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Possibility of Controlling Longitudinal Air Flow Velocity in Emergency for a Transversely Ventilated Tunnel

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Abstract

In the automobile tunnel which is ventilated by a transverse system, the exhausting and the blowing flow rates are usually equal. But it is impossible to control logitudinal air flow velocity through this ordynaly operation. It is, however, strongly desired to suppress longitudinal air flow in case of fire in the tunnel with two-way traffic so that people can safely evacuate.

The authors have studied the possibility of controlling the axial air flow velocity at an arbitary point in the tunnel by imbalance operation. A series of numelical simulations is performed in which the model tunnel (length:3000[m]) consists of two ventilation dvisions and in each division (length:1500[m]), it is assumed that the blowing and the exhausting flow rates are independently controllable.

According to a series of numerical simulation, It was made clear that the air flow velocity comes down to zero in a minute through the imbalance operation, while the velocity by the ordinary operation even increases. Further, it was possible to keep the air flow velocity to be zero by feedback control.

NOMENCLATURE

$A_r = 42.0\ [m^2]$	: Cross sectional area of the traffic room in the tunnel.
$A_t = 2.8\ [m^2]$	: Equivalent projection area of a vehicle.
$D_r = 6.0\ [m]$	: Reference diameter of the tunnel cross section.
F_r [N]	: Force by friction.
F_t [N]	: Force by vehicles.
$K_p = 200\ [m^2]$	: Proportional gain.

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$L = 3000$ [m]	: Total length of the tunnel.
$L_1 = 1500$ [m]	: Length of division 1.
$L_2 = 1500$ [m]	: Length of division 2.
dm [kg]	: Mass of air in the infinitesimal control volume.
dx [m]	: Length of an infinitesimal control volume.
$n_t = 1000$ [veh./h]	: Traffic density.
p [N/m^2]	: Pressure of air.
$Q_{b1d}, Q_{b2d} = 300$ [m^3/s]	: Design value of blowing flow rate .
$Q_{e1d}, Q_{e2d} = 300$ [m^3/s]	: Design value of exhausting flow rate.
Q^*_{b1}, Q^*_{b2} [m^3/s]	: Blowing flow rate required by the controller.
Q^*_{e1}, Q^*_{e2} [m^3/s]	: Exhausting flow rate required by the controller.
Q_{b1}, Q_{b2} [m^3/s]	: Actual blowing flow rate.
Q_{e1}, Q_{e2} [m^3/s]	: Actual exhausting flow rate.
q_{b1}, q_{b2} [m^2/s]	: Q_{b1}/L_1 , Q_{b2}/L_2.
q_{e1}, q_{e2} [m^2/s]	: Q_{e1}/L_1 , Q_{e2}/L_2.
t [s]	: time.
$T = 30$ [s]	: Control Period.
$T_Q = 30$ [s]	: Period of changing load in full span.
V_n [m/s]	: Natural wind velocity.
V_r [m/s]	: Longitudianl air flow velocity.
V_{r0} [m/s]	: V_r at the center of the tunnel.
V_{r1} [m/s]	: V_r at the entrance ($x = -1500$[m]).
V_{r2} [m/s]	: V_r at the entrance ($x = 1500$[m]).
V_{rf} [m/s]	: V_r at the accident point (x_f).
$V_t = \pm 50$ [km/h]	: Velocity of vehicles.
V_0 [m/s]	: Target value of V_r.
x [m]	: Coordinate along the tunnel axis.
x_f [m]	: Accident point.
ΔQ_2 [m^3/s]	: $Q^*_{e2} - Q^*_{b2}$.
$\lambda_r = 0.025$	: Coefficient of pipe friction loss.
$\rho = 1.20$ [kg/m^3]	: Density of air.
$\rho_t = 0.02$ [veh./m]	: Traffic density.
$\zeta_e = 0.6$	: Coefficient of entrance loss.

Scripts

$+, -$	: denote the value to be in positive/negative direction.

Superscripts

$n, n-1$	: time step of control period.

INTRODUCTION

It is desireable to reduce the longitudinal air flow velocity in case of fire in the tunnel served for two-way traffic so that a favorable evacuation circumstance can be obtained. As a countermeasure, when a fire breaks out in a transversely ventilated tunnel, it is generally considered that the smoke can be removed by an exhaust operation at the section. However, the situation in which the smoke can not be removed by this method often occurs because the amount of smoke is much larger than the exhausting capacity. Further, the smoke spreads by the longitudinal air flow and this disturbs that people could evacuate safely. In this view point, it is necessary to study on the possibilty of controlling the longitudinal air flow velocity at the fire point by the operation of existing ventilators.

The authors developed the areodynamic model to analyse the longitudinal air flow caused by the imbalance ventilation of blowing and exhausting. The object of the current study is set to the model tunnel consisting of two ventilation divisions, in which the blowing and the exhausting flow rate are independently controllable.

According to the above mentioned model, a numerical simulator was developed, and a sires of simulation is performed, in order to acquire better understanding of the phenomena. The possibility of controlling the longitudinal air flow at the fire point is then extensively persued.

AERODYNAMICS OF LONGITUDINAL FLOW IN A TRANSVERSELY VENTILATED TUNNEL

A model tunnel consists of two ventilation divisions. In each division it is assumed that the blowing (Q_b) and the exhausting (Q_e) are independently controllable. The ventilation system of the model tunnel is schematically shown as in Fig. 1.

Continuity Equation The variables concernig velocity or forces are defined to be positive in the direction of x coordinate. The origin of the x coordinate is at the center of the tunnel.

The continuity of flow are

$$A_r V_r(x) = A_r V_{r0} + (q_{b1} - q_{e1})\,x \qquad \text{for division 1 } (x \le 0), \qquad (1)$$

$$A_r V_r(x) = A_r V_{r0} + (q_{b2} - q_{e2})\,x \qquad \text{for division 2 } (x > 0), \qquad (2)$$

where Ar is the sectional area of traffic room, V_{r0} is the mean longitudinal air flow velocity at the center of the tunnel. Therefore, the mean longitudinal velocity $V_r(x)$ at an arbitrary point x in the tunnel, can be expressed according to continuity principle as,

$$V_r(x) = V_{r0} + \frac{1}{A_r}(q_{b1} - q_{e1})\,x \qquad \text{for division 1 } (x \le 0), \qquad (3)$$

$$V_r(x) = V_{r0} + \frac{1}{A_r}(q_{b2} - q_{e2})\,x \qquad \text{for division 2 } (x > 0). \qquad (4)$$

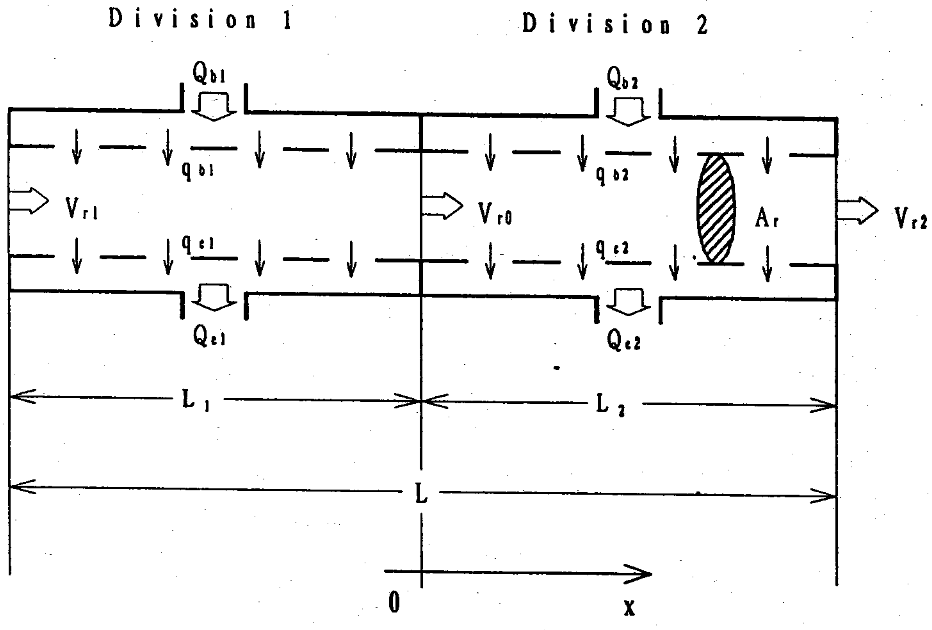

Fig. 1 Ventilation system of the model tunnel.

Momentum Equation The forces acting on the infinitesimal control volume(axial length: dx) are described as followings.

The traffic force in both directions can be summarized as

$$dF_t = \frac{\rho}{2} A_t\, dx \{\rho_{t+} (V_{t+} - V_r) |V_{t+} - V_r| + \rho_{t-} (V_{t-} - V_r) |V_{t-} - V_r|\}, \tag{5}$$

where ρ_{t+} and ρ_{t-} are the number of vehicles existing in a per unit length toward each direction. V_{t+} and V_{t-} are the velocities of vehicles with different signs.

The resistance force due to pipe friction is

$$dF_r = -\lambda_r A_r \left(\frac{dx}{D_r}\right) \frac{\rho}{2} V_r |V_r|. \tag{6}$$

The force due to the exchange of momentum by the blowing and the exhausting is ignored because its effect is considered to be small. The entrance loss and dynamic pressure loss are not also neglected for simplicity because they do not play am important role in the present study.

The momentum equation for the control volume is

$$dm \left(\frac{\partial V_r}{\partial t} + V_r \frac{\partial V_r}{\partial x}\right) = -\frac{\partial p}{\partial x} dx A_r + dF_t + dF_r, \tag{7}$$

where dm is the mass of air in the control volume $dm = \rho A_r dx$, the first of the L.H.S. terms is local acceleration and the second is convective acceleration. Substituting the relations eqs. (3) and (4) into eq. (7), it can be integrated from x=$-L_1$ to x=L_2 to form,

$$\frac{dV_{r0}}{dt} = \frac{1}{2A_r L} \left\{ L_1 \frac{d}{dt} (Q_{b1} - Q_{e1}) - L_2 \frac{d}{dt} (Q_{b2} - Q_{e2}) \right\}$$

$$- \frac{1}{A_r L}\left[V_{r0}\{(Q_{b2} - Q_{e2}) + (Q_{b1} - Q_{e1})\} + \frac{1}{2A_r}\{(Q_{b2} - Q_{e2})^2 - (Q_{b1} - Q_{e1})^2\}\right]$$
$$+ \frac{1}{\rho L}(p_1 - p_2) + \frac{1}{\rho L A_r} I, \quad (8)$$

where

$$I = \int_{-L_1}^{L_2} (dF_t + dF_r)dx. \quad (9)$$

Now, $p_1 - p_2$ is given from the natural wind velocity V_n as

$$p_1 - p_2 = \left(1 + \zeta_e + \lambda_r \frac{L_r}{D_r}\right) \frac{\rho}{2} V_n |V_n|, \quad (10)$$

where V_n is the air flow velocity which would occur if there were no disturbance by vehicles and ventilators.

SIMULATION MODELS

The simulator contains aerodynamic, tarffic and controller models. Fig. 2 shows the schematic construction of the simulator, in which how these three models are related. The explanation of each model follows.

Aerodynamic Model: Equation (8) is used.

Traffic Model: Traffic speed and density are constant in ordinary situation. On the other hand, the *emergency* condition is supposed as follows. As soon as the accident occurs at time t=0, fire breaks out. Then all the vehicles toward the accident stop at once, while the vehicles leaving from the fire point are not disturbed at all.

Controller Model: Explained in the later section. The mean longitudinal velocity at the fire point (V_{rf}) is calculated from equations (3) and (4) with the measured velocity at the center of the tunnel (V_{r0}) and the fire point (x_f).

Ventilators: The flow rate of each ventilator is controlled by specifying blade angle. It is assumed that the blade angle rotates full span in time T_Q. Required flow rates (Q_b^*, Q_e^*) by the controller are inputted and actual flow rates (Q_b, Q_e) are outputted in the model.

Anemometer: An anemometer is placed at the center of the tunnel and the mean longitudinal air flow velocity (V_{r0}) is measured.

Flame Sensors: The flame sensors are supposed to be placed in a certain pitch so that the fire point (x_f) can be detected with an enough accuracy.

Fire point: The examples in this paper is limited for the cases in which a fire point is in division 1, but it can be easily extended for the other cases from symmmetry.

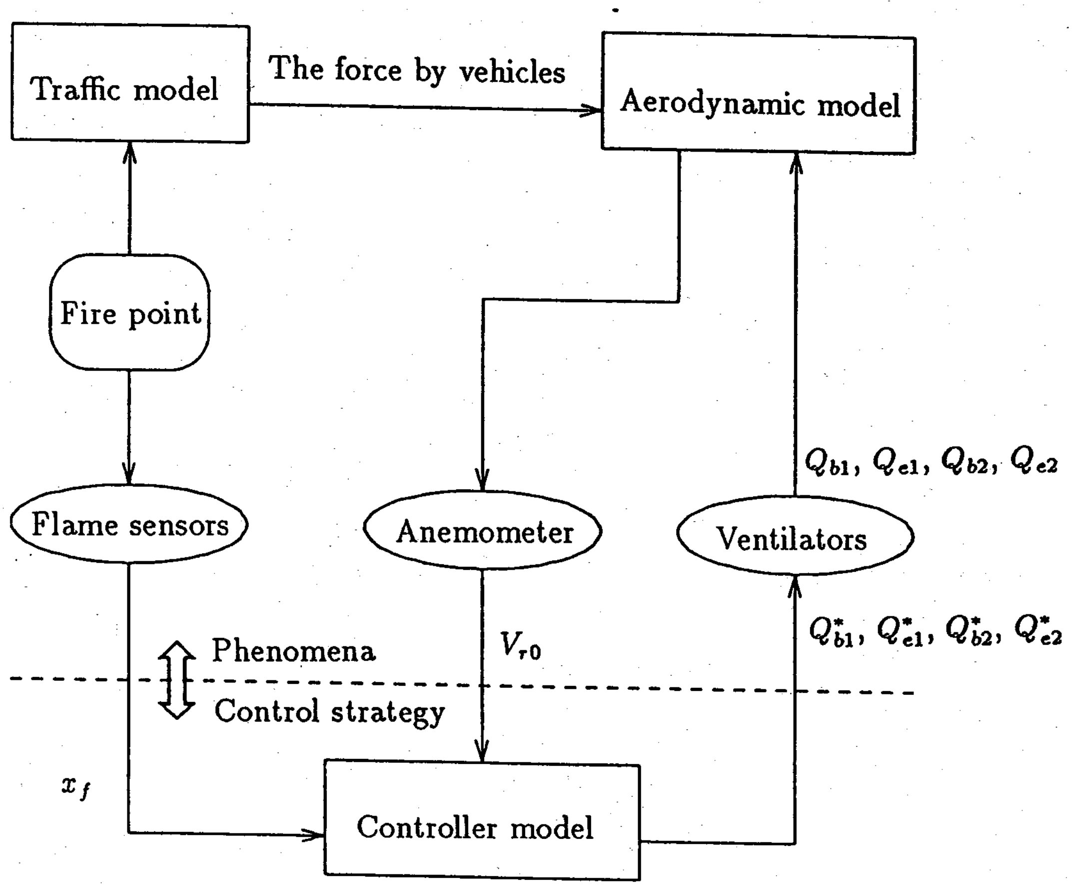

Fig. 2 Structure of the simulator.

TRANSIENT CHARACTERISTICS OF THE LONGITUDINAL AIR FLOW VELOCITY BY IMBALANCE CONTROL

In the first stage, the authors would like to explain the phenomena under extremely simple step operations, so that a better understanding with regard to longitudinal flow is attained. Among a large number of simulation results, two typical cases (case 1, case 2) are demonstrated in the present paper.

Exhausting and blowing flow rates are usually equal in the transverse ventilation tunnel. Under this operation the longitudinal air flow velocity is constant within a certain ventilation division. On the other hand, if the exhausting and the blowing flow rate are not equal, the longitudinal air flow varies by place. The behaivor of the longitudinal air flow caused by the imbalance ventilation is exlained in this section.

The common conditions in this section follow: Before the time t=0[s], the ventilation is in normal oparation, or all the ventilators are in full load. At time t=0[s], a set of instruction is sent from the controller to the ventilators. Natural wind velocity is 0.0 m/s and traffic dencity is kept constant as 1000[veh./h](1:1) during the whole simulation period, while the differnce in condition between the case 1 and the case 2 is the set of instruction sent from the controller to the ventilators.

Case 1 The instruction of the flow rates for the case is:

$$Q^*_{b1} = 0\ [\mathrm{m}^3/\ \mathrm{s}],\ Q^*_{e1} = Q_{e1d}\ [\mathrm{m}^3/\ \mathrm{s}],\ Q^*_{b2} = 0\ [\mathrm{m}^3/\ \mathrm{s}],\ Q^*_{e2} = 0\ [\mathrm{m}^3/\ \mathrm{s}].$$

Fig. 3 shows the transient of longitudinal air flow and flow rates of ventilators. It takes 30 seconds for the fans after the instruction of zero operation to reach the final state. After the time t=30[s] the longitudinal velocities do not change in time. The longitudinal air flow velocities are constant in space in division 2 because Q_{b2} is always kept equal to Q_{e2}. On the other hand, velocity varies by place in division 1. The difference between the longitudinal velocity $V_{r2}(=V_{r0})$ in division 2 and V_{r1} at the entrance in division 1 is 7.1 m/s, which is the flow rate(Q_{e1d}) divided by the cross sectional area(A_r). As a larger pipe friction loss occurs in division 2, $|V_{r1}|>|V_{r2}|$. Thus, it is found that a large amount of longitudinal velocity is induced by imbalance ventilation.

Case 2 The instruction of the flow rates for the case is:

$$Q^*_{b1} = 0\ [\mathrm{m}^3/\ \mathrm{s}],\ Q^*_{e1} = Q_{e1d}\ [\mathrm{m}^3/\ \mathrm{s}],\ Q^*_{b2} = Q_{b2d}\ [\mathrm{m}^3/\ \mathrm{s}],\ Q^*_{e2} = 0\ [\mathrm{m}^3/\ \mathrm{s}].$$

In fig. 4, it is found that $V_{r1}=V_{r2}, V_{r1}=-V_{r0}$. As is stated before, in the present paper, entrance loss and dynamic pressure loss are not taken into account. Therefore, the phenomenon occured in division 1 corresponds with the one, which is seem under the situation that the exhausting is only done for the half length of the tunnel, and vice versa for division 2, as is shown in fig. 5.

The above mentioned results are instructive for constructing a proper control scheme in that the dynamics of the air flow is clearly demonstrated.

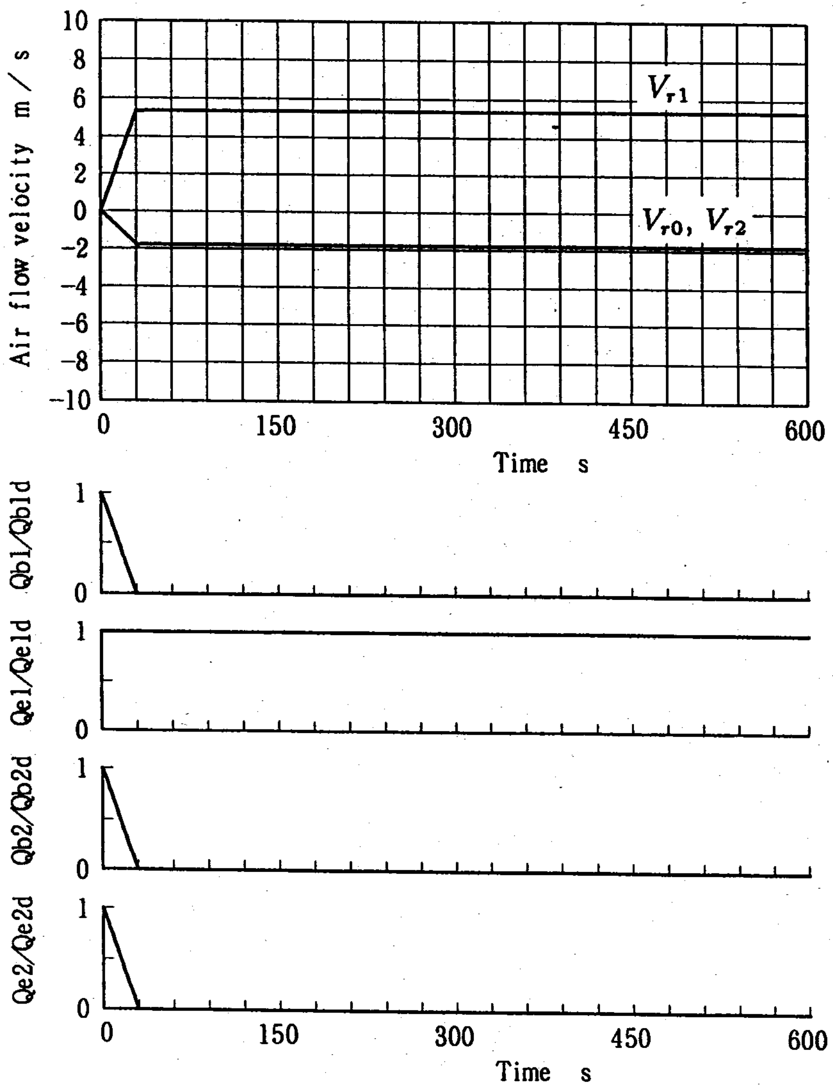

Fig. 3 Transient of air flow velocities and flow rates. (case 1)

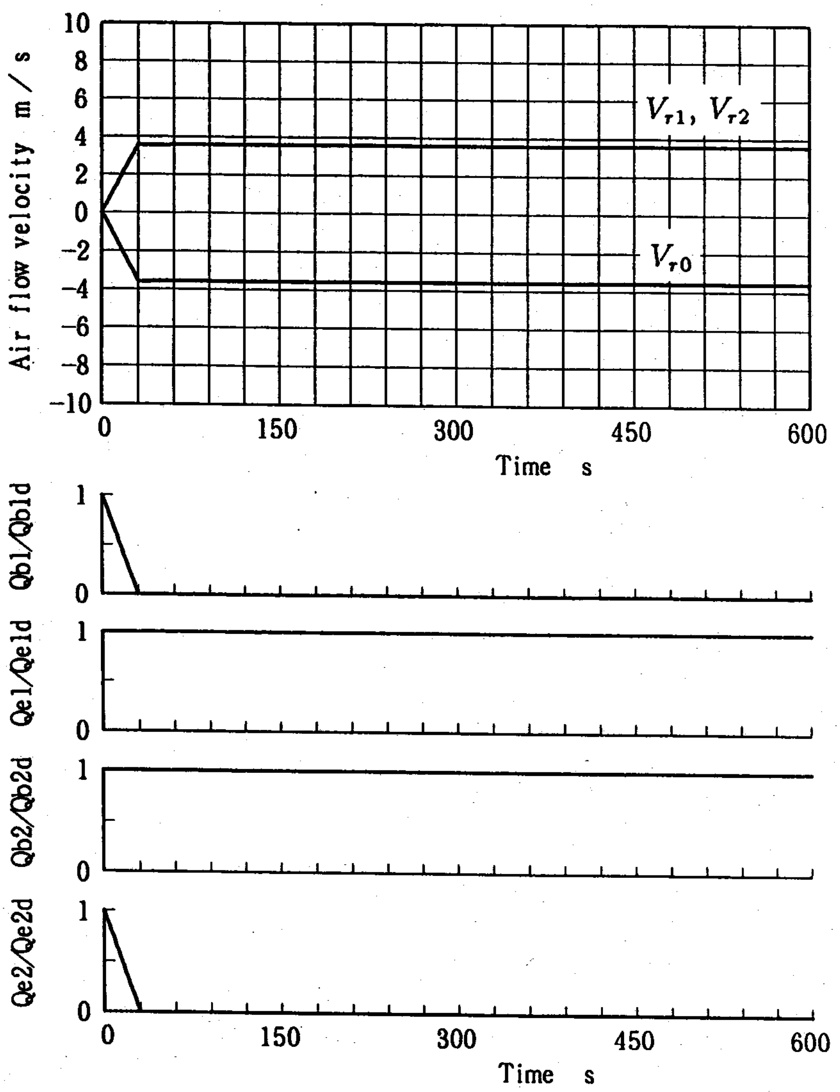

Fig. 4 Transient of air flow velocities and flow rates. (case 2)

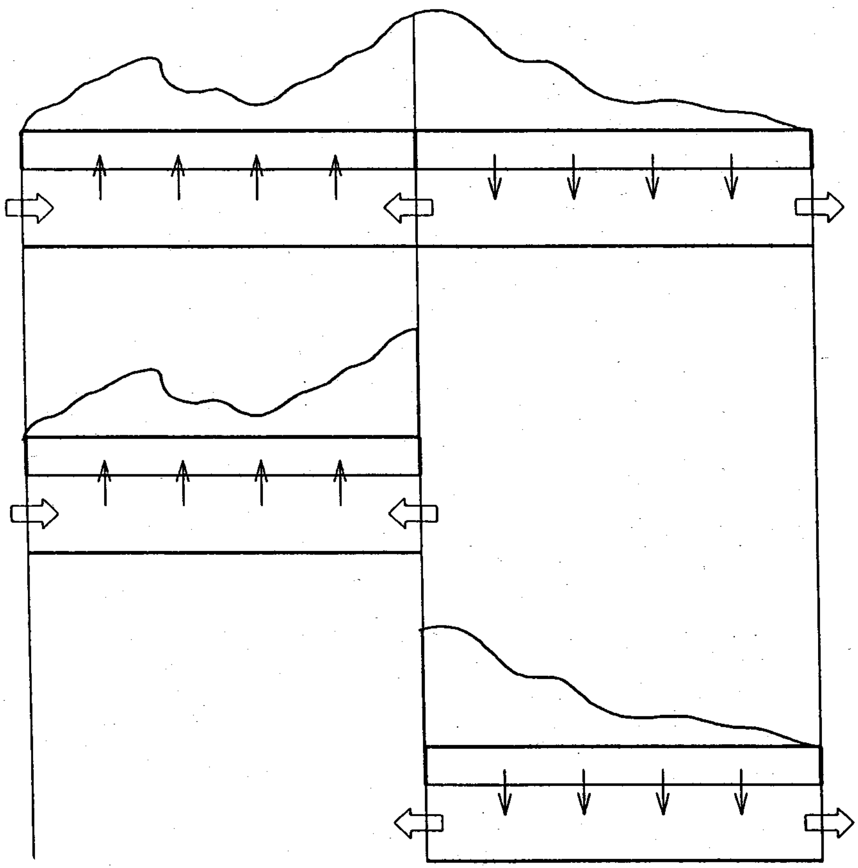

Fig. 5 Case 2 coincides with two separate tunnels.

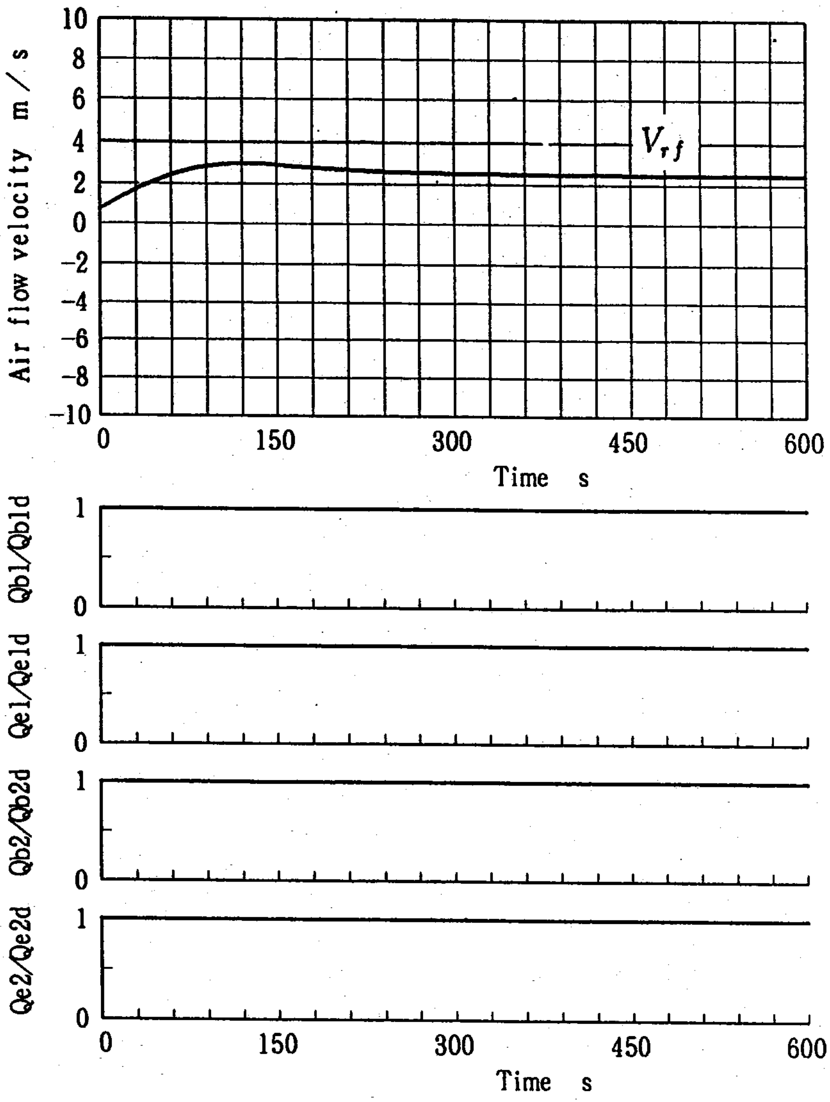

Fig. 6 Air flow velocity under ordinary operation.

EMERGENCY VENTILATION CONTROL

It is commonly assumed in this section that at time t=0[s] an accident occurs at the point x_f=−750[m], under the conditions in which natural wind velocity is 2.5 m/s and the traffic density is 1000[veh./h](1:1). Fig. 6 shows the longitudinal air flow velocity (V_{rf}) at the fire point when the ordinary ventilation is kept after fire, in case such as the flame sensor do not work. The velocity rises by the imbalance of the traffic condition. But it is strongly desired to suppress the velocity so that people can safely evacuate. From this veiw point, the authors examined to suppress the longitudinal air flow velocity by imbalance control of the blowing and exhausting in the next *Open Loop Control*.

Open Loop Control This control is performed by imbalance of flow rates in division 2 while the ventilation in division 1 is shut down. The simulation is executed under the same conditons as in fig. 6. The longitudinal air flow velocity (V_{rf}) at time t=0[s] is larger than zero due to positive natural wind.

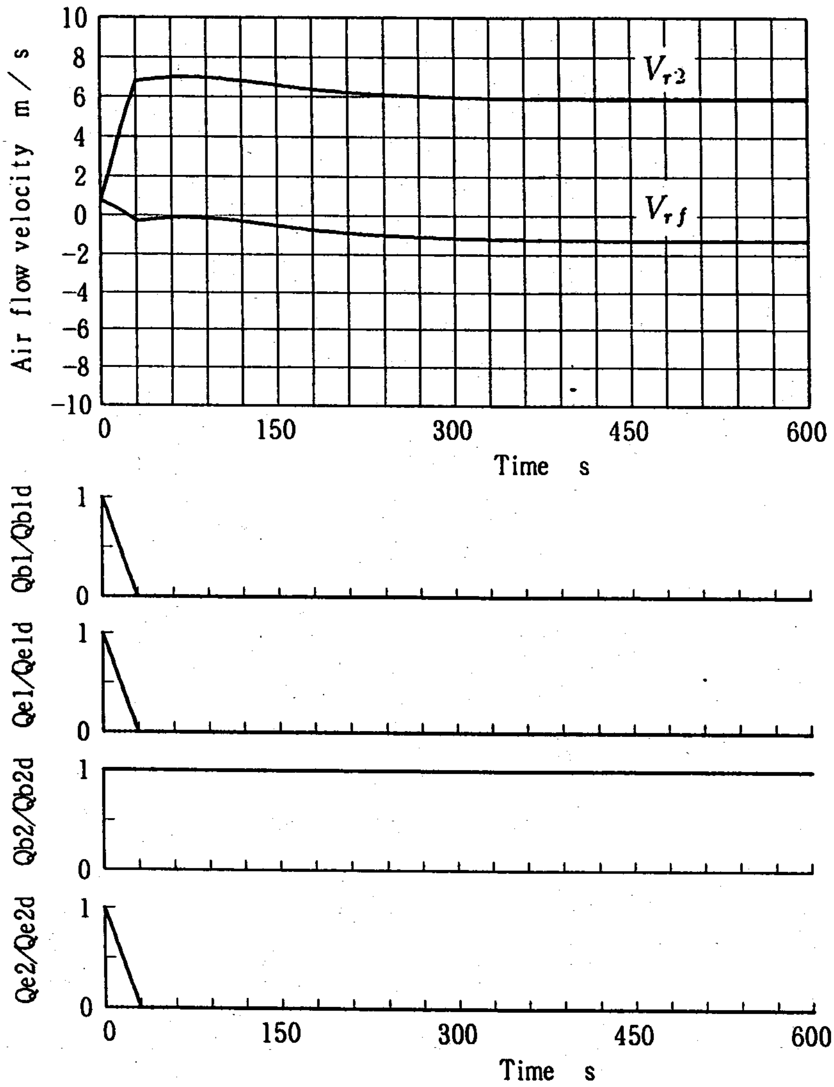

Fig. 7 Air flow velocity under open loop control.

The instruction of the flow rates generated by the controller is:

$Q^*_{b1} = 0$ [m^3/ s], $Q^*_{e1} = 0$ [m^3/ s], $Q^*_{b2} = Q_{b2d}$ [m^3/ s], $Q^*_{e2} = 0$ [m^3/ s].

The result is demonstrated in fig. 7. The aim of this control is to make the velocity (V_{rf}) below zero as soon as possible. The velocity comes down to zero in 30 seconds. Then it rises for a moment because of the effect of traffic imbalance but it does not exceed zero. On the other hand, the air flow velocity (V_{r2}) at the entrance (x_f=−1500[m]) rises over 6 m/s because of the pipe friction loss in division 1. For a more unfavorable conditions of traffic and natural wind, there can be cases for which V_{rf} dose not arrive zero. However, it will be possible to keep the longitudinal air flow velocity to be zero for this case by proper control of the blowing and the exhausting.

Feedback Control The authors propose a feed back control algorithm, for which the performace is demonstrated. This method is the proper control of the flow rates in dvision 2.

In order to bring the longitudinal air flow velocity to the target value V_0 the controller generates a set of instruction to ventilators every 30 seconds.

The difference between the exhausting (Q_{e2}) and the blowing flow rate (Q_{b2}) in division 2 is defined as

$$\Delta Q_2 \equiv Q_{e2} - Q_{b2}, \tag{11}$$

where $-Q_{b2d} \leq \Delta Q_2 \leq Q_{e2d}$. At the time step n, ΔQ_2 for the next control period is determined by

$$\Delta Q_2^n \equiv \Delta Q_2^{n-1} - K_p \left(V_{rf}^n - V_0 \right), \tag{12}$$

where K_p is propotional gain and V_0 is the target value of V_r at the fire point. In the following simulations, K_p=200[m^2] and V_0=0.0[m/s] are adopted.

According to the value ΔQ_2^n at a certain control period ,the controller generates a set of instruction as follows:

$$\begin{array}{llll} Q_{b2}^* = 0 & Q_{e2}^* = \Delta Q_2^n & \text{if} & \Delta Q_2^n > 0 \\ Q_{b2}^* = 0 & Q_{e2}^* = 0 & \text{if} & \Delta Q_2^n = 0 \\ Q_{b2}^* = |\Delta Q_2^n| & Q_{e2}^* = 0 & \text{if} & \Delta Q_2^n < 0 \end{array}$$

and the ventilation in division 1 is shut down (Q_{b1}^*=0, Q_{e1}^*=0 at $t \geq 0$).

Fig. 8 illustrates the result of this feedback control simulation under the same condition as fig. 6 and fig. 7. From the figure the concept of the proposed control is clearly understood in that the object value V_{rf} is kept at zero under the sacrifice of the velocity in division 2. At time t=0[s] the longitudinal air flow velocity (V_{rf}) equals 0.7 m/s, so the controller generates a set of instruction and flow rates accordingly change. However, the velocity rises for a moment by the effect of the traffic imbalance because of the delay time of ventilator. But the velocity comes down after 15 seconds as a result of the imbalance of flow rates arising. Further, at 45 seconds the velocity achives the target value zero, and afterwards the velocity keeps zero by proper control of the flow rates. For instance, in response to the traffic imbalance abating, the flow rate (Q_{b2}) could be lower from t=90[s].

Fig. 9 shows the other example of this feedback control under the negative natural wind velocity −2.5 m/s and the same traffic conditions. At time t=0[s] the longitudinal air flow velocity (V_{rf}) is less than zero, so $Q_{b2}^* < Q_{e2}^*$ is specified. But as a result of the velocity (V_{rf}) rising by the traffic imbalance, $Q_{b2}^* > Q_{e2}^*$ for t=60[s] to t=180[s]. After time t=180[s], the effect of the traffic imbalance disappear and $Q_{b2}^* < Q_{e2}^*$ in order to cancel the natural wind. It is well controlled in this case by properly combinated operation of the blowing and the exhausting.

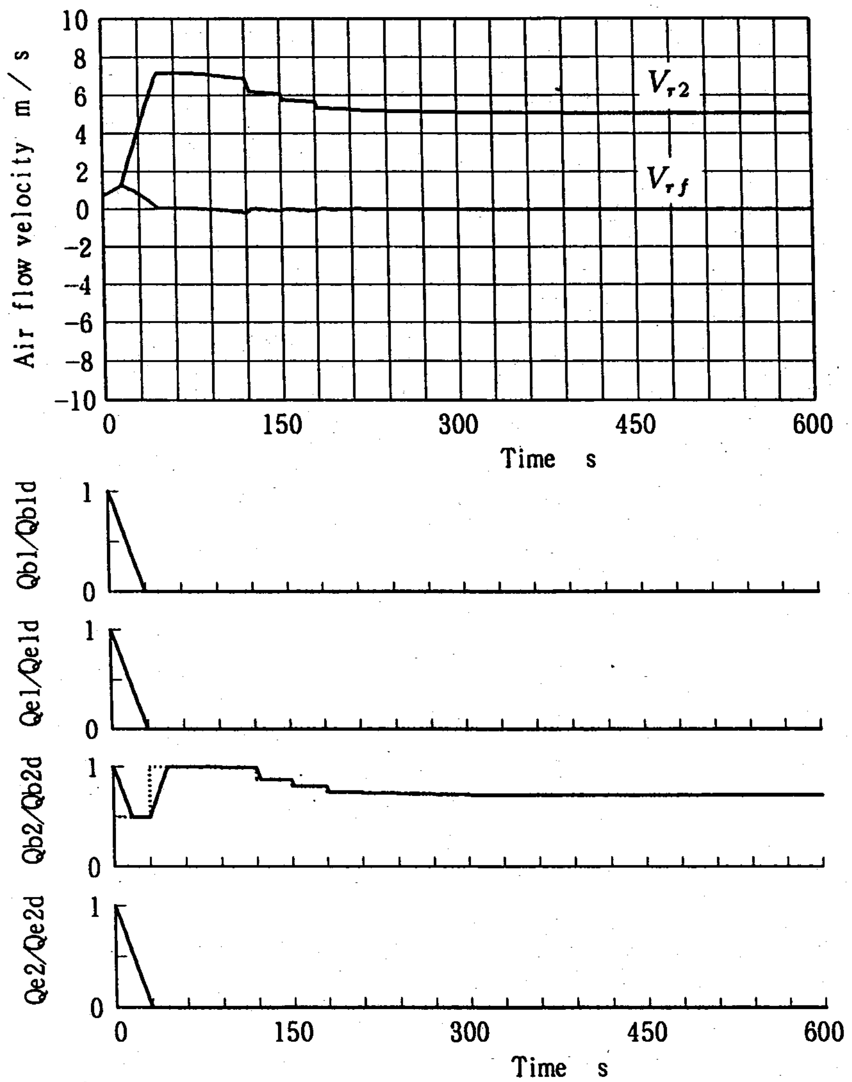

Fig. 8 Air flow velocity under feedback control. (Case for positive natural wind)

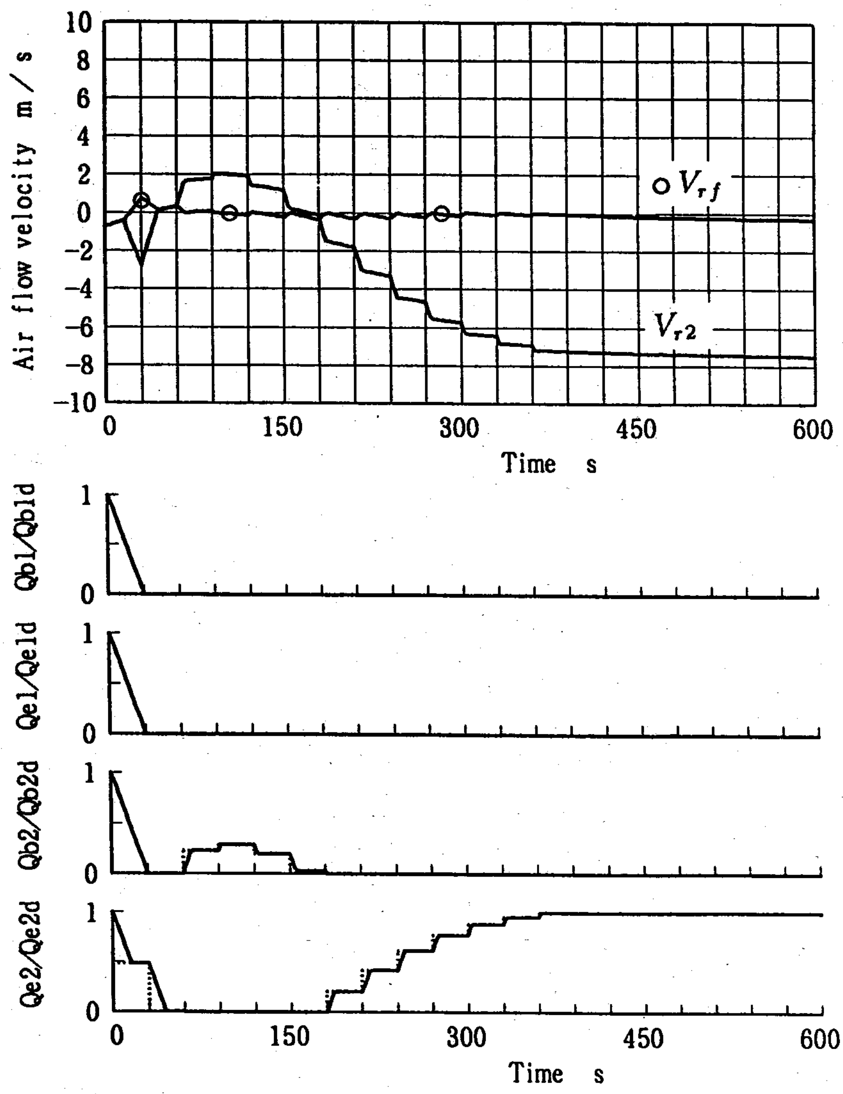

Fig. 9 Air flow velocity under feedback control. (Case for negative natural wind)

CONCLUSION

Main results obtained in the present work are summarized as follows:

1. An aerodynamic model to analyse the longitudinal air flow under the imbalance of the blowing and the exhausting ventilation for a transversely ventilated tunnel is developed. Further, numerical simulator is constructed based on the model.

2. It was made clear how the longitudinal air flow velocity behaves in space and time, when the ventilators are operated in imbalance conditions. From the present results, one can understand the possibilty and importance of controlling the longitudinal air flow velocity for emergency case even in a transversely ventilated tunnel.

3. The longitudinal air flow velocity is reduced to zero within a minute and is kept calm by the feedback control of the imbalance ventilation under supposed conditions.

4. In the simulation cases in the sections "Open Loop Control" and "Feedback Control", the ventilation in the fire zone is shut down. However, the phenomena brought by this correspond to those by the condition that the blowing and the exhausting are fully operated, with which smoke can be removed.

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