4	Congestion6	Bora3	Congestion2	Congestion1	Bora2	Congestion0	Congestion	Congestion5	Bora5	Bora	Bora 1	Congestion4
P FIRE	MW	30	30	30	40	40	30	40	40	40	40	30	30	30
V_{Bora}	Pa	0	100	200	250	300	320	400	400	410	500	500	500	500
Tunnel Entrance:														
Tubidity (Smoke) flow	m^2/s	0	0	0	0.003587	40.04	5523	7780	7898	7916	7690	5579	5605	5878
CO	mg/s	0	0	0	48.08	489.9	512.1	1365	1391	1785	544.7	527.2	529.5	1352
NO_2	µg/s	0	0	0	1470	14839	38062	40723	41487	417557	40489	39183	39359	522192
Tunnel Tube - Sector:					Opasnost! Vatra!	Opasnost! Vatra								
Tubidity (Smoke) flow	m^2/s	19.67	30.71	32.61	763	598.6	69.21	62.26	47.7	25.34	22.00	17.31	20.71	14.2
CO	mg/s	1.053	1.643	2.958	70.17	67.8	6.322	10.77	8.284	5.657	1.536	1.612	1928	3.222
NO_2	µg/s	78.26	122.1	219.9	2085	2038	469.9	321.4	247.1	1335	114.2	119.8	143.3	1260
Tunnel Exit:														
Tubidity (Smoke) flow	m^2/s	5280	5232	5473	0	0	0	0	0	0	0	0	0	0
CO	mg/s	282.7	279.9	496.5	0	0	0	0	0	-352.2	0	0	0	-438
NO_2	µg/s	21010	20803	36902	0	0	0	0	0	-313715	0	0	0	-419157

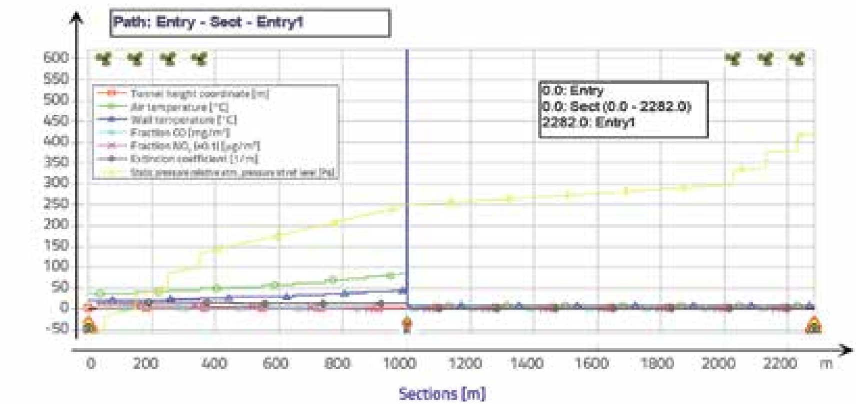

Figure 1. Eastern tube, longitudinal ventilation, fire 1000 m, 14 fans, conditions at 500 Pa

drops to 10 °C almost immediately. In a storm of this intensity, the tunnel must be immediately closed! The heat release rate is 30 MW.

From the representation of the wall temperature in Figure 3, it can be seen from the display of the wall temperature that it significantly rises in the immediate area of the fire, L = 1000 m. It can reach up to 600 °C. Due to the strong Bora wind, the walls of the tunnel tube cool down faster on both the primary and secondary sides. Heat release rate (HRR) = 30 MW

Table 3 displays the parameters of CO, NO_2, and turbidity of the smoke flow at various wind counter pressures of the Bora wind operating at the tunnel entrance, tunnel sector (meaning the entire tube), and tunnel exit. The programme issues a danger alert in the event of a Bora wind counter pressures at 250 and 300 Pa, when the fire power is 40 MW and its length is 10 m. In this case, reaching the allowed critical values of the aforementioned parameters is impossible.

When the wind speed exceeds 30 m/s, the operator closes down the tunnel!

3.1. Analysis and simulations

Diagram 1 illustrates the graphical altitude course of the route; static pressure course; CO, NO_2 concentrations course; extinction course; and air and surface temperature course (Bora simulation, Table 2). In the simulation, the heat release rate (HRR) is 30 MW, location is 1000 m from the entrance portal, all fans are included, normal power is 30 kW, and the Bora wind speed is 500 Pa. The eastern tunnel tube length L = 2278 m. The simulation time is t = 1 h. There is no piston effect.

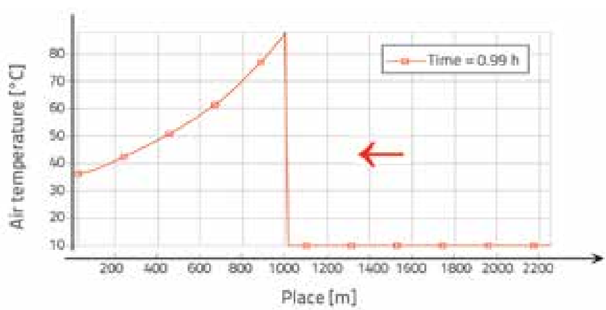

Figure 2. Display of air temperature in the tunnel tube L = 2278 m

Figure 2 shows the temperature of the air, T_{air}, is displayed. It is observed that there is a temperature increase of over 90 °C on the primary side, at the distance from the tunnel tube entrance to the fire, as a result of the backflow brought on by an excessively strong Bora. The impact of the very potent Bora is also felt in the area behind the fire because the air temperature

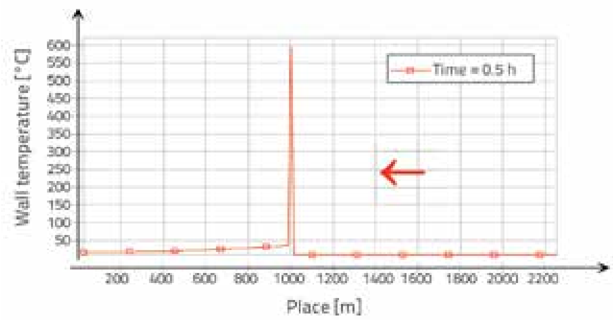

Figure 3. Display of the wall temperature in the tunnel tube L = 1000 m

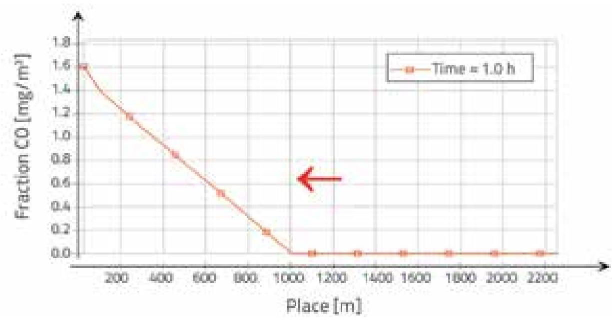

Figure 4. Demonstration of the CO value in the tunnel tube at L = 2278 m

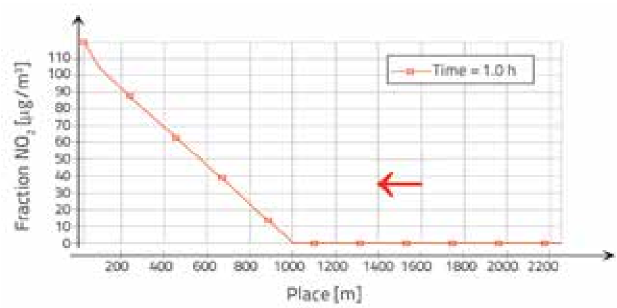

Figure 5. Demonstration of the course of NO_2 values in the tunnel tube at L = 2278 m

Figure 4 shows the progression of CO concentration in the tunnel tube at a length of L = 2278 m. The Bora causes a return flow of CO. On the primary side, increased CO levels can be seen in the direction from the fire to the tunnel entrance. All fans are included. Because the Bora is stronger, the tunnel must be closed immediately.

Figure 5 shows the evolution of NO_2 concentration in the tunnel tube at L = 2278 m length. Due to too strong a Bora wind, NO_2 travels in the same direction as CO, from the fire to the tunnel entrance. The return flow of NO_2. All fans are included. Bora is more powerful than the fans.

Figure 6 depicts the progression of smoke concentration (extinction) in the tunnel tube. Because the Bora is stronger than the fans, the value in the first part before the fire is greatly increased. The smoke makes its way back to the tunnel's entrance. The return flow of the smoke.

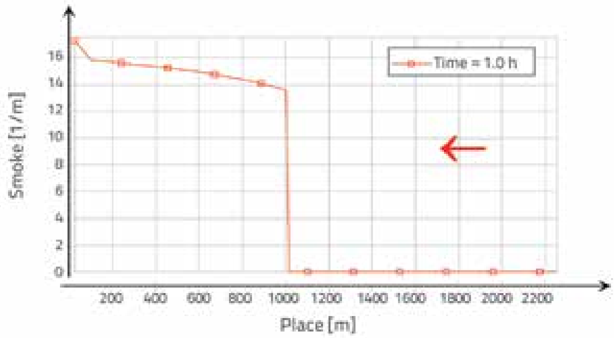

Figure 6. Display of extinction in the tunnel tube at L = 2278 m

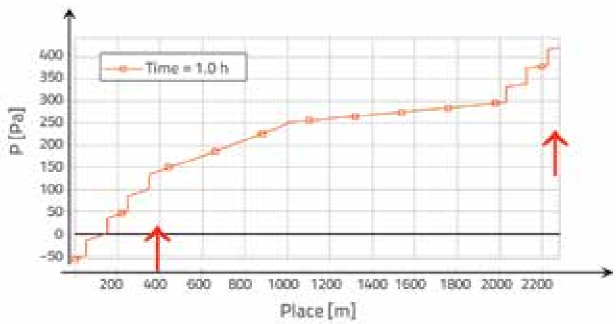

Figure 7. Display of the pressure distribution in the tunnel tube at L = 2278 m

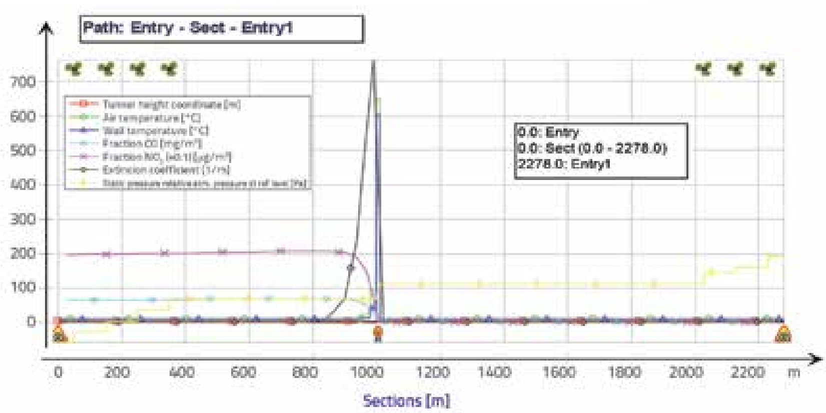

Figure 9. Kastelec–Eastern tube, longitudinal ventilation, 40 MW fire, 14 fans, conditions at 250 Pa

Figure 7 depicts the pressure flow at a distance of L = 2278 m in the eastern tunnel tube. In the vicinity of the fan, the pressure increases rapidly. All fans are turned on. The pressure increases in the area behind the fire, L = 1000 m.

Figure 8 demonstrates the air speed in the eastern tunnel tube at a distance of L = 2278 m. Due to the strong Bora wind, the air speed has a negative sign and is turned in the opposite direction.

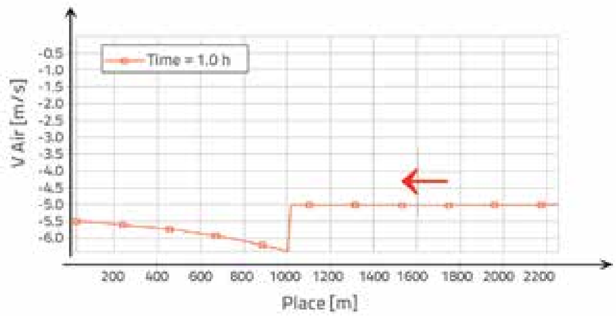

Figure 8. Display of air velocity in the tunnel tube at L = 2278 m

Figure 9 includes:

- 14 fans turned on, resulting in increased energy consumption
- The length of the fire is 10 m.
- The temperature of the walls is not significantly higher, and the critical air speed is too low: 1.278 m/s.
- The fire has a power of 40 MW, all fans are on, and the power of the Bora is 250 Pa. The Bora wind is stronger.
- The eastern tunnel tube measures L = 2278 m in length.

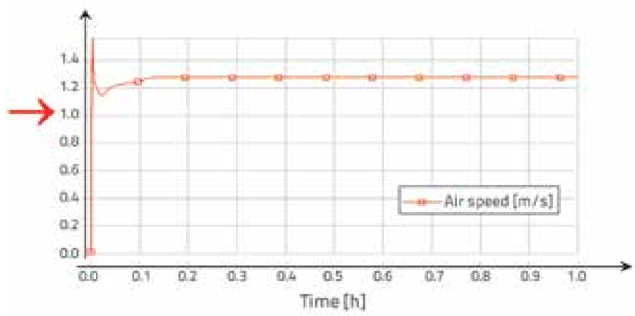

Figure 10. Display of air velocity in the tunnel tube at time t = 1 hour

Figure 10 depicts the air flow rate in the tunnel tube with 14 fans running for one hour. As can be seen from the diagram, within the allotted 180 seconds, the reached air speed is NOT higher than the prescribed 1.50 m/s critical speed. There is a realistic possibility of smoke moving backwards.

4. Conclusion

This study is focused on the critical air velocity in the tunnel tube and its correlation to the Bora pressure distribution inside the tunnel. To prevent the fire and smoke from spreading in the opposite direction, the fans must operate in accordance with RVS guidelines and achieve an average air speed of at least 1.5 m/s in the cross section of the tunnel tube, considering smoke stratification in mind. Because of the controlled ventilation, the outside air cannot or is not allowed to affect the rapid cooling of the resulting flue gases (stratification is maintained), resulting in a partial return flow rate of flue gases. Parametric studies were conducted on the effects of Bora, a strong wind with variable directions and intensities that has a significant impact on the demanding ventilation even when acting in the opposite direction of traffic. The fire load has a significant effect on the critical air velocity. To determine the critical air velocity in the tunnel tube, it is necessary to take into account the longitudinal slope of the tunnel tube and other parameters. The length of the smoke is shorter at higher longitudinal ventilation rates, but the fire load can be stronger as a result. When determining the critical air velocity in the tunnel tube, it was discovered that the air temperature T_{air} decreases with an increase in wind-induced pressure p, and consequently, the amount of flow rate Q also rises. No matter how powerful the fire load is, the critical air velocity (v_{crit}) is typically constant or always exceeds the 1.5 m/s critical speed limit, with the exception of 250 Pa. From a value of 300 Pa onwards, the air flow rate Q increases for calculated fire loads. At a pressure distribution of 250 Pa, both the temperature T and the amount of smoke increase drastically. In the primary section of the tunnel tube, the air flow rate Q changes direction (-), but the quantity for lesser fire loads (up to 50 MW) remains nearly constant. When the fire load exceeds 100 MW, the air speed increases more slowly. At pressure distributions p greater than 300 Pa, a decrease in temperature T and amount of smoke, as well as an increase in air flow rate Q, are observed. When the flow direction Q is reversed, smoke begins to spread into the primary section of the tunnel tube. When Bora blows into the exit portal of the tunnel tube, the flow rate Q has a negative sign (-), the pressure distribution p remains constant, fire temperature T rises, and fire length decreases. The flow rate Q does not increase at the same pressure distribution as the fire length increases. The speed of the air v_{crit} is opposite to the movement of the vehicles. When the length of the fire is increased, the temperature drops and the amount of smoke ε increases. On the diagrams, it can be seen that in the secondary zone, all values are low and constant when the Bora blows from Ljubljana in the range of 250–500 Pa toward the exit portal of the eastern Kastelec tunnel tube. If the Bora wind counter pressure is higher than the air pressure produced by the fans, the emissions return to the tunnel tube rather than exiting through its north portal. Furthermore, the speed of the Bora wind can make it difficult to remove flue gases from the tunnel. The speed of the Bora wind can make it difficult to remove flue gases from the tunnel. High gust pressures of between 250 and 500 Pa cause the airflow to be diverted in the opposite direction (-). Therefore, even if there is no fire, even at lower pressure distribution, from 200 Pa and above, but strong surges in accordance with RVS regulations occur, the tunnel tube should be closed! In the event of a fire, the most unfavourable air flow speed is 3.00 ÷ 6.00 m/s. At lower speeds, there is a smaller, but not dangerous, return movement of smoke, but at higher speeds, the intense air movement lowers the combustion temperature, and the smoke descends to the ground. When compared to the PIARC recommendations in the event of fire loads, a tunnel air movement speed of up to 1.50 m/s is required, preferably in a positive direction. In the event of a fire, the airspeed increases significantly due to the production of smoke at the site of the fire load (due to continuity). Because the average velocity is generally lower than the critical velocity, backlayering of smoke typically occurs. The authors of the study are aware that the appearance of air speed that is opposite to the drive direction inside the tunnel tube is contrary to the generally accepted operational principles of ventilation in fire conditions. However, the authors believe that this issue, especially in the case of the effect of strong winds on the tunnel ventilation system, needs further discussion and research.

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