© Strojniški vestnik 46(2000)7,422-428
ISSN 0039-2480
UDK 624.19:628.83:614.84
Pregledni znanstveni članek (1.02)

© Journal of Mechanical Engineering 46(2000)7,422-428
ISSN 0039-2480
UDC 624.19:628.83:614.84
Review scientific paper (1.02)

Model določitve kritične hitrosti ventilacije v primeru požara v cestnem predoru pri izotermnih pogojih

A Critical-Velocity Determination of Road-Tunnel Ventilation in Isothermal Conditions of a Fire-Incident Model Test

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Ta prispevek predstavlja eksperimentalno določitev kritične hitrosti zraka in značilnosti za oceno učinkovitosti vzdolžne ventilacije v cestnih predorih v primeru požara. Določitev kritične hitrosti zraka pri izotermnih razmerah vzdolžne ventilacije je potekala v cestnem predoru ″Sveti Rok″, ki so jo izvajali v Inštitutu za pomorske in posebne raziskave v Zagrebu. Posebna pozornost je bila namenjena analizam porazdelitve dima v neposredni bližini simuliranega ognja za različne požarne obremenitve in različne vzdolžne hitrosti zraka. Analiza je bila narejena s pomočjo vizualizacije porazdelitve ″mrzlega″ dima, ki je bil simuliran z mešanico hlapov helija in parafina. Prispevek ocenjuje eksperimentalne rezultate kritične hitrosti zraka na modelu ter rezultate nedavnih raziskav.

(Ključne besede: predori cestni, sistemi prezračevalni, kritična hitrost zraka, določevanje hitrosti)

This paper shows an experimental determination of the critical air velocity, characteristic for an evaluation of the efficiency of road-tunnel longitudinal ventilation in fire-incident conditions. Determination of the critical air velocity was made in isothermal conditions of a model testing of the “Sveti Rok” road-tunnel longitudinal ventilation, performed in the hydrodynamic laboratories of the Marine Research and Special Technologies Institute in Zagreb. Special attention was paid to the analysis of smoke distribution in the close vicinity of a simulated fire source for different fire loads and different longitudinal air velocities. The analysis was made by visualisation of the distribution of “cold” smoke simulated with the mixture of helium and paraffin vapours. The paper evaluates the results of an experimental determination of the critical air velocity on the scale-model with available recent results of ventilation-system field tests.

(Keywords: road tunnels, ventilation systems, critical velocity determination, air velocity)

0 UVOD

Ventilacijski sistemi imajo pomembno vlogo pri preprečevanju požarov v predorih zaradi odvajanja toplote in pri ″nadzoru″ dima. Zelo pomemben je ″nadzor″ dima pri vzdolžnih ventilacijskih sistemih, saj je pri tem tipu ventilacije dim, z uporabo impulznih ventilatorjev, nameščenih na stropu, odstranjen skozi isti prostor, kjer poteka evakuacija potnikov. Zaradi tega mora ventilacijski sistem v primeru požara zagotoviti dotok pare, ki mora potiskati dim v nasprotni smeri evakuacije potnikov in dostopa gasilcev. Kritična hitrost zraka je prav gotovo najbolj pomemben parameter za določitev učinkovitosti vzdolžne ventilacije v primeru požara. Označena je kot ″najmanjša vzdolžna hitrost pare, ki je povprečena prek prereza, pri kateri je dim ″odstranjen″. Glavna zahteva za uspešno odvajanje dima je doseči

0 INTRODUCTION

Ventilation systems have an important role in tunnel-fire protection because of their capability to withdraw the heat generated during the fire and to “control” smoke. Smoke control is extremely important in longitudinal tunnel ventilation systems since in this type of ventilation the smoke is forced, with the help of ceiling-hung impulse fans, through the same space of the tunnel tube through which the passengers’ evacuation is carried out. Because of this, in the case of fire, the ventilation system must secure an efficient air stream which will push smoke in the direction opposite to the evacuation of passengers and firemen access. The critical air velocity is most certainly the essential parameter for determining the efficiency of longitudinal ventilation in fire conditions. It is defined as the “*minimum longitudinal air stream velocity, averaged along the cross-section, at which the smoke backlayering is made impossible*”. Achieving the critical air velocity is a kritično hitrost zraka, ki omogoča intervencijo gasilcev ter njihovo varno delo v bitki z ognjem. Nezanesljivi ventilacijski sistemi, ki ne zagotovijo kritične hitrosti zraka v primeru požara, neposredno ogrožajo gasilce, ki so vstopili v predor in pričeli gasiti, pa tudi potnike, ki se umikajo prek nezadimljenega dela predora proti izhodu, drugemu predoru ali v zaklonišče.

basic prerequisite for successful tunnel smoke purging which enables the intervention on the part of fire brigades and their safe work on fire fighting. An unstable ventilation system, which cannot reach the critical air velocity in fire conditions, directly endangers firemen who have entered the tunnel tube and begun fire fighting, as well as the passengers who are moving, in the stage of evacuation, along the unsmoked part of the tunnel towards the exit, the other tunnel tube or the shelter.

1 TEORETIČNA DOLOČITEV KRITIČNE HITROSTI ZRAKA

1 THEORETICAL DETERMINATION OF CRITICAL AIR VELOCITY

Izrazi za oceno kritične hitrosti zraka v predoru (w_c) so razviti iz najbolj preprostih oblik, ki povezujejo odvisnost:

Expressions for estimating the critical air velocity in the tunnel (w_C) have evolved from the most simple form, which shows the functional connection:

$$w_C = f\left(\sqrt[3]{\frac{Q}{B_t}}\right) \quad (1),$$

kjer pomenita Q toplotno obremenitev in B_t širino predora. Thomasova empirična enačba:

where Q is the fire thermal load and B_t the tunnel tube width, through the Thomas' empirical expression:

$$w_C = \left[\frac{gQH}{\rho_0 T_0 c_p A}\right]^{1/3} \quad (2),$$

kjer so g gravitacijski pospešek, h višina predora, ρ_0 gostota zraka, T_0 temperatura vstopajočega zraka, c_p specifična toplota zraka, A površina prečnega prereza predora, kar vse vodi k spremembi Thomasovega izraza [1]:

where g is gravity, H is the tunnel tube height, ρ_0 is the air density, T_0 is the temperature of the incoming air, c_p the specific air heat and A the surface of the tunnel tube cross-section, all up to the modification of Thomas' expression which has been confirmed by field tests [1]:

$$w_C = K_1 K_2 \left(\frac{gQH}{\rho_0 T_D c_p A}\right)^{1/3} \quad (3),$$

kjer so:
- količnik $K_1 = Fr_C^{-1/3}$
- količnik $K_2 = 1 + 0{,}037\ (\text{strmina})^{0,8}$
- povprečna temperatura dima $T_D = \dfrac{Q}{\rho_0 c_p A w_C} + T_0$

where:
- coefficient $K_1 = Fr_C^{-1/3}$
- coefficient $K_2 = 1 + 0{,}037\ (\text{gradient})^{0,8}$
- average temperature of smoke $T_D = \dfrac{Q}{\rho_0 c_p A w_C} + T_0$

Enačba (3) za oceno kritične hitrosti (w_c) zahteva iterativni postopek, ki ga uporabljamo tudi pri računanju povprečne temperature dima. Froudovo število v količniku K še dodatno pripomore k zapletu ocene, saj ne poznamo vseh elementov za njegovo določitev.

The above-mentioned formula (3) for the critical velocity (w_C) estimate requires an iterative procedure since the same is also contained in the expression for the average smoke temperature. Introduction of the Froude number through the coefficient K_1 additionally complicates the estimate since not all elements for its determination are known.

2 DOLOČITEV KRITIČNE HITROSTI ZRAKA S PRESKUSI

2 EXPERIMENTAL DETERMINATION OF CRITICAL AIR VELOCITY

2.1 Splošno

2.1 General

Določitev kritične hitrosti zraka s preskusi:

a) testiranje ventilacije in možnosti požara,
b) na testnem modelu ventilacije in požara pri izotermnih in neizotermnih pogojih.

Najbolj obsežne terenske raziskave obnašanja različnih ventilacijskih sistemov v primeru požara so bile opravljene v zapuščenem

Experimental determination of critical air velocity can be made by:

a) field tests of ventilation and fire incident;
b) scale-model tests of ventilation and fire incident in isothermal and non-isothermal conditions.

So far the most complex and comprehensive field test of the behaviour of various ventilation systems in fire-incident conditions was performed in the abandoned Mepredoru Memorial [1] (ZDA, 1993 do 1995) pod pokroviteljstvom Federalne cestne administracije, skladno s programom Tehničnega komiteja 5.9 ASHREA. V sklopu omenjenih raziskav so bile poleg kritične hitrosti vzdolžnega sistema ventilacije raziskane tudi toplotne obremenitve do 100 MW. Rezultate ocen kritične hitrosti dobimo s spremenjeno Thomasovo enačbo. Raziskave so pokazale, da kritična hitrost zraka ne presega vrednosti 3 m/s v razponu toplotnih obremenitev od 5 do 100 MW.

Testni model pri neizotermnih pogojih temelji na toplotnih virih z bistveno zmanjšano toplotno obremenitvijo. Oka in Atkinson sta leta 1996 izvedla preskus neizotermnega testnega modela, ki je ugotavljal porazdelitev dima v povezavi z vzdolžno ventilacijo [2]. Glavni namen je bil določitev kritične hitrosti zraka v odvisnosti od različnih toplotnih obremenitev požara, ki je bil simuliran z zgorevanjem propana.

Testni modeli požara in ventilacije pri izotermičnih pogojih navadno temeljijo na t.i.″mrzlem″ dimu, ki je pravzaprav mešanica enega od lahkih plinov (npr. helij) z zrakom, dušikom ali ogljikovim dioksidom. Za namen boljše vizualizacije so dodali barvne komponente, npr. paro glicerina. Toplotne obremenitve v testnem modelu ne ustrezajo tistim v primeru požara, z njimi niti ne moremo predstaviti vseh potrebnih fizikalnih lastnosti požara kot celotnega pojava. Kakorkoli že, navkljub očitnim omejitvam, ki spremljajo raziskave ventilacije v primeru požara pri izotermnih pogojih, dobljene vrednosti resničnih meritev v primerjavi z računalniškimi simuliranji ne odstopajo veliko. Omenjeni rezultati se nanašajo na določitev kritične hitrosti zraka in vizualizacije porazdelitve dima v bližini simuliranega vira ognja.

2.2 Model določitve kritične hitrosti pri izotermnih pogojih

2.2.1 Model, namen in pogoji testiranja

Določitev kritične hitrosti zraka pri izotermnih pogojih so izvajali skupaj z modelom testiranja ventilacije v predoru Sveti Rok in v Inštitutu za pomorske in posebne raziskave v Zagrebu [3]. Model je vključeval uporabo vzdolžne ventilacije v razmeroma dolgem predoru z dvosmernim prometom. Namen testiranja je bil, poleg določitve vpliva prometa na učinkovitost delovanja ventilacijskega sistema, tudi napoved obnašanja sistema v primeru požara. Kritična hitrost zraka je bila določena za tri toplotne obremenitve 5, 10 in 20 MW. Podatki in rezultati so prikazani v preglednici 1.

morial tunnel [1] (USA, 1993 to 1995.), under the auspices of the Federal Highway Administration, according to the Technical committee 5.9 ASHREA program. The critical velocity of the longitudinal ventilation system, including the fire loads up to 100 MW was also determined within the scope of these tests. The tests resulted in a modification of the standard Thomas' formula for the critical velocity estimate which thus acquires the form of the above-mentioned expression (3). Subject tests have established that the critical air velocity does not exceed the value of 3 m/s for a wide range of fire loads from 5 to 100 MW.

Model tests in non-isothermal conditions are based on the real heat source with an essentially reduced heat load that is appropriate to the model. An example of a non-isothermal model test is testing of the smoke distribution in conjunction with the longitudinal ventilation made by Oka and Atkinson in 1996 [2]. The basic purpose of this testing was a determination of the critical air velocity depending on different heat loads of fire stimulated by the propane burner operation.

Model tests of the fire incident and tunnel ventilation in isothermal conditions are usually based on so-called "cold" smoke which is actually a mixture of one of the "light" gases (e.g. helium) with air, nitrogen or carbon dioxide. For the purpose of improved visualisation, coloured components are added, for example, glycerine vapours. This type of testing cannot model the heat loads adequately in case of fire, nor is it possible to present all the necessary physical properties of fire as a complex phenomena. However, in spite of obvious limitations which accompany the isothermal tests of ventilation in fire conditions, the obtained results of some physical values which characterise the behaviour of the ventilation system in fire conditions, have shown good correlation with field tests and computer simulations. First of all, the mentioned results refer to a determination of the critical air velocity and a visualisation of the smoke distribution close to the simulated fire source.

2.2 Determination of critical velocity in isothermal conditions of model tests

2.2.1 Model, purpose and conditions of testing

Determination of the critical air velocity in isothermal conditions was carried out during model testing of the ventilation of the *Sveti Rok* tunnel in the hydrodynamic laboratories of the Marine Research and Special Technologies Institute in Zagreb [3]. The proposed design solution included the use of longitudinal ventilation in a relatively long single-tube tunnel with bi-directional traffic. Determination of the critical velocity was made for three standard fire loads of 5, 10 and 20 MW. Because of the complexity of the mentioned tests the interval of fire loads was not extended to values above 20 MW. Input data and the results of the subject tests are shown in *Table 1.*

Zgoraj omenjene raziskave so se odvijale na tako imenovanih majhnih fizikalnih modelih (razmerje 1:25). Model predora je imel obračališče, dve zavetišči (oziroma vhoda v zavetišči), tri obcestna počivališča in pet baterijskih ventilatorjev z resnično dolžino 675 m (dolžina na modelu 27 m). Pleksi steklo (debeline 3 mm) je bilo nameščeno po predoru in omogočalo nadzor širjenja dima med simuliranjem požara in tudi nadzor pretoka prometa.

The above-mentioned model tests were carried out on a so-called "small" physical model (Scale 1:25) and for tunnel modelling the central section which includes one turning gallery, two shelters (i.e. entrances into shelters), three lay-bys for stopping vehicles and five fan batteries with the actual length of 675 m (model length 27 m). Perspex (3 mm in thickness) was used for the tunnel lining to enable monitoring of the spreading of smoke during the fire incident simulation as well as the control of traffic flow.

Preglednica 1. *Podatki in rezultati za določitev kritične hitrosti na modelu in v predoru*
Table 1. *Input data and results of critical velocity determination on model and on site*

NA TERENU / ON SITE	***Toplotna obremenitev / Thermal load***	***MW***	**5**	**10**	**20**
	ekvivalentna površina gorenja / equivalent burning area	*m^2*	*2*	*4*	*8*
	nastala količina dima / generated volume of smoke	*m^3/s*	*20*	*33*	*60*
NA MODELU / ON MODEL	*ekvivalentna površina gorenja / equivalent burning area*	*cm^2*	*32*	*64*	*128*
	nastala količina "mrzlega dima" / generated volume of "cold smoke"	*l/s*	*6,4*	*10.6*	*19.2*
	pretok zraka skozi predor / air flow through tunnel	*m^3/s*	*0,0393*	*0.0458*	*0.0467*
	hitrost toka zraka skozi model predora / air stream velocity through the model tunnel tube	*m/s*	*0,423*	*0.493*	*0.503*
	razdalja med "čelom" dima in mestom gorenja / distance of the smoke layer face from the place of fire	*m*	*-2,0 do/to -1,8*	*-2.0 do/to -1.8*	*-2.0 do/to -1.8*
REZULTATI / RESULTS	***razdalja[1] med "čelom" dima in mestom gorenja (na kraju samem) / distance[1] of the smoke layer face from the place of fire (on site)***	*m*	***- 50 do/to - 45***	***- 50 do/to - 45***	***- 50 do/to - 45***
	hitrost toka zraka skozi predor (na kraju samem) – kritična hitrost w_c / air stream velocity through the tunnel (on site) - critical velocity w_c	*m/s*	***2,115***	***2,465***	***2,515***

(1) Negativen predznak pomeni, da je razdalja merjena v nasprotni smeri od smeri toka zraka med odstranjevanjem dima
(1) Negative sign denotes that the distance is measured in the direction contrary to the direction of air flow during the "smoke purging" regime

2.2.2 Rezultati

V skladu z rezultati testnega modela je odvisnost kritične hitrosti od toplotne obremenitve prikazana na sliki 1. Razvidno je, da krivulja kritične hitrosti enakomerno narašča glede na toplotno obremenitev in pri veliki toplotni obremenitvi se asimptotično približuje vrednosti 3 m/s, z drugimi besedami, občutljivost kritične hitrosti se zmanjšuje v območju večjih toplotnih obremenitev, kar v praksi omogoča uspešno odstranjevanje dima iz predora v širokem razponu toplotnih obremenitev do 100 MW s hitrostjo okrog 3 m/s.

Slika 2 prikazuje medsebojno odvisnost kritične hitrosti zraka in toplotne obremenitve s Froudovim številom kot parametrom. Prej omenjeni spremenjeni Thomasov izraz (3), ki je bil preverjen v predoru Memorial, je bil uporabljen tudi za določitev družine krivulj $w_c = f(Fr,Q)$. Razvidno je, da je krivulja $w_c = f(Q)$, ki smo jo dobili s ekstrapolacijo merjenih vrednosti testnega modela, ki so bili izvajani v

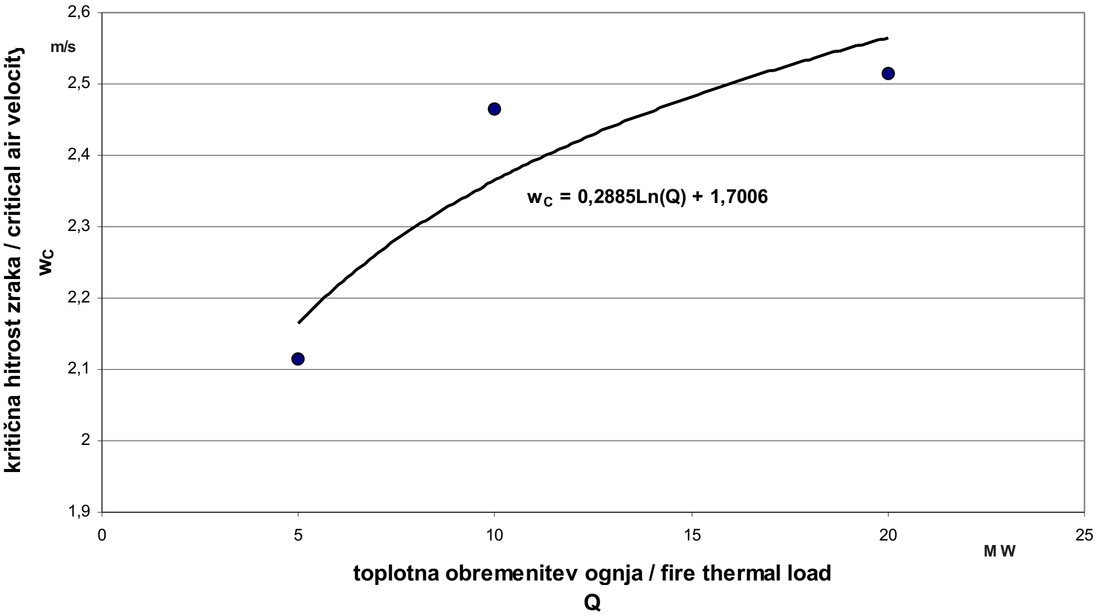
2.2.2 Results

In compliance with the results of model tests, the critical velocity dependence on the fire load is shown in *Figure 1*. It is clear that the critical velocity is a uniformly growing fire load curve which for high fire loads asymptotically aims at the value of 3 m/s. In other words, the "sensitivity" of the critical velocity drops in the area of high fire loads and in practice it enables the successful smoke purging of the tunnel for a wide range of fire loads up to about 100 MW with the speed of about 3 m/s.

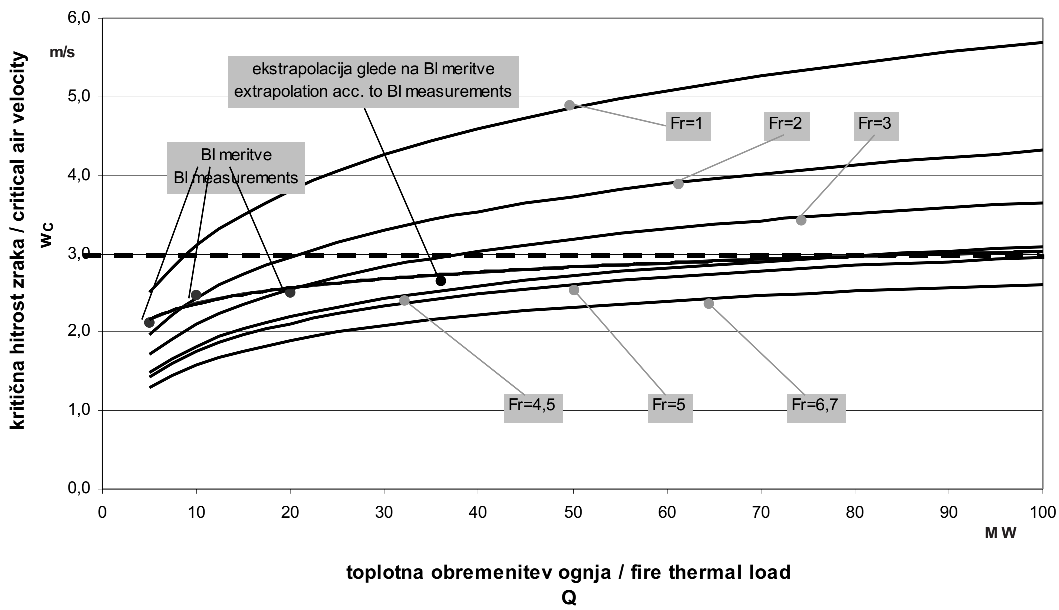
Figure 2 shows the interdependence of the critical air velocity and the fire thermal load with the Froude number as a parameter. For this, previously mentioned modified Thomas' expression (3), checked during testing in the Memorial tunnel was used for determining the curve family $w_C = f(Fr, Q)$. It is visible that the curve $w_C = f(Q)$, obtained by extrapolation of measured values of model tests carried out in the Marine Research and Special Technologies Insti-

Iinštitutu za pomorske in posebne raziskave (BI), se dobro ujemajo s teoretično krivuljo za vrednost parametra Froudovega števila 4,5, še posebno v območju višjih toplotnih obremenitev. Enako vrednost Froudovega števila so omenili tudi avtorji testiranj v predoru Memorial [1] kot vrednost, ki najbolj približa teoretične in praktične preskuse. Določene odmike od kritičnih hitrosti, merjenih v BI, v primerjavi s teoretičnimi vrednostmi v območju toplotnih obremenitev, lahko pojasnimo z dejstvom, da je bila gostota mrzlega dima nespremenljiva za celotno področje med 5 in 20 MW, kar pa ni stvarno. Omenjena gostota ustreza

tute (BI), matches well the theoretical curve for parameter value of Froude number 4.5, particularly in the area of higher fire loads. The same value of Froude number is mentioned by the authors of tests performed in the *Memorial tunnel* [1], as the value which best “adapts” the theoretical expression to the field tests. Certain deviations from critical velocities measured in the BI, in comparison with theoretically computed value in the range of lower fire loads, are explained by the fact that the density of “cold” smoke was kept constant for the entire testing interval from 5 to 20 MW, which is not a physical reality. The mentioned density corresponded to an assumed smoke



Sl. 1. *Odvisnost kritične hitrosti zraka od toplotne obremenitve ognja*
Fig. 1. *Dependence of critical air velocity upon simulated fire load*



Sl. 2. *Odvisnost kritične hitrosti zraka od toplotne obremenitve s Froudovim številom kot parametrom*
Fig. 2. *Dependence of critical air velocity upon simulated fire load, with Froude number as parameter*

načrtovani temperaturi dima 1350 °C, kar je še vedno prevelika vrednost za požare take toplotne obremenitve. Upoštevajoč dejstvo, da je dejanska temperatura dima za omenjene temperaturne obremenitve manj od 1350 °C in bi zato morala biti gostota mrzlega dima večja od tiste, ki so jo uporabili pri testiranjih (0,182 kg/m^3). Iz tega lahko sklepamo, da bi krivulja BI in teoretična krivulja za w_c dale boljše rezultate, kakor če bi računali z manjšimi toplotnimi obremenitvami.

temperature of 1350°C, which is still too high a value for fires of this low thermal load. Considering the fact that the actual temperature of smoke for the mentioned fire loads is less than 1350°C and that therefore the density of "cold" smoke should have been higher than the one used during model testing (0.182 kg/m^3), it can be concluded that the BI curve and the theoretical curve for w_C would have given much better agreement than the achieved one at mentioned lower fire loads.

3 SKLEP

Vrednosti kritične hitrosti zraka, ki smo jih dobili s testiranjem ventilacije v predoru Sveti Rok pri izotermnih pogojih, se ujemajo s teoretičnimi izračuni. Majhne odmike v območjih manjših toplotnih obremenitev lahko pojasnimo s povečanjem gostote mrzlega dima, ki ustreza dejansko nižjim temperaturam dima v predorih. Gostota uporabljenega mrzlega dima, ki ustreza resnični temperaturi dima 1350 °C je nižja od tiste, ki se pojavi v predorih v primeru manjših toplotnih obremenitev. Izotermni pogoji testiranja niso vplivali na verodostojnost pridobljenih podatkov o kritični hitrosti zraka, čeprav je problem fizikalnih vrednosti povezan izključno z delovanjem ventilacijskega sistema pri neizotermnih pogojih.

3 CONCLUSION

Measured values of critical air velocities obtained by model tests of the Sveti Rok tunnel ventilation in isothermal conditions have a high degree of agreement with theoretically computed and on-site confirmed values. The slight deviations noted in the area of lower fire loads can be annulled by an increase of the "cold" smoke density that is appropriate to actually lower temperatures of smoke on site. In that sense the density of used "cold" smoke, which corresponds to the real temperature of smoke of 1350°C, has shown to be lower than the one which occurs on site for the case of observed smaller values of fire loads. Isothermal conditions of testing, however, have not affected the credibility of the obtained data on the necessary critical air velocities, although it is the question of the physical value which is connected exclusively with operation of the ventilation system in fire, i.e. in distinctly non-isothermal conditions.

4 OZNAČBE
4 SYMBOLS

kritična hitrost	w_C	m/s	critical velocity
toplotna obremenitev ognja	Q	W	fire load
širina predora	B_t	m	width of tunnel
višina tunela	H	m	height of tunnel tube
gostota zraka	ρ_0	kg/m^3	air density
temperatura zraka	T_0	K	air temperature
temperatura dima	T_D	K	smoke temperature
spec. toplota zraka	c_p	J/kgK	spec. air heat
površina prereza predora	A	m^2	tunnel cross-section area
Froudovo število	Fr	-	Froude number

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Prejeto:
Received: 15.8.2000

Sprejeto:
Accepted: 10.11.2000