5th International Symposium on the
AERODYNAMICS & VENTILATION OF VEHICLE TUNNELS
Lille, France: 20-22 May, 1985

PAPER B2

EMERGENCY OPERATION OF VENTILATION FOR THE KAN-ETSU ROAD TUNNEL

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Summary

The Kan-etsu Road Tunnel is equipped with a longitudinal ventilation system in spite of its length of 10.9 km, the longest road tunnel in Japan. The study on the performance of normal ventilation was already presented at the 4th ISAVVT. In the present paper, the authors will discuss in detail the operation methods of ventilators related to refuge circumstances when fire breaks out in the tunnel.

The authors have made a thorough investigation on the spatial and temporal distribution of smoke through numerical simulation under the various operation regimes which might be installed in the actual system.

Shutdown of all ventilators is the simplest and immediately obvious mode of operation. With this mode, it is possible to maintain safety under most of the situations. In some cases, however, on account of unbalanced traffic or strong ventilation draft by natural wind, a critical situation may be expected to occur.

One of the improvements to this primitive method is a feedback control of the axial flow velocity in the tunnel. If the jet fans could be properly operated according to the situation inside the tunnel, the most favorable circumstance to the refugee could be realizaed. We set the criteria that the flow velocity in the tunnel would come down to zero as soon as possible and keep it. The control system was established on the simulator, in which traffic and wind velocity data are utilized. By this mode, the wind velocity could be successfully reduced to values below 1 m/s within three minutes at the most for all simulation cases.

Held at the Lille Chamber of Commerce. Organised and sponsored by BHRA, The Fluid Engineering Centre. Co-sponsored by Pole de Mecanique de la Region Nord/Pas-de-Calais, France and P.L.C. Peters Ltd., U.K.

NOMENCLATURE

c = concentration of smoke
D = coefficient of diffusion
F_t = Forces acting on the air column in the tunnel
I = intensity of light through the smoke of concentration c
I_0 = intensity of light through clean air
l = length between the light emmiter and the detector
M = mass of the air column
q = production term of smoke
t = time coordinate
U_p = refuge velocity
V_r = air flow velocity in the axial direction of the tunnel
x = space coordinate in the axial direction of the tunnel
(positive is taken toward north)

Suffix

i = 1, 2 or 3 : number of tunnel section

CORRECTIONS

p. 78 l. 7 emmiter --> emitter
p. 79 l. 20-21 ventilatior --> ventilator
p. 80 l. 26 telefones --> telephones
p. 83 l. 16-17 the resistance is proportional to the square of current -->
the resistance is proportional to the current

p. 87 in Fig. 3 i_1^2, i_2^2, i_3^2 --> i_1, i_2, i_3

1. INTRODUCTION

The Kan-etsu tunnel, although it is the longest road tunnel in Japan, is equipped with a longitudinal ventilation system with vertical shafts and electric precipitators, from the point of economy in construction and operation. Because the longitudinal system is applied to such a long tunnel for the first time in the world, detailed investigations were performed on ventilation operation both for normal and abnormal situations.

In the study of normal operation, emphasis was placed upon how to ventilate properly, keeping polutant concentrations below certain levels, while, at the same time, observing economy. According to a series of numerical simulations under various control systems, we have found it best to control ventilators with a combined feedback-feedforward controller system, taking polution concentrations and traffic into account (Ref. 2). The system is being constructed so that this control method could be realized.

The most serious situation among abnormal cases is fire in the tunnel. It is important from the side of operation to secure such circumstances that people can take refuge safely when a fire breaks out. Because smoke is likely to disturb the action of taking refuge, it had been hoped to study precisely the relationship between the emergency operation of ventilation and the resultant behaviour of smoke.

The authors have investigated through numerical simulations how well the ventilatiors could be operated in emergency cases, against the effect of traffic and natural wind. As connecting tunnels between the main and the refuge tunnel are installed every 350m in the direction of the tunnel shaft, it is considered to be safe when the people arrive at this point. The most important problem is therefore reduced to suppressing the movement of smoke especially in the first few minutes.

For the first stage, the behaviour of smoke is investigated under various traffic, natural wind conditions and fire point locations, when all the ventilators are shut down as soon as the fire is detected. The next alternative is a trial to reduce the dependence of the wind velocity upon traffic and natural wind, by means of blowing a large amount of air in the sections other than the one including the fire point. And the most sophisticated method is the feedback control of jet fans with regard to the air flow velocity, taking traffic data also into account.

For each operation mode, various cases are numerically simulated. Typical results are demonstrated and discussed. Finally a proposal is made as to how the result of this study could be realized in the actual system.

2. THE FEATURE AND THE EQUIPMENT OF THE TUNNEL

2.1 The feature of the Kan-etsu tunnel

The Kan-etsu tunnel is a part of the 300 km long Kan-etsu highway which combines Tokyo and Niigata. The tunnel is at about 150 km north north west of Tokyo. After ten-odd years from the start of planning, it is now almost completed and is under the final construction stage to be open for public service in November 1985. The final plan is to serve four lanes with two tunnels, but it will be used as facing traffic with the first tunnel until the density of traffic grows up to a certain level. The tunnel could attract world attention not only from its length of 10,885m but also from its equipment.

The standard cross sectional area of the main shaft is 61.5 m^2. It has two vertical shafts which are about 10m in diameter with the length of about 200m each. The pilot tunnel, with its sectional area of 25 m^2, runs parallel to the main tunnel, and will be used as a refuge tunnel. For this reason, connecting tunnels are dug between the main and the refuge tunnel, numbering up to 34 (refer Ref. 1).

2.2 Ventilation for the ordinary case

Kan-etsu tunnel is remarkable in that it is equipped with the longitudinal ventilation system in spite of its length. Although the authors have discussed the normal ventilation method in detail elsewhere (Ref. 2), the basic concept will be given here again. The design conditions for facing traffic are

Maximum traffic flow	1515 /h
Average speed	60 km/h
Rate of diesel engined vehicles	34.2 %
Allowable light transmissivity	40 % (for 100m)
Allowable CO concentration	100 ppm
South/north facing traffic ratio	60% / 40%
Natural wind	-2.5 m/s (toward south)
Direction of ventilation air flow	toward north

Under these conditions, the allowable concentrations have to be maintained by means of the two ventilation stations at the bottom of the vertical shafts, the five electrostatic precipitator stations, and 52 jet fans (1.5m in diameter). The necessary air flow rate for the above conditions is shown in Fig. 1, together with the resultant concentration distributions of smoke and CO. The relative value 1 corresponds to 40% of light transmissivity and 100 ppm of CO respectively. In practice, however, the distributions change with time on account of the change of traffic and natural wind. We have proposed the combined feedback-feedforward control system to cope with this difficulty in the last report (Ref. 2), and the equipments are being prepared to convert the proposal into reality.

2.3 Installations against disaster

It is strongly desirable to inform the control center urgently when fire breaks out or an accident happens, so that they can take quick measures against it. For this purpose, the following equipments are going to be installed.

2.3.1 Communication equipment

As communication equipment, push button communicators, fire detectors, emergency telefones and retardation detectors are being installed.

2.3.2 Emergency warnings

Warning displays at the entrance and inside of the tunnel, flicker lamps, warning lamps and sirens are being installed in order to inform the people of the accident and let them stop or keep off the tunnel.

2.3.3 Fire extinguishing equipment

Fire extinguishers, fire plugs, hydrants and water sprays are being installed.

2.3.4 Refuge guide equipment

In order to guide people to the safe place in case of emergency, markings for emergency exit, refuge guide beacons, medium wave re-broadcasting equipment, loud speakers, ventilators for the refuge tunnel and the emergency lighting equipment are being installed.

3. NUMERICAL SIMULATION OF EMERGENCY OPERATION

3.1 The purpose of simulation in the emergency case

The Kan-etsu tunnel is equipped with a longitudinal ventilation system, which means it is ventilated by blowing air in the direction of the tunnel axis. For this reason, and also because the air in the tunnel has a large amount of inertia, it is not easy to reduce its velocity in a short time, which is strongly desired in case of fire. Moreover, in this event, the traffic flow is likely to change very rapidly, which makes the situation more complicated, so that we cannot guarantee to get favourable conditions only by stopping all the ventilators. Therefore it was necessary to find out suitable emergency ventilation modes for the actual system through executing numerical simulations under several alternative modes and considering the result. For this simulation, the most likely or the most severe conditions are assumed for traffic, natural wind, smoke intensity etc.

3.2 Simulation models

In constructing the simulator, it is necessary to express the phenomena by a simplified mathematical model, including its intrinsic properties. Here, we will present the aerodynamic model, the smoke diffusion model, and the traffic model.

3.2.1 The aerodynamic model

Aerodynamically, the whole tunnel is considered to consist of three sections, divided by the two vertical shafts. We are going to combine the equations of motion for each section under conditions of continuity for pressure and flow rate. We suppose that the effect of compressibility can be neglected without disturbing the overall phenomena. Thus, the movement of the air column in the tunnel section i is described by Newton's equation of motion as if it is a solid body.

$$\frac{dV_{ri}}{dt} = \frac{F_{ti}}{M_i} \quad , \quad (i = 1, 2 \text{ or } 3) \qquad (1)$$

F_t is the total force acting on the air column of the corresponding section including the piston force of cars, the driving force by ventilators and jet fans, the force by natural wind and the resistance by friction. Full expressions for these are shown in the last report (Ref. 2). Natural wind velocity denotes the air flow velocity in case that there are no vehicles and no operation of ventilators. Eq. (1) is solved numerically by transforming into difference equation with 10 seconds of time division. The spatial coordinate is taken positive toward north.

3.2.2 The diffusion model of smoke

Although smoke usually stays only near the ceiling around the fire source because of heat, we use a one dimensional model of convection and diffusion for simplicity.

$$\frac{\partial c}{\partial t} = - V_r \frac{\partial c}{\partial x} + D \frac{\partial^2 c}{\partial x^2} + q \qquad (2)$$

The left hand side denotes temporal change of smoke density at a certain point, whereas on the right hand side, the first term corresponds to convection, second term to diffusion and the third term to generation. By using this model, it is supposed that the results of the simulation give worse situations because smoke is treated as being mixed within each cross section even in the vicinity of the fire point. In other words, we can expect that the results of simulation show the safer side through this model from the view point of being the material for consideration and decision. c denotes the absolute concentration of smoke, which is related to the light transmissivity through length l as

$$I = I_0 e^{-cl} \qquad (3)$$

In this simulation, the diffusion term is neglected because it is thought to be small enough compared with the convection term, since there is no disturbance by vehicles in the region considered. Eq. (2) is solved as a difference equation with the time step of 1 second and the spatial step of 10m. The solution V_r of Eq. (1) is interpolated into every 1 second and used when solving Eq. (2). The range of x to be considered is each one kilometer in both direction from the point of fire.

3.2.3 The traffic model

The traffic model used in the simulation of emergency should satisfy such conditions as having enough stability and reproductivity, and also express the deceleration process of a group of cars reasonably. From this point of view, a macro model is used in this simulation, expressing cars as a continuous distribution in time and space, in which the deceleration process is formulated as approximate equi-deceleration movement.

3.3 Assumed conditions for simulation

3.3.1 Intensity curve of smoke generation

According to the measurement of the generation process of smoke, CO and NO_x by the experiment of burning passenger cars and large-sized buses in an actual scale tunnel, it was found that the quantities of CO and NO_x are relatively small so that they would not affect the refuge action direct. Therefore, we only have to cope with smoke. With regard to the generation intensity of smoke, which is the product of volumetric generation and its concentration, we have superimposed various experimental curves, and established a hypothetical curve as shown in Fig. 2 so that it contains almost all of them.

3.3.2 Traffic flow before the accident and the points where cars stop

We slide the design values to the status of traffic flow before the accident, which reads

maximum traffic flow	1515 /h
Average speed	60 km/h
Rate of diesel engined vehicles	34.2 %
South/north facing traffic ratio	60% / 40%

Cars are assumed to stop in the following way

i) After the accident, cars are accumulated at that point from both directions.
ii) After the information displays "FIRE: STOP!" are lighted, cars running toward fire point are accumulated at 18 emergency park areas and at the entrances of the tunnel.
iii) All the cars moving further from the fire point are not controlled at all.

Deceleration process of cars is as such: a car begins braking 2.5 seconds later than the car just in front of it has begun braking, they stop finally in 10m pitch. The macro model was so approximated that cars reduce their velocity as equi-deceleration.

3.3.3 The point of fire

We assume one of the following three as the fire point, at each section of the tunnel

T1 : 1.1 km from the south portal (in the 1st section)
T2 : Middle point of the whole tunnel (in the 2nd section)
T3 : 1.1 km north from the 2nd vertical shaft (in the 3rd section)

3.3.4 Time serial process

The outbreak of fire is chosen as the origin of time coordinate, an accident happens one minute earlier than that (-1 min.). On the information displays, "FIRE: STOP!" is lighted at +1 min.. In other words, at -1 min., an accident happens, cars begin to be accumulated at the point. At 0 min., flame comes out, and detected by a fire detector, ventilator operation is automatically switched into emergency mode, and the generation of smoke increases. At +1 min., warning is displayed on information boards, and cars stop at the emergency park areas and the entrances of the tunnel.

3.3.5 Natural wind

Because the velocity of air flow is more difficult to be brought down, +2.5 m/s (toward north) is mainly taken, in the direction that coincides with the direction of the ventilation air flow. However, a lot of case studies are also performed for -2.5 m/s, +4 m/s and -4 m/s.

Among the above mentioned items, 3.3.2 and 3.3.4 are also modified for a further variety of simulation cases, but we are not going to mention them in the present paper.

3.4 Emergency operation mode of ventilation

Because of the complexity in such a big tunnel system, it is almost impossible that the operators make decision properly on each ventilators in case of fire. Therefore, it is basically supposed that ventilation operation is automatically switched over to previously specified emergency mode when the fire is detected.

K1 : Shutdown of all the ventilators and jet fans
This is the operation to stop all the ventilators and jet fans as soon as a fire breaks out. In case of failure in power line, we are forced to choose this mode. The wind velocity in the tunnel does not always behave in a favourable manner in this operation on account of the piston force by cars and of the natural wind.

K2 : To blow a large amount of air in the sections other than at the fire point
Characteristics of longitudinal ventilation of the tunnel is understood in analogy with electric circuit shown in fig. 3. Resistance of pipe flow and electronic resistance, pressure difference (or driving force in terms of pressure) and voltage, air flow rate and current correspond to each other. But we have to pay attention to the specific nonlinear characteristic that the resistance is proportional to the square of current. According to this property, if we blow a large amount of air flow at the sections other than the one includind fire point to make resistance larger, the effect of cars and natural wind could be reduced. As an example, when fire occurs in the first section, the air is blown into the tunnel through the first vertical shaft and driven towards the north portal by means of jet fans.

K3 : Automatic control based upon traffic and air velocity data
This is the mode to control jet fans based upon data both from traffic counters and anemometers so that air flow in the tunnel comes to zero. In this study, vertical shafts are closed, treating the tunnel as "one shaft".

4. RESULT AND CONSIDERATION

4.1 The relationship between refuge speed and smoke concentration

Among products, heat, smoke and hazardous gases that merge from fire in the tunnel, it is smoke that directly inhibits people from taking refuge. It is said that normal walking velocity without smoke, for example when going to office in the morning, is 1.0 m/s to 2.0 m/s. There is another report on the study of a fire case in underground shopping center that people could walk to refuge with 1.6 to 1.8 m/s even in smoke of 0.6 1/m lead by a man familiar with the building. In the present study, refuge speed U_p is assumed to be 1.7 m/s in the smoke thinner than 0.1 1/m, and 1.0 m/s in it less than 0.4 1/m. These values are considered to be low enough for safety due to the fact that the tunnel has rather simple structure and that the emergency lighting is expected. Moreover, we set the target that people do not experience the smoke more than 0.4 1/m until they arrive at the connecting tunnel within 350m.

4.2 Simulation output and its interpretation

Results of numerical simulations are graphically printed out to display the distribution of smoke in time and space. Fig. 4 shows how it is displayed. The axis of abscissa denotes the spatial coordinate x, taken with the fire point as origin. One division corresponds to 200m. The vertical axis downward is temporal coordinate t with two minutes' division. The broken line denotes the boundary of smoke concentration 0.01 1/m, whereas chained line 0.1 1/m and black line 0.4 1/m. The bold line shows the process of the refuge of a person who was at the point of fire. This line is drawn under the assumption described in 4.1. We can see the development of refuge process how the persons have experienced the smoke until he arrives at the connecting tunnel which locates within 350m.

Again, Fig. 4 (case 1) is the result for the case of fire point T1, natural wind

+2.5 m/s (toward north) and the operation mode K1. Because the fire point is very near to the south portal, most of the cars toward south stop very soon at the emergency parkings, on the other hand, cars toward north are not controlled. Thus a big unbalance in traffic force occurs. And natural wind also acts in the same direction, which results in the air flow velocity in the tunnel not settling down in several minutes, keeping more than 2 m/s. With regard to safety, however, the person at the origin has almost finished taking refuge only through smoke less than 0.1 1/m, which could be judged safe.

Fig. 5 (case 2) is for fire point T3, natural wind -2.5 m/s and the operation mode K1. In this case, the piston force of vehicles and the natural wind effect both in the negative direction, which causes the reversal of the wind direction soon after the outbreak of fire. Therefore, it is not dangerous for the people who have been in northern side (right hand side in the figure), but rather there arises possibility that the people on the other side are exposed to danger. One of the two bold lines in the left side, shows the process of refuge when the person starts at the time of outbreak of fire, the other is the one when he starts after he has experienced 0.01 1/m smoke. From this result, we may draw two important conclusions : a) it is extremely important to transmit information in the earliest time and let them start refuge action. b) it is favourable to avoid the reversal of air flow direction.

In the following two figures, Fig. 6 (case 3) and Fig. 7 (case 4), we can see very clearly how the phenomena depend upon natural wind. These are both for T2 and K1, the only difference is natural wind, +4 m/s and -4 m/s. As 4 m/s is a pretty big value, we took it as an extreme example. In Fig. 6, the air flow continues in positive direction under +4 m/s natural wind, whereas it turns into opposite direction in the early time under -4 m/s.

The cases for operation K2 and fire point T2, are shown in the next two figures, in which the first and the third section are the tubes for high speed flow. Although Fig. 8 (case 5) shows a very good reduction of air speed under the natural wind of +4 m/s, in Fig. 9 the reversal of flow direction occurs early under the natural wind of -4 m/s, which is rather unfavourable. The latter is mainly caused by the fact that the piston force by cars acts in the negative direction together with the natural wind. But in view of overall performance, the operation mode K2 results in lower absolute values of the air flow velocity compared with K1 mode, as is shown in Fig. 12.

On the assumption that the traffic and the air flow velocity in the tunnel could be measured, the operation is performed with automatic control of jet fans, based upon these data. Fig. 10 (case 7) and Fig. 11 (case 8) are the results for these cases (K3 operation). The former is under the natural wind of +4 m/s, on the other hand, the latter is under -4 m/s. In both cases, the wind velocity is suppressed to a small value within three minutes, which creates suitable circumstances for refuge action. In these cases, we put a severe restriction that jet fans cannot be reversely driven until they stop in 90 seconds. We confirm the high quality in performance of operation K3 also in Fig. 12.

5. CONCLUSION

The authors have performed a series of computer simulation for the behaviour of smoke in the Kan-etsu tunnel in case of fire caused by an accident. One dimensional convection model is used in this analysis. Under the assumed conditions which could be close to reality, the dependence of the circumstances in the tunnel upon the piston effect of vehicles and the natural wind is studied under following three modes of emergency operation of ventilation.

K1 : Shutdown of all the ventilators and jet fans
K2 : To blow a large amount of air in the sections other than at the fire point
K3 : Automatic control based upon traffic and air velocity data

As is seen in the typical examples discussed in section 4, the operation K1 to stop all the ventilators is not desirable enough under some conditions of cars and natural wind. Improved operation modes K2 and k3 are therefore proposed, and are confirmed for better performance. Among them, the mode of feed back control to air flow velocity with the aid of traffic data (operation K3) worked out extremely excellent and stable even under a variety of severer conditions.

In the actual tunnel, the equipments are being installed so that all three operation modes K1, K2 and K3 are possible. Although we aim at the realization of K3 operation on the one hand, the simpler modes K2 and K1 are considered as backups on the other hand.

In transferring the operation modes cultivated and verified through numerical simulation into the actual system, there is no doubt that a wide range of confirmations and tests are needed. Some of them should be executed on the spot.

ACKNOWLEDGEMENT

This paper is based on the research work made by the committee for the study on the ventilation of the Kan-etsu tunnel organized by the Expressway Research Foundation of Japan (Kosoku Doro Chosakai). The authors acknowledge the Foundation and the members of the committee. They also wish to acknowledge Japan Highway Public Corporation (Nihon Doro Kodan), the orderer of the research, for its permission of this publication.

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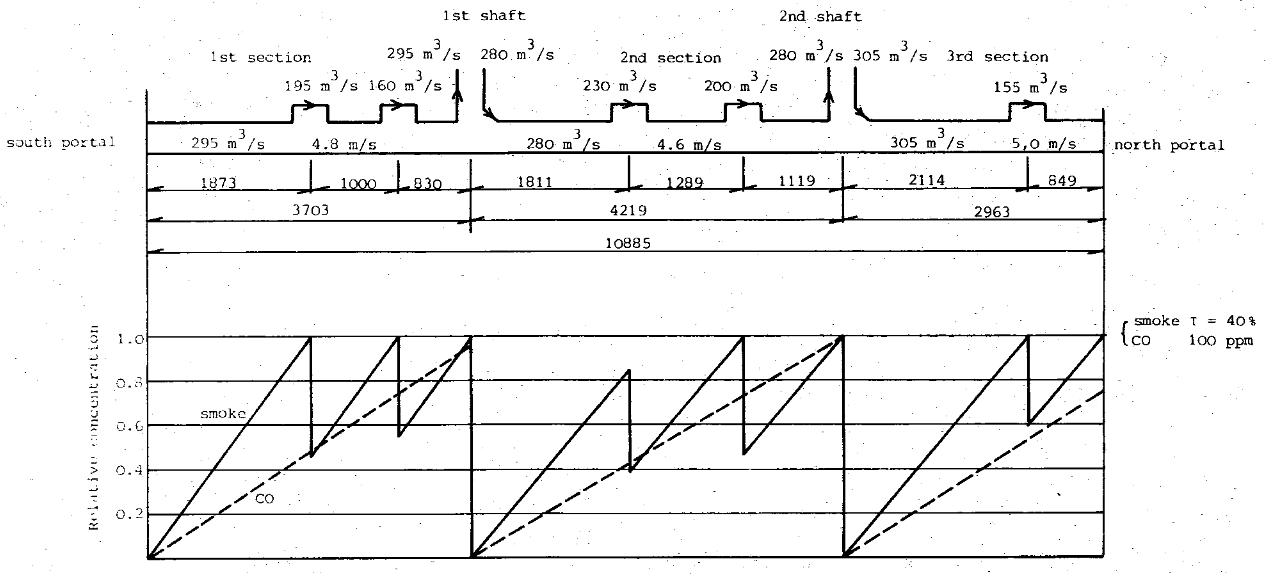

Fig. 1 Necessary ventilation and resultant concentration distribution of smoke and CO for design condition

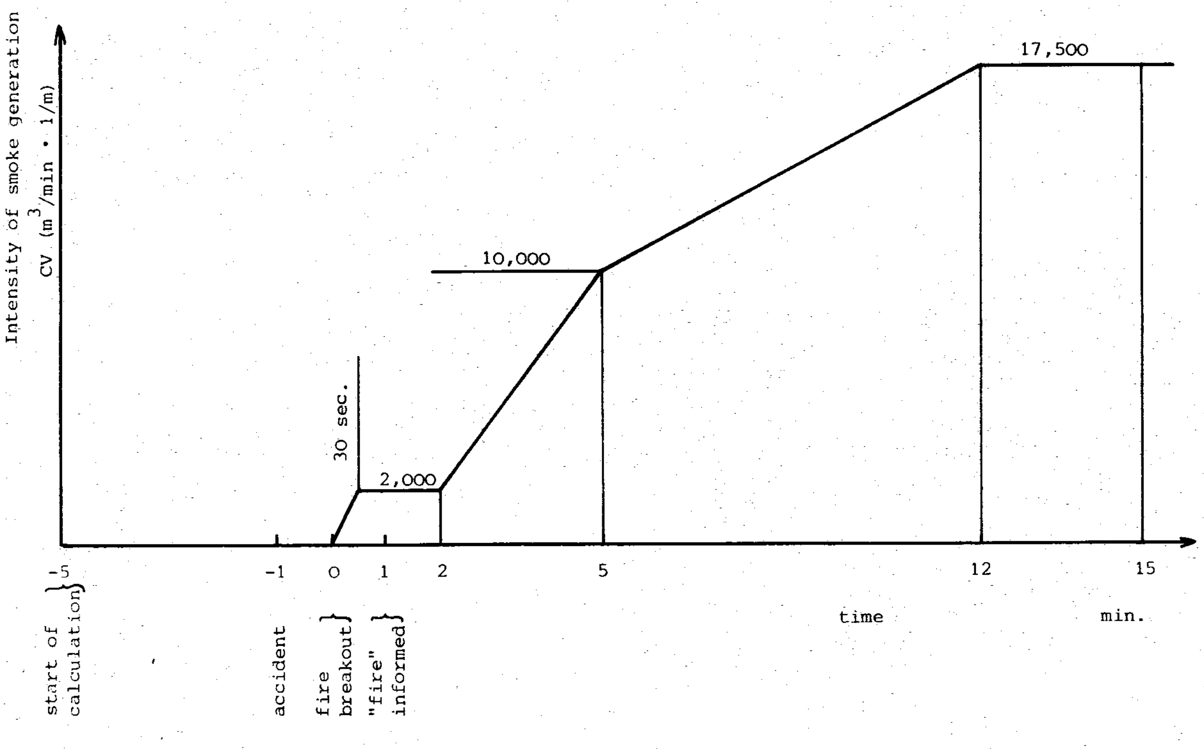

Fig. 2 Intensity curve of smoke generation

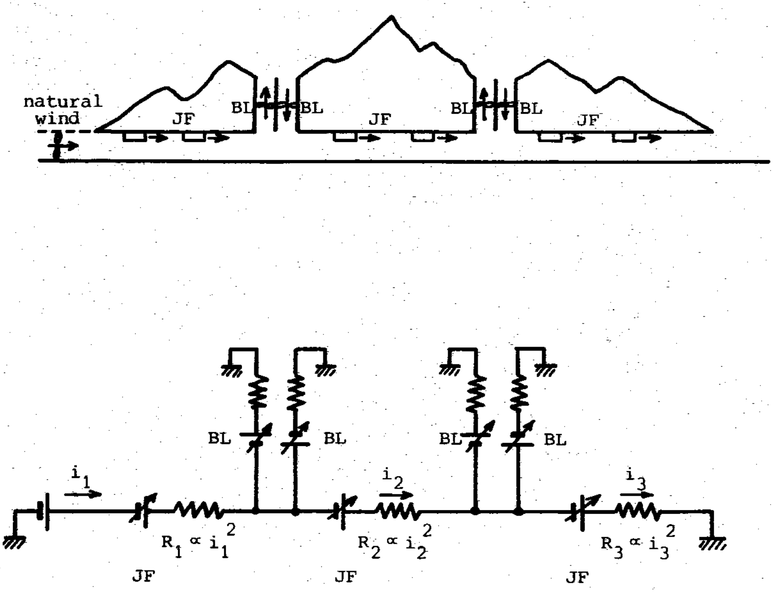

Fig. 3 Analogy of ventilation characteristics to electrical circuit

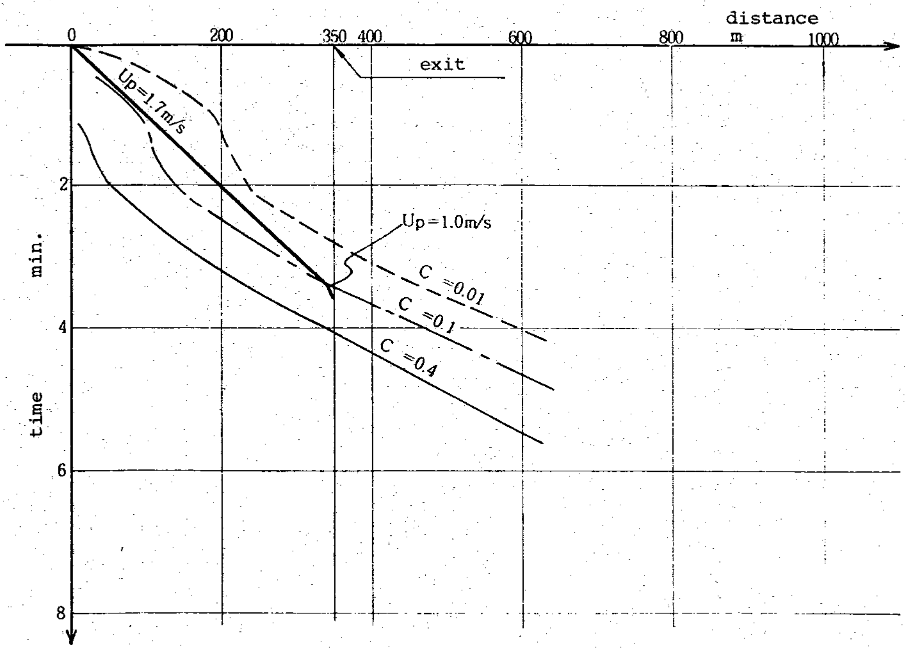

Fig. 4 Behaviour of smoke (case 1: T1, K1, +2.5 m/s)

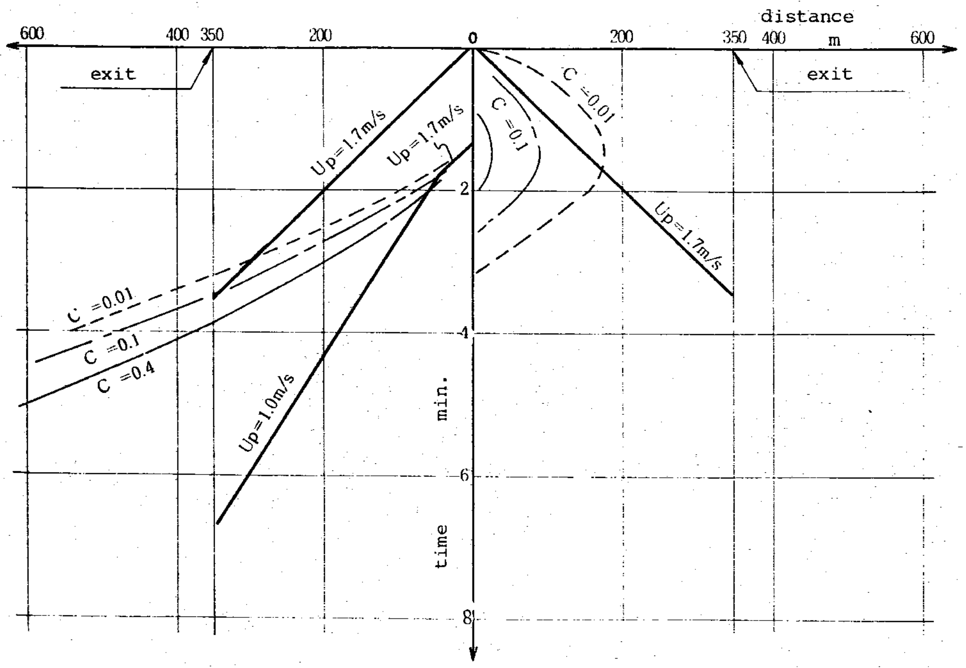

Fig. 5 Behaviour of smoke
(case 2: T3, K1, -2.5 m/s)

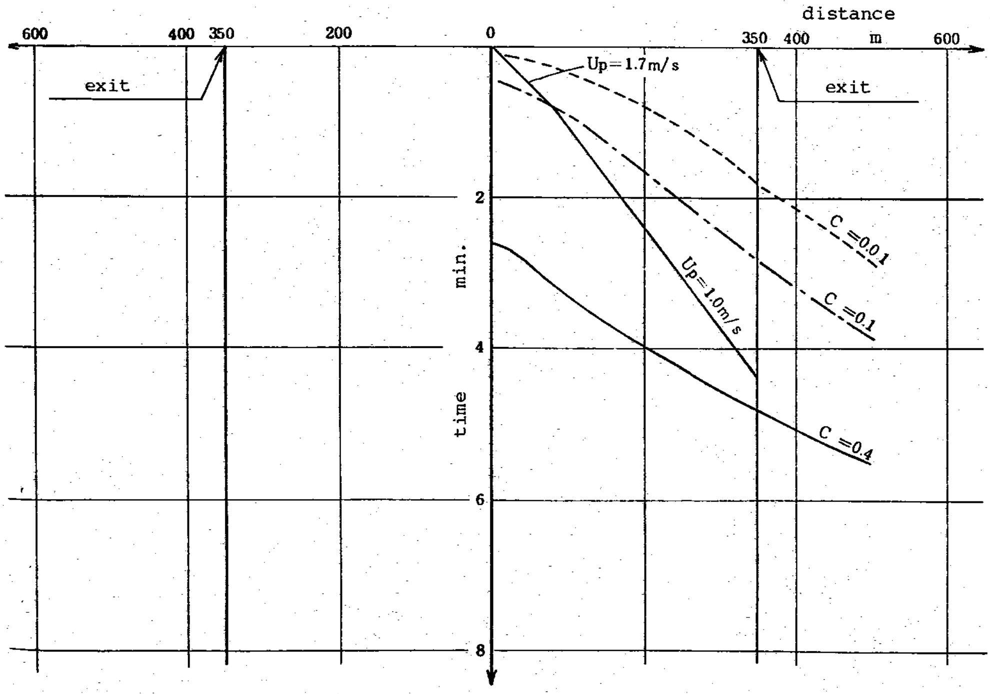

Fig. 6 Behaviour of smoke
(case 3: T2, K1, +4 m/s)

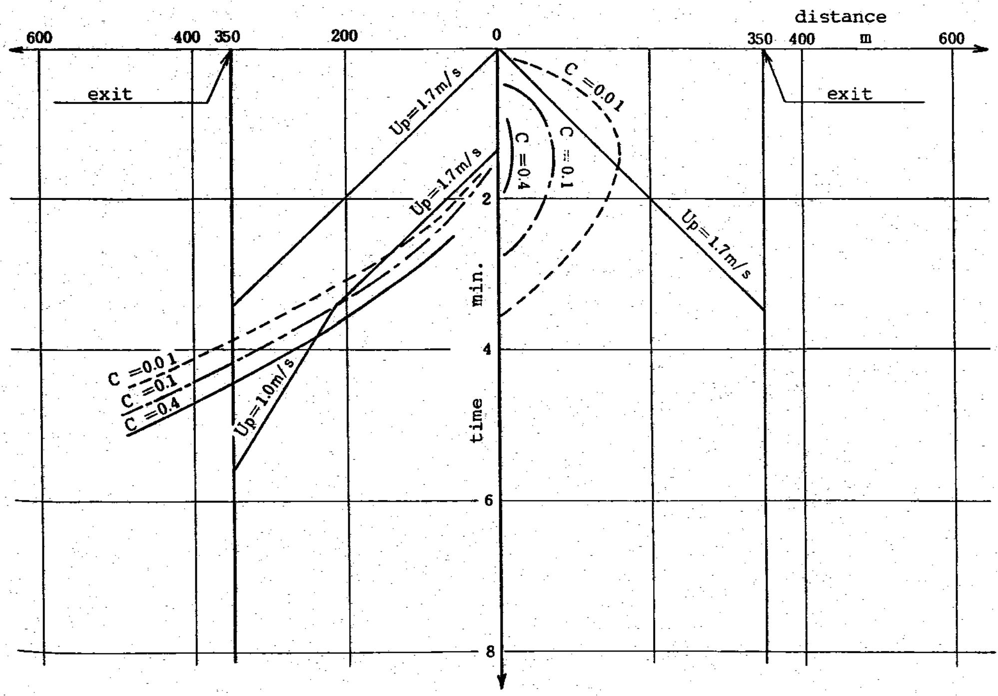

Fig. 7 Behaviour of smoke
(case 4: T2, K1, -4 m/s)

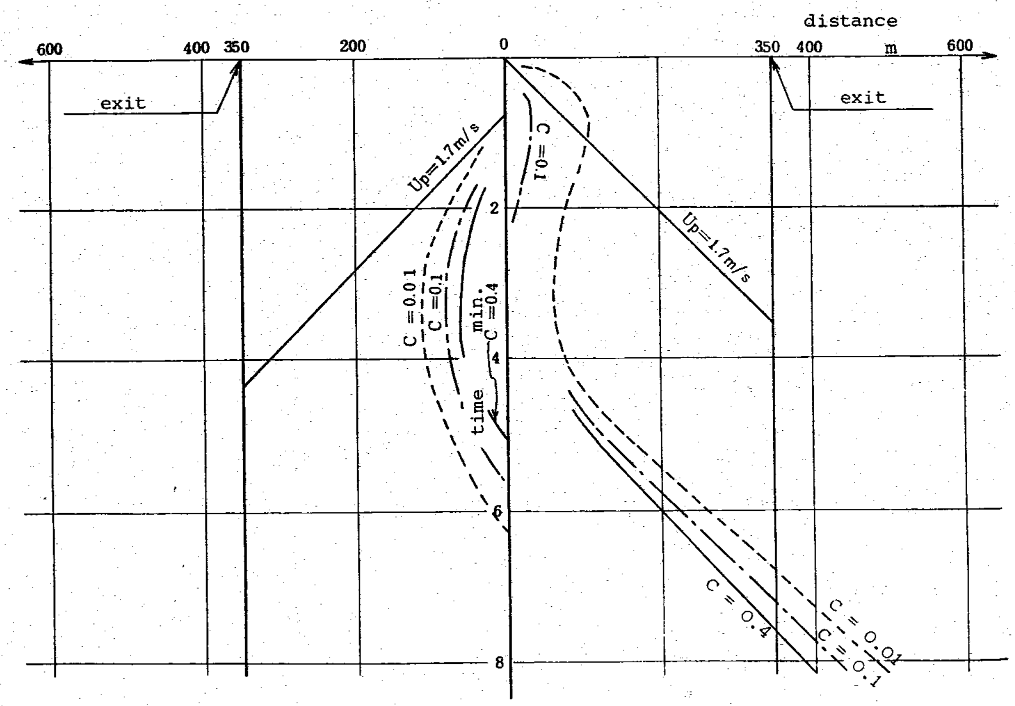

Fig. 8 Behaviour of smoke
(case 5: T2, K2, +4 m/s)

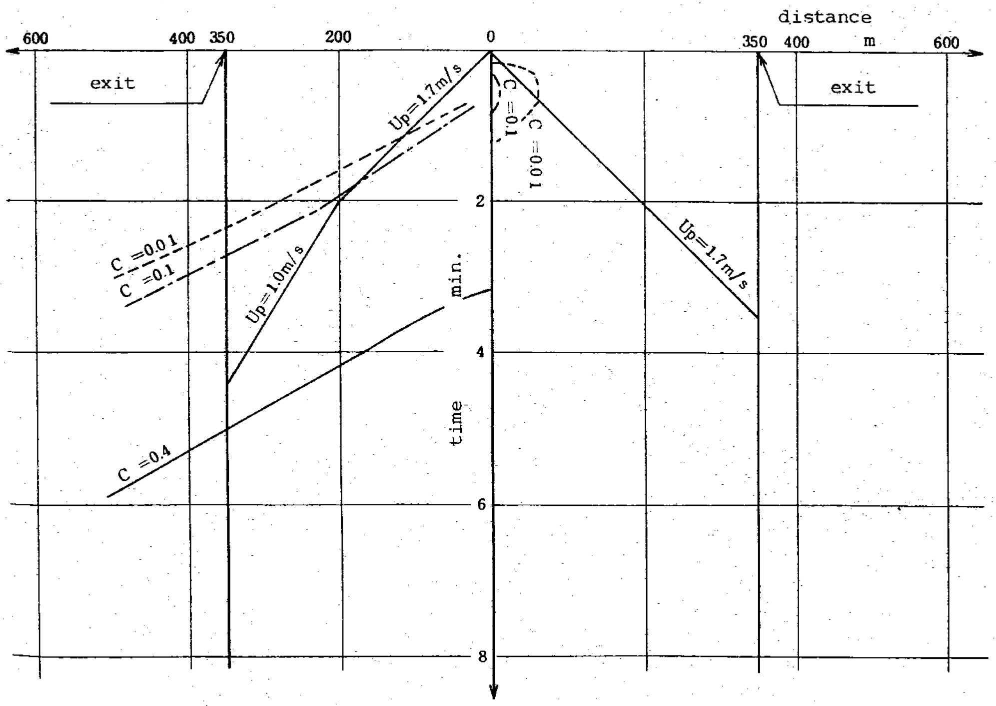

Fig. 9 Behaviour of smoke
(case 6: T2, K2, -4 m/s)

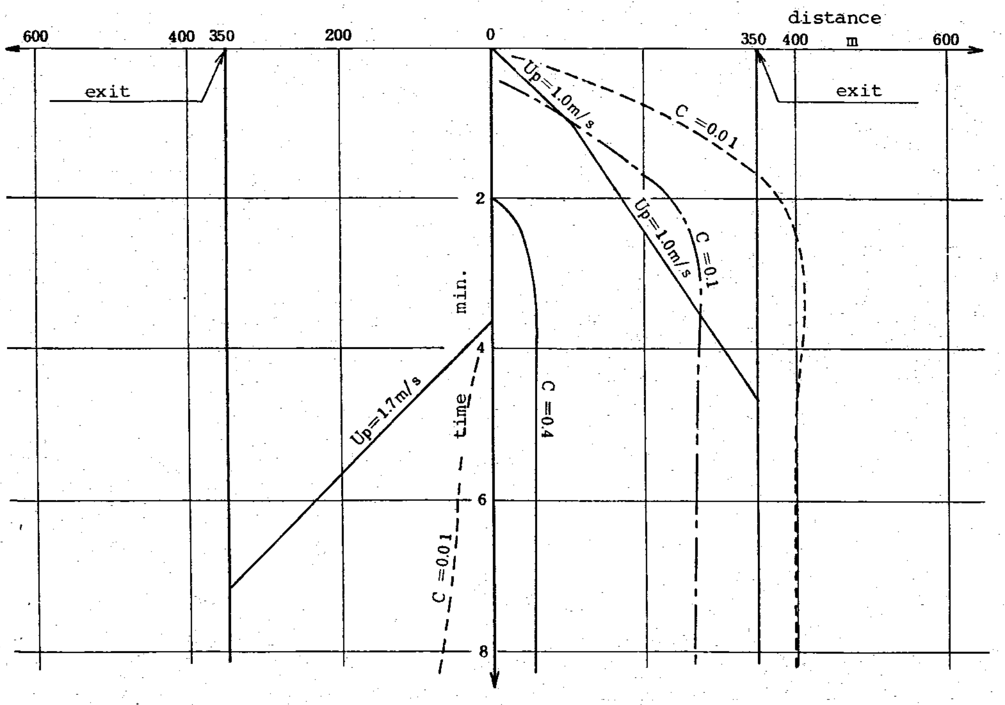

Fig. 10 Behaviour of smoke
(case 7: T2, K3, +4 m/s)

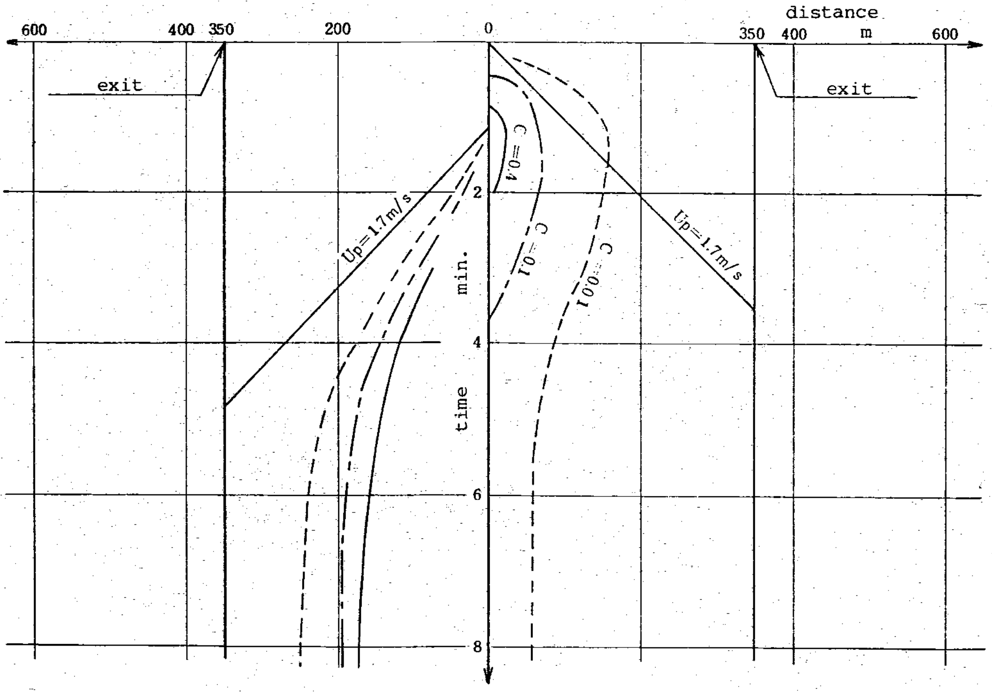

Fig. 11 Behaviour of smoke (case 8: T2, K3, -4 m/s)

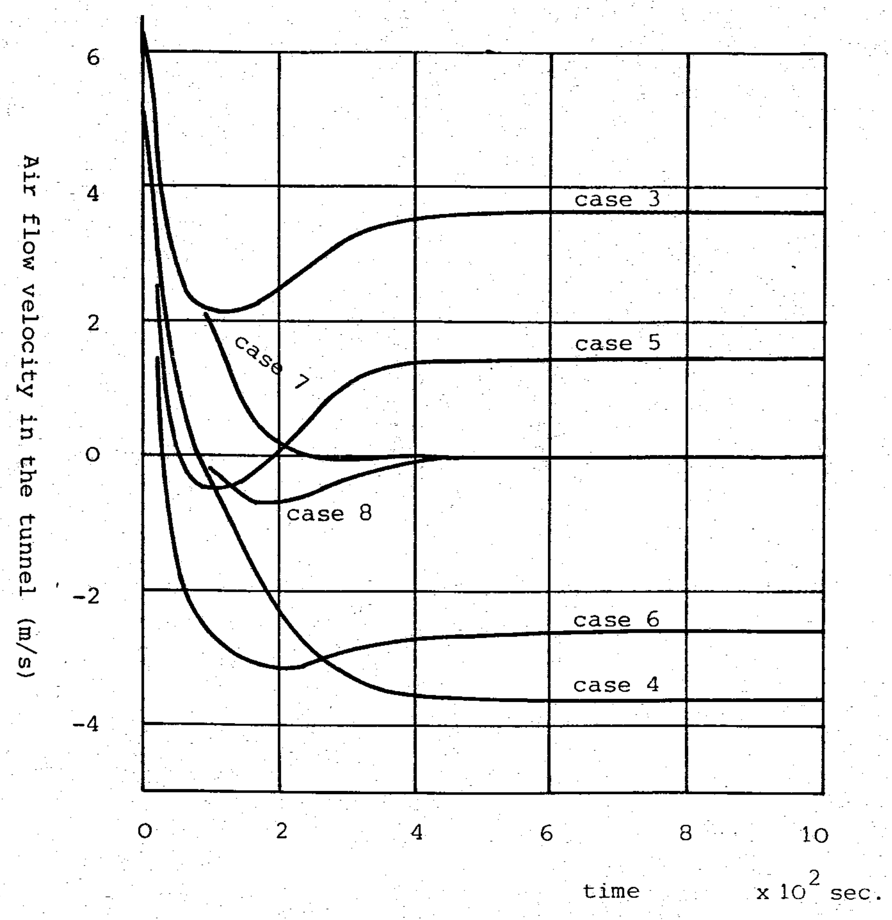

Fig. 12 Air flow velocity in the tunnel