The Emergency Control of Ventilation for the Trans-Tokyo Bay Tunnel

Akisato MIZUNO*　Toshiharu SASAMOTO†　Isao AOKI‡

Abstract

The Trans-Tokyo Bay Tunnel with the length of 10km is under construction. The longitudinal ventilation system with jet fans, electirostatic precipitators and vertical shaft is going to be equipped. As the tunnel is ventilated with a rather high velocity of air flow(up to 8 m/s), it is desirable to suppress it to lower values of 2 to 3 m/s in case of emergency so that people can safely evacuate.

The possibility of the suppression of the longitudinal air flow velocity in a tunnel ventilated by jet fans is discussed earlier by the authors. The currernt study is the extension under the similar control concept how the vertical shaft could be added to jet fans contributing to the suppression of the axial flow with a large amount of inertia.

According to a series of numerical simulations the effect of the vertical shaft fans is proved to be extremly strong within the first minute. It is also made clear that the proposed optimal control algorythm plays excellent performance in swiftness and stability.

NOMENCLATURE

The variables used in the paper is discribed below accompanied by typical or constant values aside.

$A_b = 20.33$ [m^2] : Area of blow-in from the vertical shaft fan.
$A_j = 1.84$ [m^2] : Area of jet fan discharge. (1500 mm in diameter)
$A_r = 78.20$ [m^2] : Sectional area of traffic room in the tunnel.

---

*Kogakuin University, Department of Mechanical Engineering, Nakano-machi 2665, Hachioji-shi, Tokyo 192

†Fuji Electric Co. Ltd., Social System Engineering Dept., New Yurakucho Bldg., 12-1, Yurakucho 1, Chiyoda-ku, Tokyo 100

‡Nihon Doro Kodan(Japan Highway Public Corporation), Highway Facilities Division, 3-2, Kasumigaseki 1, Chiyoda-ku, Tokyo 100

Aerodynamics and Ventilation of Vehicle Tunnels, pp. 365–384

$A_t = 2.77$ [m^2] : Mean projection area of vehicle.

$D_r = 9.2$ [m] : Equivalent diameter of the tunnel cross section.

F_j [N] : Force driven by the jet fans.

F_r [N] : Force by friction.

F_t [N] : Force by vehicles.

F_T [N] : Overall force ancting on the air column in the tunnel.

F_w [N] : Force by natural wind.

$K_j = 1.0$: Coefficient of pressure rise by jet fans.

L_a [m] : Location of the accident.

$L_r = 9492$ [m] : Total length of the tunnel.

$L_{r1} = 4702$ [m] : Length of the section 1.

$L_{r2} = 4790$ [m] : Length of the section 2.

L_t [m] : Length of the region where traffic exists.

$m_1 = 4.412 \times 10^5$ [kg/m^3]: Mass of air in the section 1.

$m_2 = 4.495 \times 10^5$ [kg/m^3]: Mass of air in the section 2.

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

$N = 2470$ [veh./h] : Traffic density.

n_j : Number of jet fans in operation. (Negative number for reverse operation)

$n_{j1max} = 15$: Number of jet fans installed in section 1.

$n_{j2max} = 15$: Number of jet fans installed in section 2.

n_t : Number of vehicles existing in the tunnel section.

p_1, p_2 [Pa] : Pressure outside the entrance/exit of the tunnel.

p_T [Pa] : Pressure at the junction of the two sections in the tunnel.

p_{T0} [Pa] : Pressure outside the vertical shaft.

Q_b [m^3/s] : Flow rate of the supply air fan.

$Q_{b0} = 620$ [m^3/s] : Design flow rate of the supply air fan.

Q_e [m^3/s] : Flow rate of the exhaust fan.

$Q_{e0} = 620$ [m^3/s] : Design flow rate of the exhaust fan.

Q_r [m^3/s] : Flow rate of the tunnel cross section: $= A_r V_r$.

t [s] : Time.

$T = 10$ [s] : Control period.

$V_j = 30.0$ [m/s] : Velocity of jet fan discharge. (Absolute value)

$V_n = 0, \pm 2.5$ [m/s] : Natural wind velocity.

V_r [m/s] : Air flow velocity in each section of the tunnel.

$V_{r0} = 0$ [m/s] : Target value of V_r in the section including the point of accident.

$V_t = 50$ [km/h],[m/s] : Speed of vehicles.

w : Weighting parameter.

δ_b : Relative blade angle of supply air fan. ($0 \leq \delta_b \leq 1$)
δ_e : Relative blade angle of exhaust fan. ($0 \leq \delta_e \leq 1$)
Δp [Pa] : Pressure difference between the portals.
$\lambda_r = 0.025$: Coefficient of pipe friction loss.
$\rho = 1.205$ [kg/m^3] : Density of air. (20°C, 1 atm)
$\rho_t = 0.0494$ [veh./m] : Density of traffic.
$\zeta_e = 0.6$: Coefficient of entrance loss.

Suffix

1,2 Section number of the tunnel.

INTRODUCTION

The Trans-Tokyo Bay Highway is a 15.1 km toll highway connecting Kawasaki and Kisarazu which are situated at both sides of the Tokyo Bay. The highway consists of two 10 km long tunnels under the Kawasaki waters where marine traffic is heavy, a 4.5 km bridge over the Kisarazu waters where marine traffic is sparse, and two gigantic man-made islands. The construction was commenced in 1988 and is to be completed in 1996.

The tunnels are planned to be ventilated by longitudinal system with a vertical shaft, electro-static precipitator stations and jet fans. Even in such a tunnel, which is served as one-way traffic, it is considered to be important that the countermeasure of emergency ventilation control is properly prepared so that the passengers are assured a favorable circumstance for evacuation in case of fire.

One of the authors has proposed an optimal ventilation control for tunnels with the length of around 3 km[1]. The current study is devoted to the confirmation of controllability of the longitudinal air flow by the same concept in the Trans-Tokyo Bay Tunnel by means of numerical simulations. The models for the aerodynamic behavior used in the current analysis is established by the previous studies[2],[3] by the authors and is proved to be appropriate by comparison with practical experiments[4].

FEATURE OF THE VENTILATION SYSTEM

The Trans-Tokyo Bay Tunnel is planned to be ventilated with a longitudinal system, equipped with a vertical shaft ventilation station, electro-static precipitator stations and jet fans. The current analysis and discussion is limited to the east bound tunnel for simplicity, as the other shaft is quite similar and most of the results obtained here can be also applied to the other. The upstream part before the vertical shaft is called as "section 1", and the other as "section 2". The main feature of the tunnel and its ventilation specifications are presented in **NOMENCLATURE**.

SIMULATION MODELS

Aerodynamic Model Main concept of the aerodynamic model for the numerical simulation is same as the one used for the study of the Kan-etsu tunnel[5]. The air column in the tunnel is treated as incompressible, and to obey Newton's second law of motion. The dynamics of the air flow in the first and the second section of the tunnel are separately formulated, and related by continuity of flow rate and pressure.

The ordinary differential equation for the air flow velocity in section 1 is described as

$$m_1 \frac{dV_{r1}}{dt} = F_{T1}, \tag{1}$$

in which the right hand side is the total force acting on the concerned air column. They are interpreted in the following formulae.

$$F_{T1} = F_{r1} + F_{w1} + F_{t1} + F_{j1}, \tag{2}$$

and resistance force by friction is

$$F_{r1} = -\left(1 + \zeta_e + \lambda_r \frac{L_{r1}}{D_r}\right) \frac{\rho}{2} A_r V_{r1} \left|V_{r1}\right|. \tag{3}$$

The force caused by the pressure difference at both ends of the section (in this case, at the entrance and the vertical shaft) is

$$F_{w1} = A_r \left(p_1 - p_T\right). \tag{4}$$

The traffic causes force by the drag of vehicles,

$$F_{t1} = \frac{\rho}{2} A_t n_{t1} \left(V_t - V_{r1}\right) \left|V_t - V_{r1}\right|, \tag{5}$$

The jet fans are the main component for driving the air flow according to the formula

$$\begin{aligned} F_{j1} &= n_{j1} K_j \rho A_j V_j \left(V_j - V_{r1}\right) && \text{for} \quad n_{j1} \geq 0, \\ F_{j1} &= -n_{j1} K_j \rho A_j V_j \left(V_j + V_{r1}\right) && \text{for} \quad n_{j1} < 0. \end{aligned} \tag{6}$$

The dynamics for section 2 is also described similarly, except that the entrance loss is eliminated and a new term F_{b2} appears due to pressure rise by blowing at the vertical shaft.

$$m_2 \frac{dV_{r2}}{dt} = F_{T2}, \tag{7}$$

$$F_{T2} = F_{r2} + F_{w2} + F_{t2} + F_{j2} + F_{b2}, \tag{8}$$

$$F_{r2} = -\left(\lambda_r \frac{L_{r2}}{D_r}\right) \frac{\rho}{2} A_r V_{r2} \left|V_{r2}\right|, \tag{9}$$

$$F_{w2} = A_r \left(p_T - p_2\right), \tag{10}$$

$$F_{t2} = \frac{\rho}{2} A_t \{n_{t2} \left(V_t - V_{r2}\right) \left|V_t - V_{r2}\right|\}, \tag{11}$$

$$\begin{aligned} F_{j2} &= n_{j2} K_j \rho A_j V_j \left(V_j - V_{r2}\right) && \text{for} \quad n_{j2} \geq 0, \\ F_{j2} &= -n_{j2} K_j \rho A_j V_j \left(V_j + V_{r2}\right) && \text{for} \quad n_{j2} < 0, \end{aligned} \tag{12}$$

$$F_{b2} = \frac{\rho}{A_r}\left\{\frac{Q_b^2}{A_b/A_r} + \frac{\left(Q_{r2} - Q_b\right)^2}{1 - A_b/A_r} - Q_{r2}^2\right\}. \tag{13}$$

The continuity of pressure holds at the junction of the two sections in that the same p_T is used in both eqs. (4) and (10). The law of conservation of mass at the junction between both sections and the vertical shaft is

$$Q_{in} \equiv A_r(V_{r1} - V_{r2}) - (Q_e - Q_b) = 0. \tag{14}$$

This relation must hold at any time step during the whole simulation.

The so called natural wind velocity V_n is the air flow velocity which would occur if there were no disturbances by vehicles and ventilators. It is considered that the natural wind in the tunnel is caused by the pressure difference at both portals of the tunnel due to meteorological condition. In the simulation, V_n is hypothsized, and Δp, p_1, p_2 and p_{T0} are calculated by the following relations, although they are constant during each simulation case.

$$\begin{aligned} \Delta p &\equiv (p_1 - p_2) \\ &= \left(1 + \zeta_e + \lambda_r \frac{L_r}{D_r}\right) \frac{\rho}{2} A_r V_n \left|V_n\right|, \end{aligned} \tag{15}$$

$$p_1 = 0, \tag{16}$$

$$p_{T0} = -\Delta p (L_{r1}/L_r), \tag{17}$$

$$p_2 = -\Delta p. \tag{18}$$

Traffic Model A simple traffic model is used in the current simulation for the emergency control of ventilation. It is hypothesized that an accident occurs at time $t = 0$, and it is detected at once with its location. According to the traffic lamps in the tunnel and at the entrance, the vehicles toward the point of the accident stop soon, then the traffic force on the air becomes negligible small. On the other hand, the vehicles leaving from the accident keep running, causing traffic force until they go out of the tunnel. From these consideration, the number of vehicles running in the tunnel section will be calculated by

$$n_t = \rho_t L_t \tag{19}$$

for each section, used in eqns. (5) and (11). Here, L_t's depend on time and location of the accident as is formulated in the followings.

If the accident is in section 1; $(0 \leq L_a < L_{r1})$,

$$L_{t1} = L_{r1},\ L_{t2} = L_{r2} \qquad \text{for} \quad t \leq 0 \tag{20}$$

$$L_{t1} = (L_{r1} - L_a) - V_t t,\ L_{t2} = L_{r2} \qquad \text{for} \quad 0 < t \leq (L_{r1} - L_a)/V_t \equiv t_0 \tag{21}$$

$$L_{t1} = 0,\ L_{t2} = L_{r2} - V_t(t - t_0) \qquad \text{for} \quad t_0 < t \leq t_0 + L_{r2}/V_t \equiv t_1 \tag{22}$$

$$L_{t1} = 0,\ L_{t2} = 0 \qquad \text{for} \quad t_1 < t \tag{23}$$

and for the accident in section 2; $(L_{r1} \le L_a \le L_{r1} + L_{r2})$,

$$L_{t1} = L_{r1},\ L_{t2} = L_{r2} \qquad \text{for} \quad t \le 0 \tag{24}$$

$$L_{t1} = 0,\ L_{t2} = (L_{r1} + L_{r2} - L_a) - V_t t \quad \text{for} \quad 0 < t \le (L_{r1} + L_{r2} - L_a)/V_t \equiv t_0 \tag{25}$$

$$L_{t1} = 0,\ L_{t2} = 0 \qquad \text{for} \quad t_0 < t \tag{26}$$

Fan Model The flow rate of the supply air fan and exhaust fan at the vertical shaft is approximated by eqs. (27) and (28), in which the flow rate of the fan is expressed in terms of pressure difference at both ends of the duct and the relative blade angles δ_b or δ_e.

$$Q_b = f_b(\delta_b, p_T - p_{T0}), \tag{27}$$

$$Q_e = f_e(\delta_e, p_T - p_{T0}). \tag{28}$$

In the actual numerical procedure, they are calculated through iteration as the solution of a simultaneous equation system of the characteristic curve of the fan and the duct loss. Delay in the vertical shaft is neglected, because it is considered to be small enough compared to the one in the main shaft.

THE DYNAMIC CHARACTERISTICS OF THE AIR FLOW VELOCITY

Simple cases are selected for the preliminary simulation in order to demonstrate the dynamic characteristics of the air flow velocity in the Trans-Tokyo Bay Tunnel. In the present paper, two typical situations with regard to the point of accident and the natural wind velocity are considered.

Table 1 Hypothesized situations

Item	Variable	Situation 1	Situation 2
Point of accident [m]	L_a	0	$L_{r1} + L_{r2}$
Natural wind velocity [m/s]	V_n	+2.5	−2.5

The situation 1 is one of the worst cases in which positive disturbances are dominant. Namely the point of the accident is at the entrance of the tunnel which causes positive driving force to the air in the tunnel until all the vehicles go out of the tunnel, along with positive natural wind (+2.5 m/s). The situation 2 is, on the other hand, the opposite extreme; the point of the accident being at the exit of the tunnel resulting in a quick extinction of traffic force, accompanied by the condition of negative natural wind (−2.5 m/s). The first case, shown in fig. 1, is the one in which all ventilators are shut down

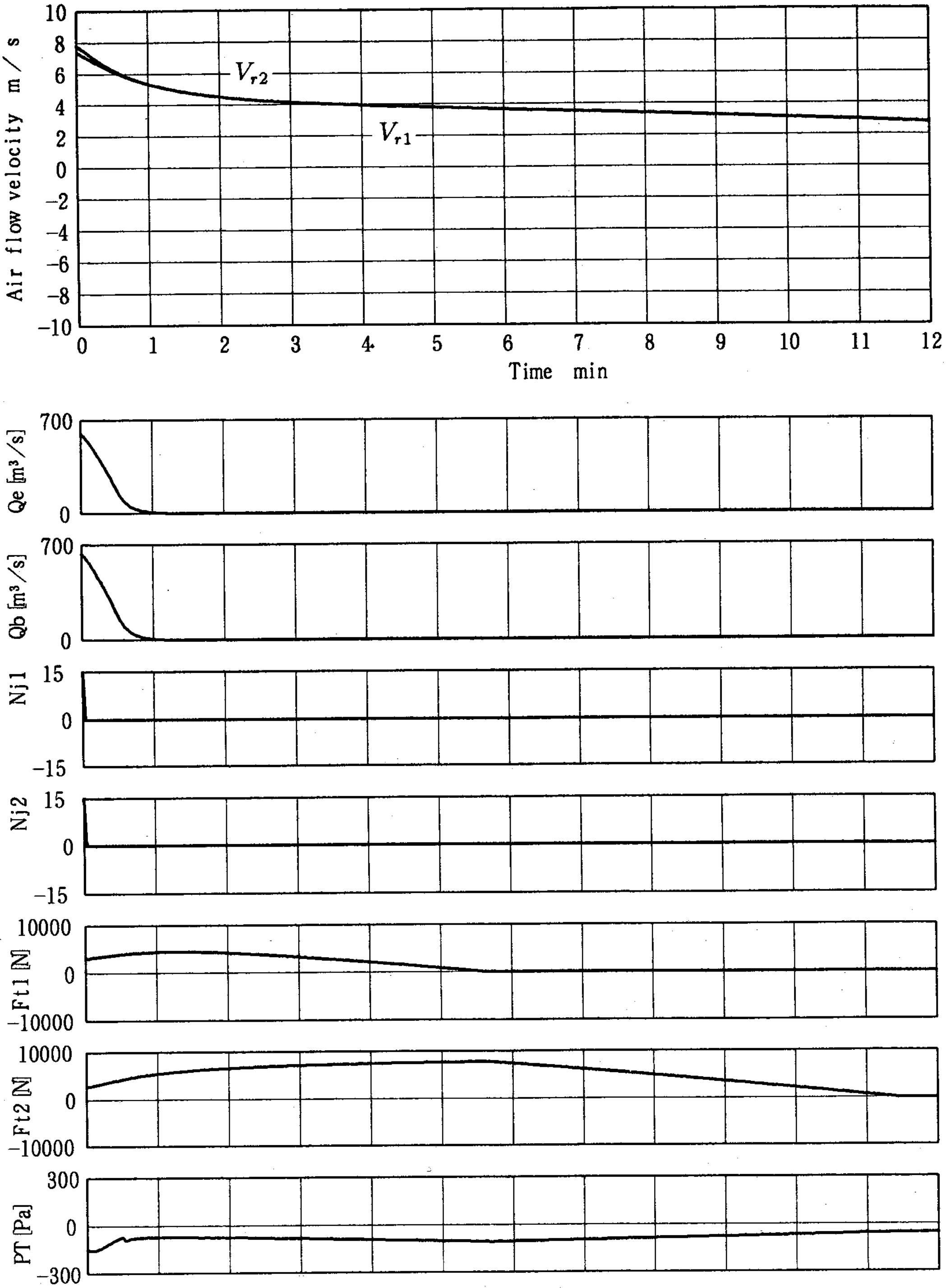

Fig. 1 The air flow velocity by shut down. (Situation 1)

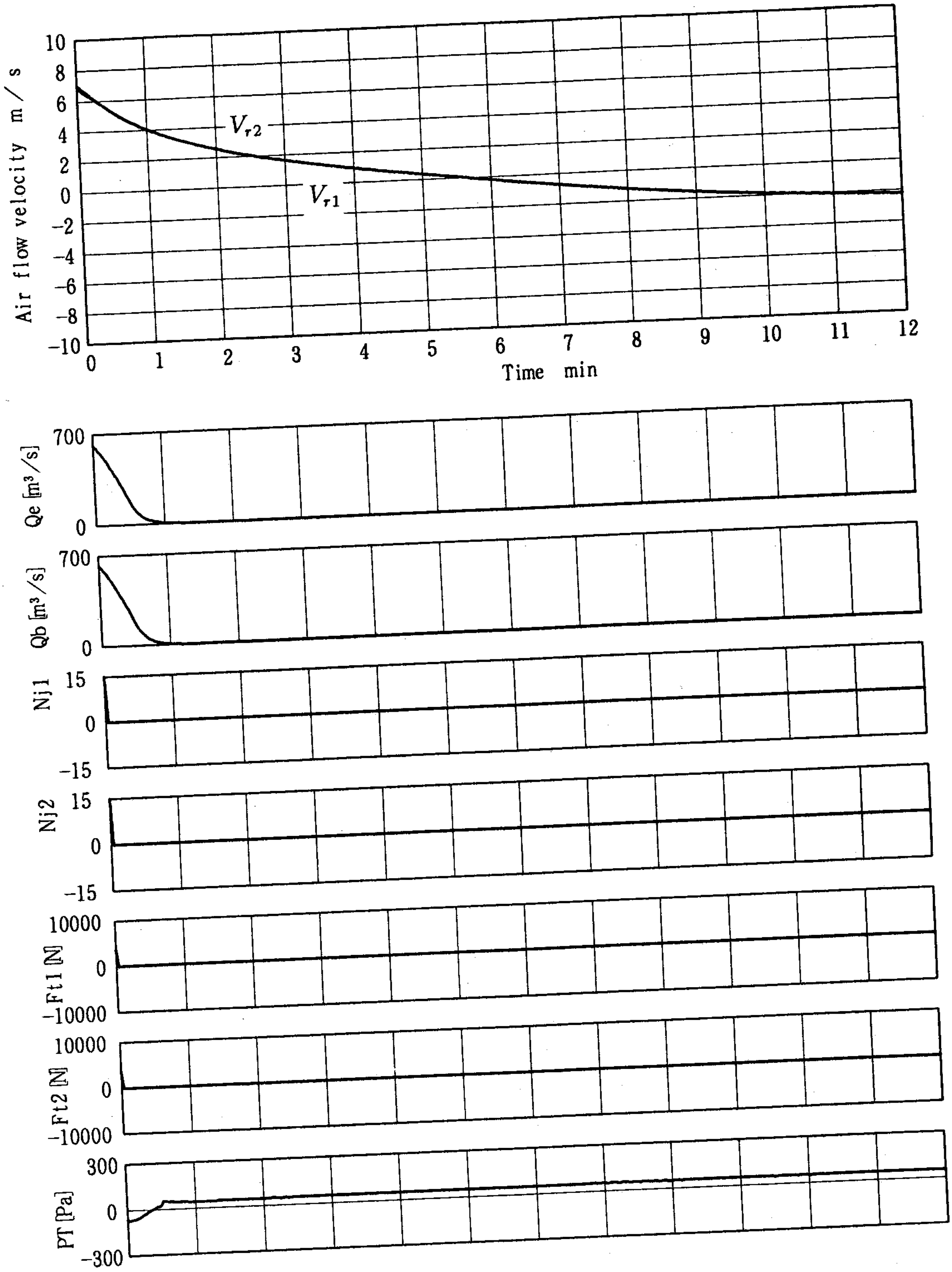

Fig. 2 The air flow velocity by shut down. (Situation 2)

at time $t = 0$, under situation 1. The result shows that it takes a lot of time until the flow velocity reaches terminal value of 2.5 m/s. On the other hand, if the hypothesized conditions tend to be negative, under situation 2, the behavior of the air flow velocity is quite different from the former case. Fig. 2 is the simulation result under the assumption of the accident point being at the tunnel exit, and the natural wind being −2.5 m/s. All the ventilators are shut down at $t = 0$ which is same as the above case. The wind velocity in the tunnel reduces more quickly, and takes negative value after 6 minutes. This means that the smoke flows reversely where vehicles remain in the tunnel. It is considered that this should be avoided from the viewpoint of safety. If the ventilators are operated in full load, instead of being shut down, under situation 1, the air flow velocity keeps a rather high value, which is also considered to be unfavorable for evacuation circumstance (Fig. 3). Similar behavior is observed under situation 2, for which the illustration is abbreviated.

The following cases are the results by switching the fans at $t = 0$ with several combinations. In the first case, in fig. 4, the fans at the vertical shaft are shut down, and all of the jet fans are reversely operated under situation 1. Here, the wind velocity in the tunnel comes down to zero in 2.5 minutes. Traffic force in section 2 takes large value because the air flow velocity takes negative values of about −5 to −6 m/s. In case that only the vertical shaft fans are available for the suppression of the air flow under situation 1, it is proper to shut down Q_e and keep Q_b maximum value, so that blockage effect would cause reduction of the air flow in section 1. Large positive value of p_T in the first minute observed is a good explanation for the effect. As the blowing of fresh air has the pressure rise characteristic, however, damping is not as strong as the former case. If the point of accident is near the tunnel exit, and the natural wind is −2.5 m/s, the reduction of air flow is much more quick, as is shown in fig. 6, only with jet fans. Similar behavior is observed by operating vertical shaft fans only (Fig. 7). In this case, the pressure at the junction p_T take large negative values in the first minute, which drives the air flow velocity in section 2 negative, showing a clear contrast to the case for fig. 5. In these two cases V_{r2} is the object of control.

OPTIMAL CONTROL OF THE EMERGENCY VENTILATION

As one of the authors has disscussed in the earlier paper[1], the concept of optimal control in case of emergency for a longitudinally ventilated tunnel is proposed, with which the air flow is brought to zero with swiftness and stability. In the present paper, above mentioned algorythm of optimal control is generalized in that not only jet fans but also vertical shaft is employed for higher performance.

The informations the controller can obtain are δ_b, δ_e, V_{r1}, V_{r2} and the number of jet fans in operation. On the other hand, Q_b, Q_e and p_T are unknowns for the controller. Under such circumstance, the algorithm of the optimal control consisits of following steps:

1) Flow rates of vertical shaft fans, Q_b and Q_e, are estimated using the relations of continuity, characteristics of the fans and resistance of the duct through the vertical shaft.

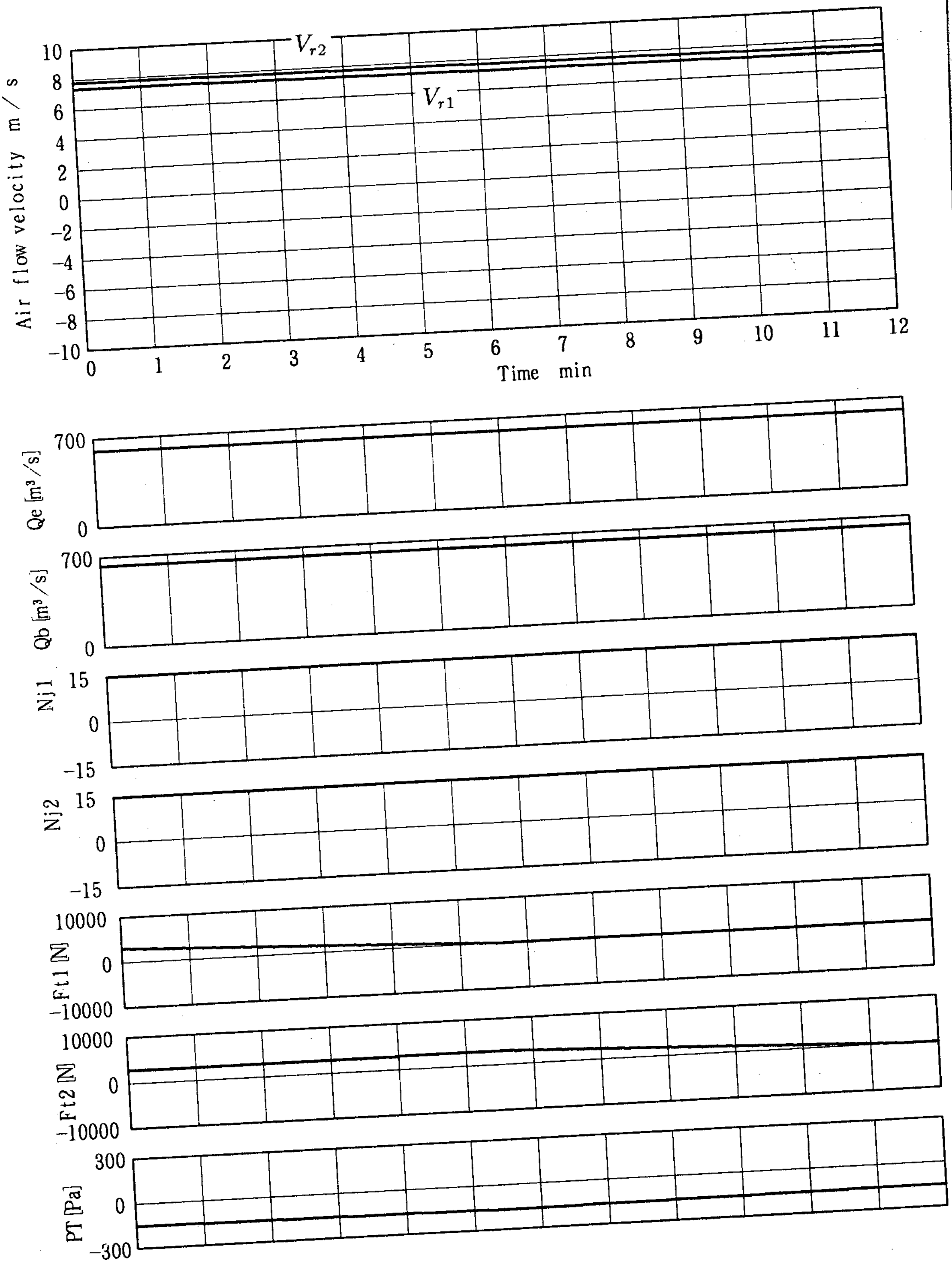

Fig. 3 The air flow velocity with continued operation. (Situation 1)

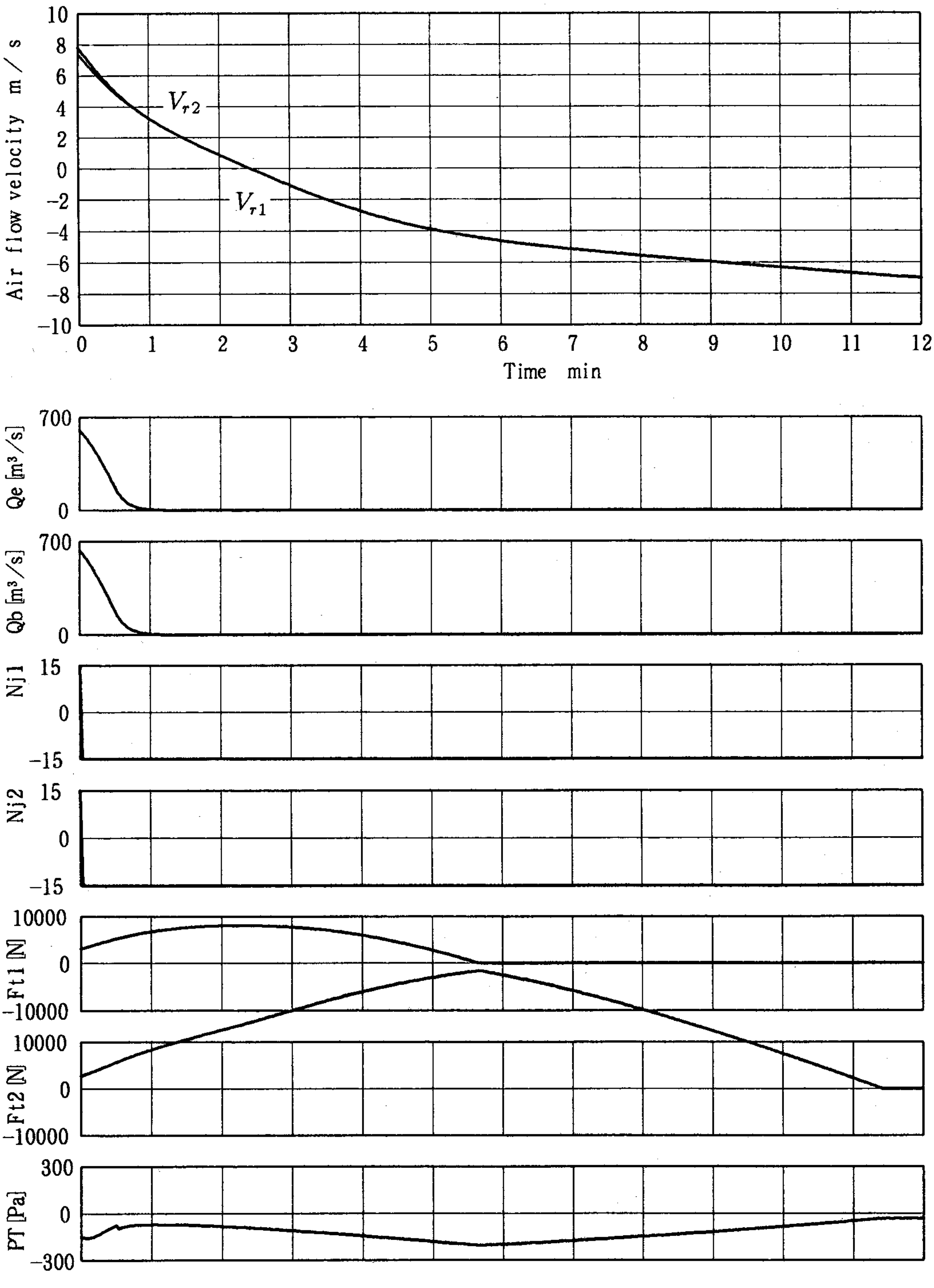

Fig. 4 The air flow velocity by reverse operation of jet fans. (Situation 1)

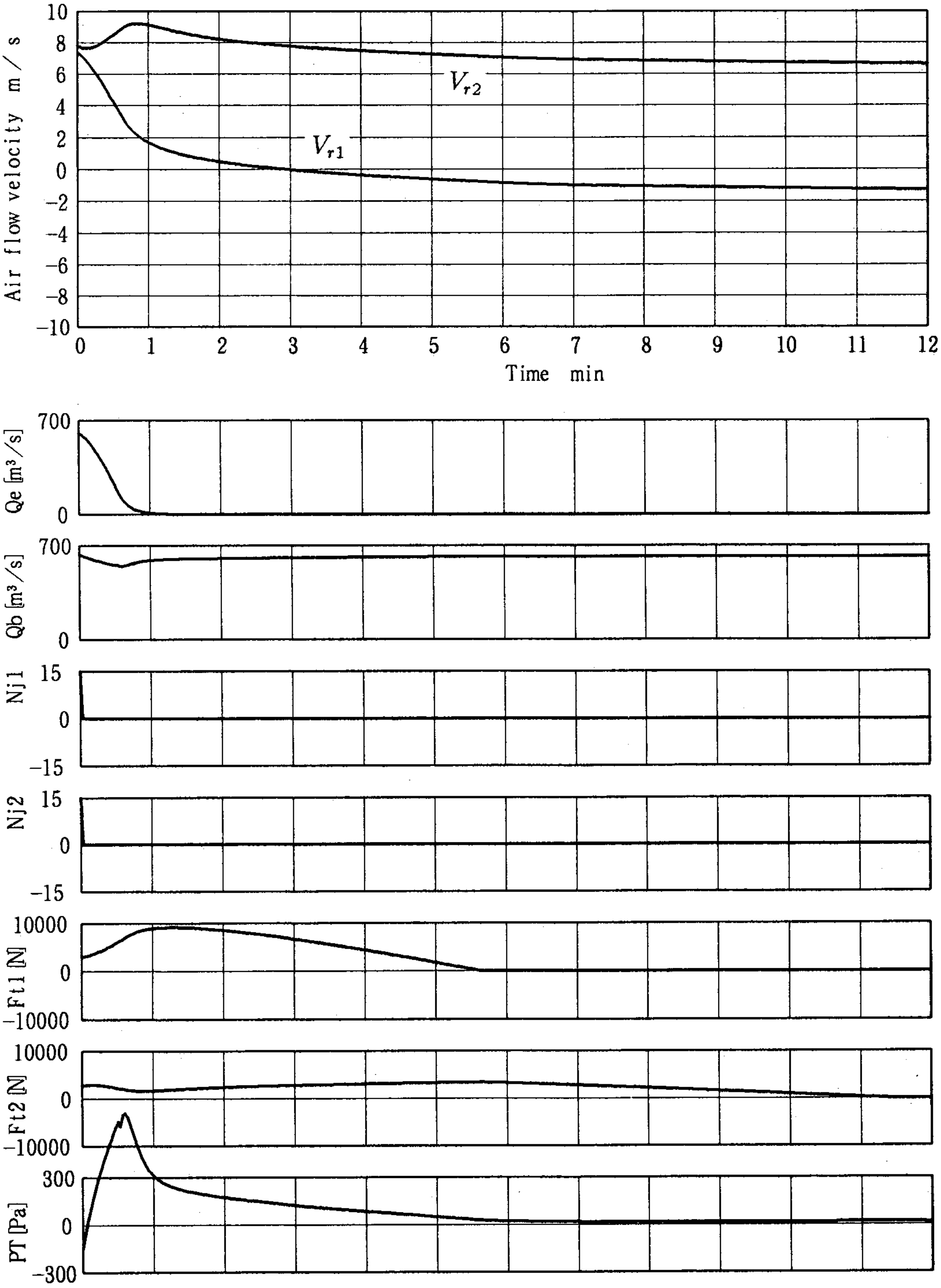

Fig. 5 The air flow velocity by imbalance operation of vertical shaft fans. (Situation1)

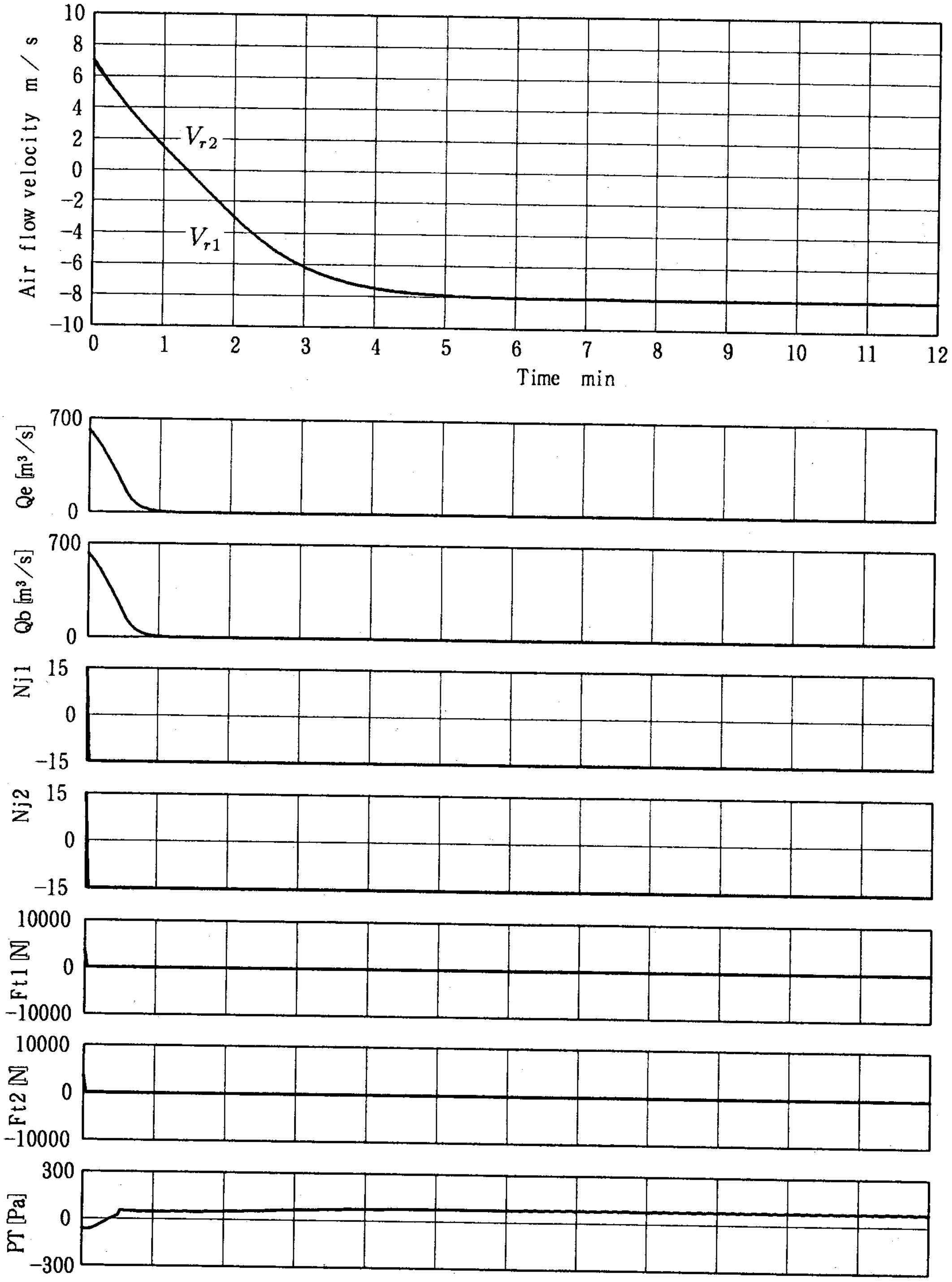

Fig. 6 The air flow velocity by reverse operation of jet fans.
(Situation2)

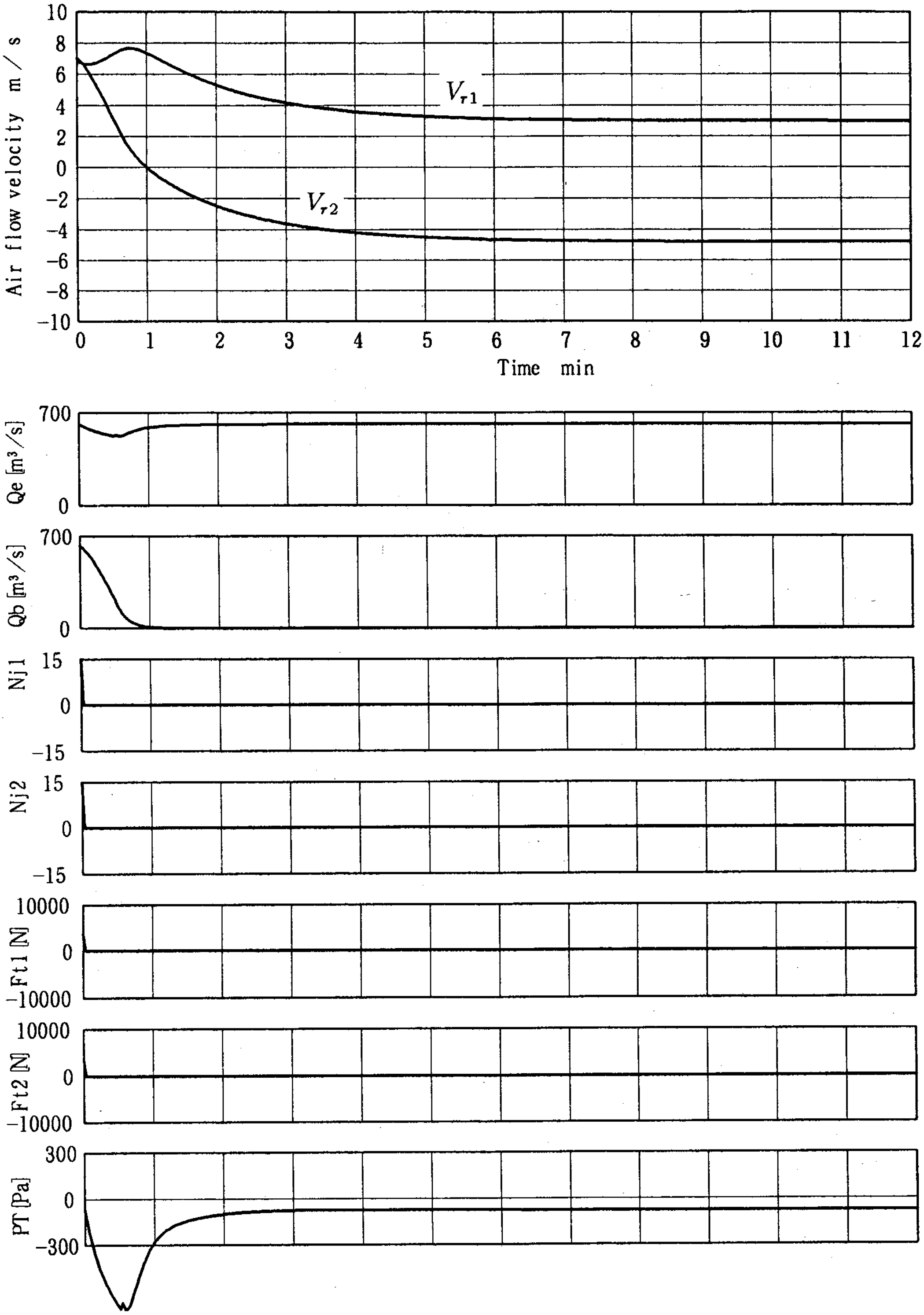

Fig. 7 The air flow velocity by imbalance operation of vertical shaft fans. (Situation2)

2) The pressure at the bottom of the vertical shaft p_T is estimated from the pressure balance of the duct resistance and the fan performance.

3) The residual forces are calculated from the acceleration of the air flow for each division. The residual force is the one which cannot be known from obtained data theoretically, but is calculated as the difference of the total force (from acceleration) and the driving force by jet fans, which is estimated in rather high accuracy.

4) Necessary force is calculated with an enough large proportional gain so that the target value is attained quickly. Responsible forces for the jet fans and the vertical shaft fans are calculated according to the prescribed weighting parameter w.

5) Blade angles of the vertical shaft fans, δ_b and δ_e, are calculated. Necessary number of jet fans n_j are calculated.

This procedure is executed at the beginning of each control period, and the instruction is transmitted to jet fans and vertical shaft fans.

SIMULATION RESULTS OF THE OPTIMAL CONTROL

Four cases are demonstrated here in order to show the effectiveness of the proposed optimal control algorythm. The target value V_{r0} is set to zero m/s for simplicity, although it will be set between 2 and 3 m/s for the safety in the upstream region. A parameter w is given to the simulator, which indicate the weighting of vertical shaft fans. When w is zero, only jet fans are active, while the vertical shaft is idle as in fig. 8 (situation 1). V_{r1} comes to zero in two minutes and stays at the value stably, although the traffic force changes violently. All the jet fans are reversely operated in the first two minutes, and the number gradually reduces itself. In this case the pressure at the junction p_T does not take a large value compared to the latter cases. When $w = 0.5$, both fans are active, and as the result, the air flow velocity reaches zero in nearly a minute, as is shown in fig. 9 (situation 1). The next case of the optimal control is executed under $w = 1.0$, for which jet fans are shut down and vertical shaft is active (Fig. 10) under situation 1. In order to reduce the velocity in the section 1, Q_e is brought to zero, while Q_b is operated in full load. A higher flow rate of supply air causes blockage effect, which brings V_{r1} to lower value quickly. The imbalance of vertical shaft fans causes strong pressure change of p_T which results in a quick change of the air flow velocity. It is, however, not so much effective because Q_b brings also momentum into the tunnel. For the situation 2, however, the operation of vertical shaft fans is effective enough, as is shown in fig. 11 ($w = 0$). In this case the exhaust flow rate Q_e affects strongly to reduce the air flow velocity in the second section. The behavior of the pressure at the junction p_T shows how it worked out well.

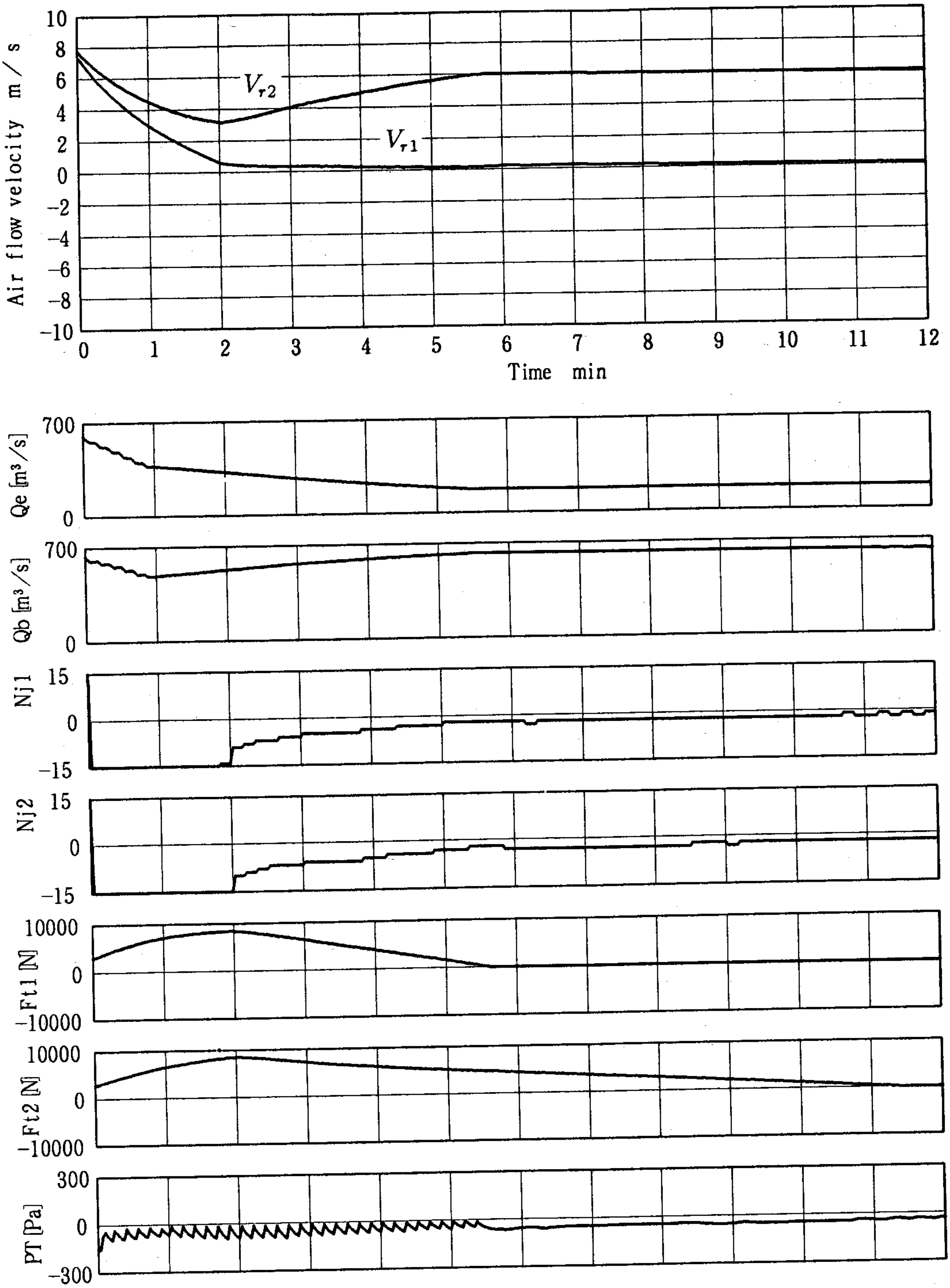

Fig. 8 The air flow velocity by the optimal control.
(Only jet fans are employed: Situation 1)

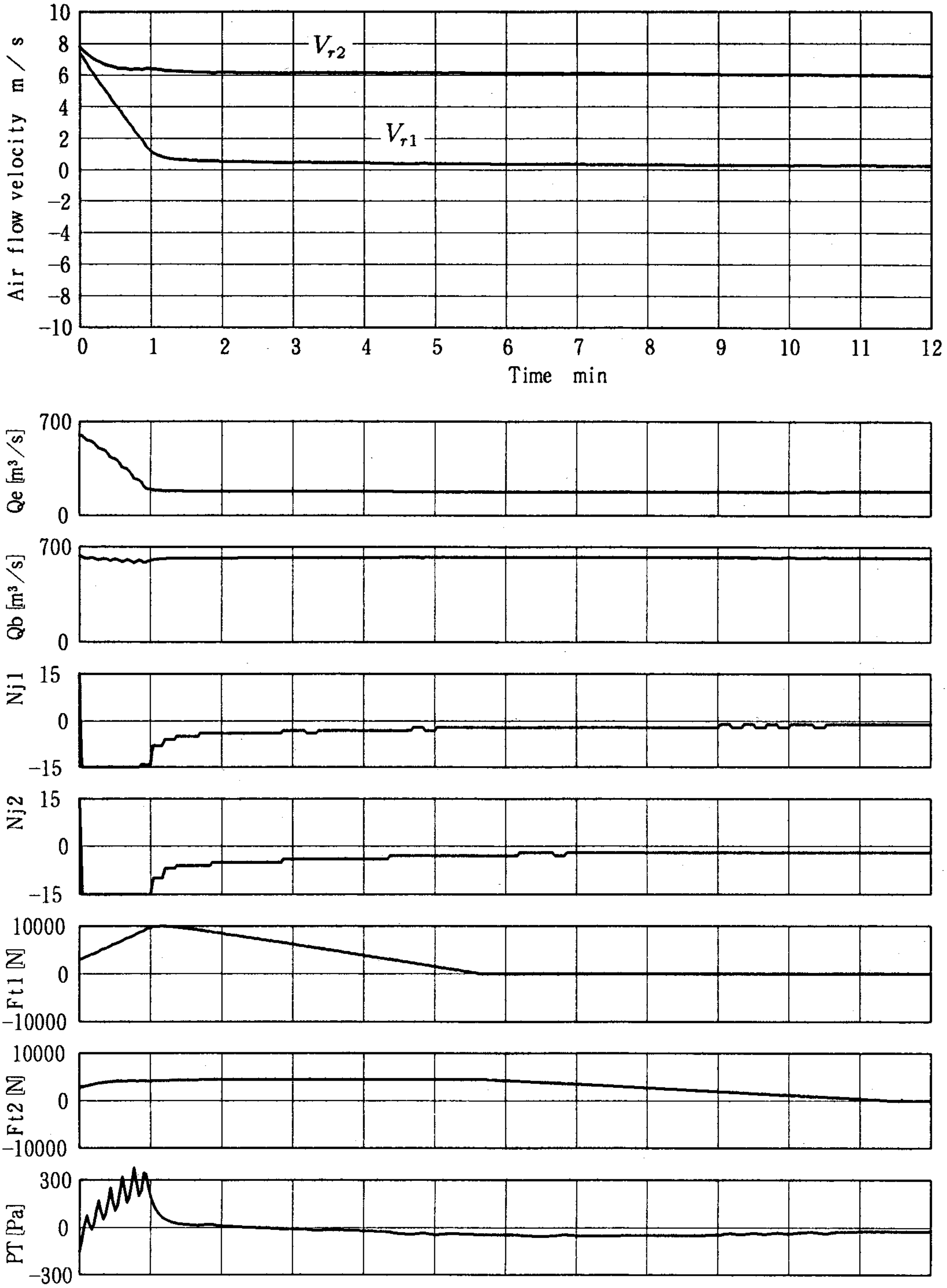

Fig. 9 The air flow velocity by the optimal control.
(Both fans are employed: Situation 1)

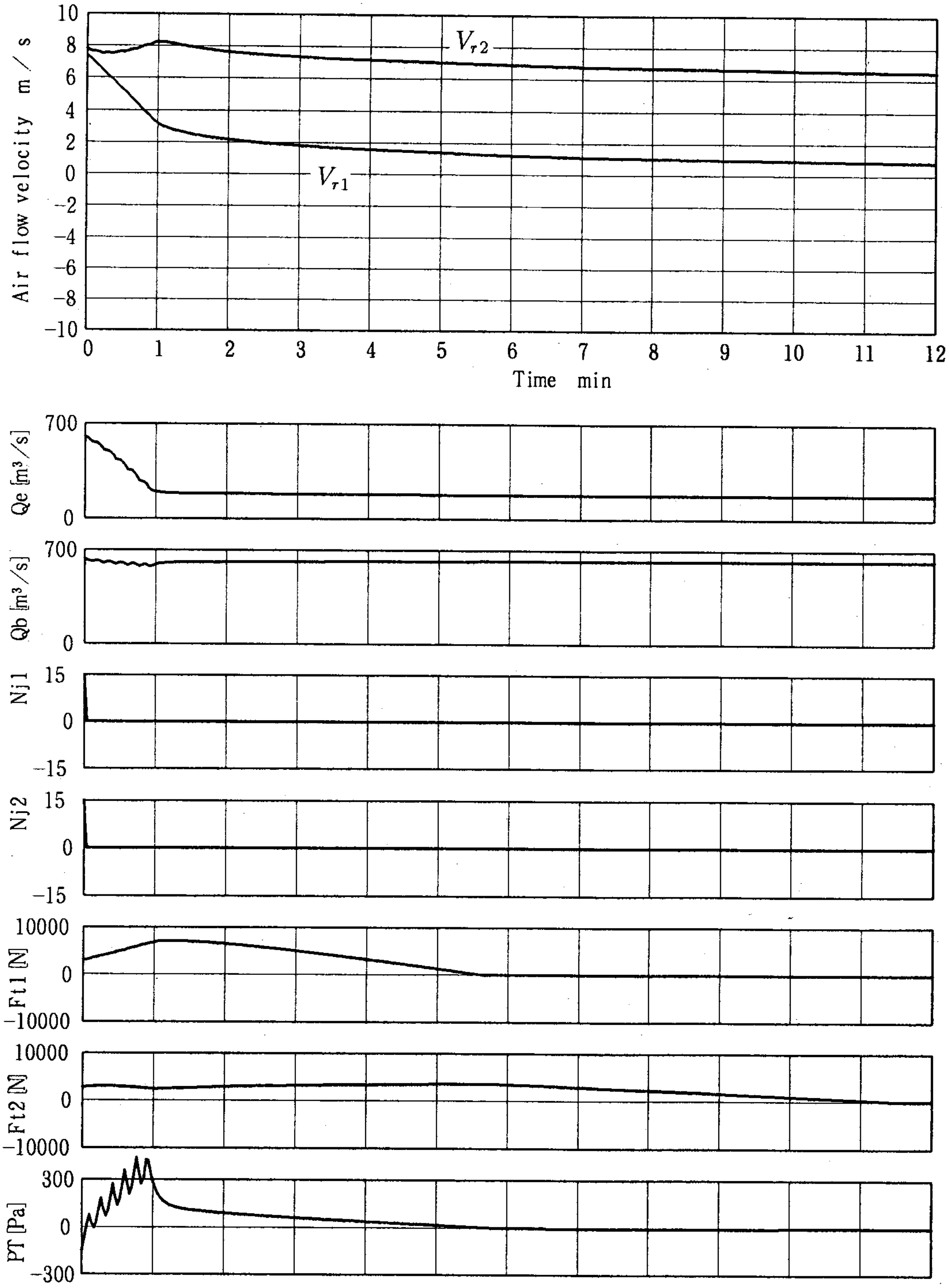

Fig. 10 The air flow velocity by the optimal control.
(Only Vertical shaft fans are employed: Situation 1)

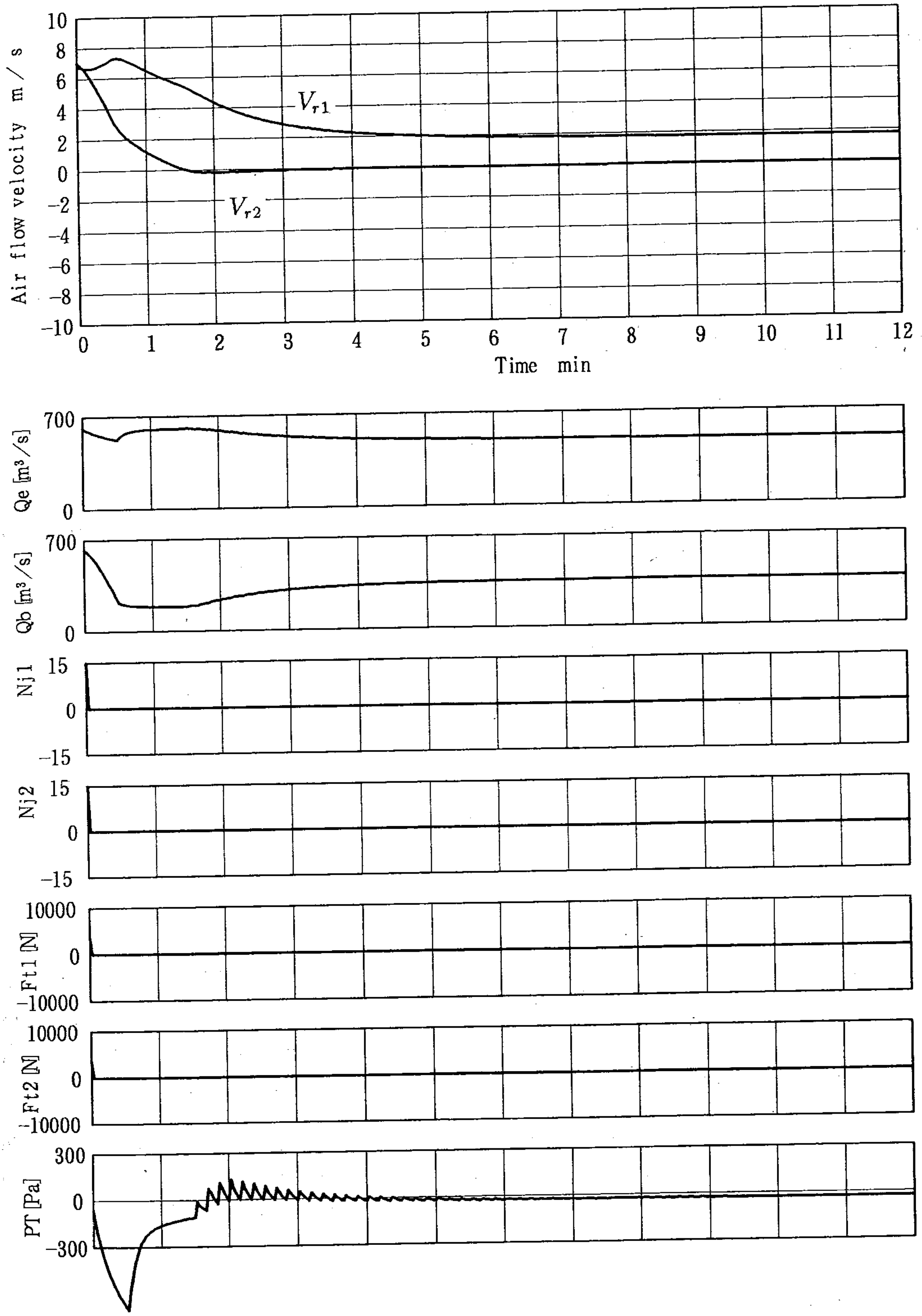

Fig. 11 The air flow velocity by the optimal control.
(Only Vertical shaft fans are employed: Situation 2)

CONCLUSION

A numerical simulator for the emergency ventilation control for the Trans-Tokyo Bay Tunnel is developed. Dynamic characteristics is studied for a better understanding to establish strategies of emergency control. An optimal control algorythm is proposed for the current ventilation system with imbalance operation of the vertical shaft fans being employed, which is the extension of the one for the simple longitudinal ventilation system driven only by jet fans. Although excellent performance is attained by the current control method, more detailed simulation is required with higher realistic models for the practical application.

REFERENCES

[1] Mizuno, A., "An optimal control with disturbance estimation for the emergency ventilation of a longitudinally ventilated road tunnel", *Proc. 3rd. International Symposium on Fluid Control, Measurement and Visualization* (FLUCOME '91), San Francisco, U.S.A. Aug. 29–31, 1991.

[2] Mizuno, A. et al, "Emergency operation of ventilation for the Kan-etsu road tunnel", *Proc. 5th International Symposium on the Aerodynamics and Ventilation of Vehicle tunnels* (Lille, France, May 20–22, 1985), Cranfield, U.K., BHRA Fluid Engineering Centre, 1985, pp.77–91.

[3] Mizuno, A. and Ohashi, H., "Emergency control of ventilation for longitudinally ventilated road tunnel", *Proc. 2nd International Symposium on Fluid Control, Measurement, Mechanics and Flow Visualisation* (FLUCOME '88, Sheffield, U.K., Sept. 5–9, 1988), 1988, pp.87–91.

[4] Mizuno, A. et al, "Practical test of emergency ventilation combined with bus firing at the Kan-etsu tunnel", *Proc. 6th International Symposium on the Aerodynamics and Ventilation of Vehicle tunnels* (Durham, U.K., Sept. 27–29, 1988), Cranfield, U.K., BHRA Fluid Engineering Centre, 1988, pp.353–366.

[5] Ohashi, H. et al, "A new ventilation method for the Kan-etsu road tunnel", *Proc. 4th International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels* (York, U.K., Mar. 23–25, 1982), Cranfield, U.K., BHRA Fluid Engineering Centre, 1982, pp.31–47.