AN AERODYNAMIC MATHEMATICAL MODEL
FOR
SUPER-HIGH-SPEED ELEVATORS

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ABSTRACT

As the cities are becoming more and more densely populated, buildings are getting higher and higher. The proposal of "kilometer-high building" has already been announced and therefore, the demand for super-high-speed elevators is highly increasing. The rated speed record of 600 m/min was achieved in 1977 and then 750 m/min in 1993. Now, elevators up to 840 m/min are being developed. The existing mechanical problems associated with the development of high speed elevators are associated with noise and vibration. For high speed elevators, aerodynamic noise is usually larger. Hence, it is essential to understand the air flow patterns around a super-high-speed elevator car. In this paper, a simplified mathematical model has been developed based on computational fluid dynamics (CFD) to study the fluid flow patterns above a travelling car. This model, though very much different from the real situation, is the beginning point of a comprehensive model. It can be used to simulate some interesting phenomena inside the hoistway. The ultimate goal is to make use CFD models as a computer assisted tool to design a new car frame such that the problems of noise and vibration can be solved under super-high-speed operation. It must be noted that the models are used for designing external car frame and hence high accuracy from CFD point of view is not the most critical issue to be considered.

1 INTRODUCTION

As the cities are becoming more and more densely populated, buildings are getting higher and higher. The proposal of "kilometer-high building" was announced decades ago. Therefore, the demand for better services in vertical transportation within buildings is rapidly increasing because citizens live and work in higher and higher buildings. The highest building in the world is now slightly over 100 storeys but the concept of `kilometer high' building has been under active consideration. Hong Kong will be having her highest building in the world, the Nina Tower, within four years time and Shanghai will be having one as well. The efficiency of these high rise buildings very much relies on an effective vertical transportation system which can provide both superior quality and quantity of services. Quality of service refers to short waiting time and short journey time. Quantity of service refers to high handling capacity. Fig. 1 shows a post-modern design of elevator systems in a new commercial building in Japan, the Shin Umeda City - Umeda Skybuilding in Osaka.

In accordance with Fortune (Fortune 1995), the key to efficient, mega high-rise elevator design is to stack local zones served by their own local elevators on top of one another. These local zones are then served by very high-speed, sky-lobby shuttle elevators, serving express between the ground terminal floor(s) and the sky lobby(ies). With a view to this approach, the speed of elevators in the future will continuously be increasing. The rated speed record of 600 m/min was achieved in 1977 in Tokyo and then 750 m/min in 1993 in Yokohama. Now, elevators up to 840 m/min are being developed. It is not so difficult to increase the rated speed of drive motors or the gear ratio to achieve a higher rated speed for elevators. However, super-high-speed elevators suffer from two major mechanical problems, namely excessive vibration and aerodynamic noise.

The first problem is associated with the increasing drag force exerted by the high-speed air movement around an ascending or descending elevator car. These problems, which are generated from the aerodynamics of the system, hinder the development of higher speed elevators and they must be solved in order to make the vertical transportation keep abreast with the construction of super-high-rise buildings in the next century. Human response is greatest at low frequencies and therefore, vibration limits in the range from 1 Hz to 80 Hz must be met. Double compensating pulleys, divided counterweights and dampers (Miyoshi 1995) were developed to reduce vertical vibration in long-stroke elevators. The idea of "active suspension" (Nai 1995) which includes some kind of controllable actuator supplying energy to the system, car velocity control and non-contacting guide shoes were developed to improve the riding quality during high-speed travelling. Hoistways of larger sizes can help but the price of land becomes a significant problem in a densely populated city.

In accordance with CIBSE Guide D, in-car noise levels, machine room noise levels and lobby noise levels must be under control. Active control of noise (Nagayasu 1995) was developed but it was mainly for reducing the noise from the ventilating fan and air duct. Although the problem can be partially solved by introducing building materials with good sound reduction properties, the basic solution is to reduce the noise generated by a moving car.

With the view to all the problems mentioned above, it is a necessity to make a revolution on the external structure of elevator cars so as to keep the noise levels, vibration levels and drag force to a minimum subject to a limited size of hoistway. This is a new design concept but the initial step is to produce a comprehensive, realistic and reasonably accurate mechanical model of a super-high-speed elevator car inside a conventional hoistway so that the aerodynamic properties can be studied thoroughly.

2 EXISTING METHODS TO STUDY AERODYNAMIC PROPERTIES

In order to study the production of aerodynamic noise for super-high-speed elevators, a miniature elevator was constructed in a wind tunnel (Matsukura 1992) based on a 1:12.5 ratio. The average wind velocity inside the duct was 30 m/s. An "oil flow pattern method" was applied as well to visualise the air flow over the surfaces of the elevator car. It was also shown experimentally that the vibration level of the car had been quite proportional to the travelling speed (Matsukura 1992). A water tank

(Teshima 1992) was also used to observe the overall flow and to visualise the flow around the model submerged in water using a tracer. The Re number based on the car width and the main stream speed was approximately 800. A numerical simulation was also carried out (Teshima 1992) because it the tank could not simulate the relative speed between the car and the wall of hoistway while a Re number of 1.3 x 10^5 had been assumed.

3 THE NEWLY DEVELOPED SIMPLIFIED AERODYNAMIC MODEL

A one-dimensional model has been initially used to study the air flow pattern inside the hoistway. Lots of assumptions here have been made so that this model is very much different from the real situation but this model can give us an insight to the changing patterns of air flow when the elevator car is accelerating. The assumptions made are show below:

a) An up-travelling car is simulated;
b) The leakage of air downwards around the car is neglected;
c) The gravity of air is neglected and hence the potential energy of air;
d) The leakage of air through landing doors is neglected;
e) The irregular shape of car and hoistway is not taken into account of.

The typical aerodynamic characteristics, i.e. pressure distributions, have been revealed when the speed and acceleration are high. Reference is made to Figure 1. A cylindrical hoistway, of area A, is assumed. The total vertical height of the hoistway is L. Distance, x, is measured right up from the top of the elevator car. An exit at the top and centre of the hoistway is provided with an area A_e. This opening is conventionally the channel of air flow between the machine room and the hoistway and it is the only opening in the whole hoistway in our simplified model. The elevator car acts like a piston inside a cylinder and its area is equivalent to the cross-sectional area of the hoistway. It always starts from an initial velocity, V_0 m/s with an acceleration, a m/s^2. The instantaneous velocity of the elevator car, at time t s, is equal to V_I m/s. The velocity of air at an level, x, is equal to V m/s.

The simplified mathematical model adopted here is the one-dimensional inviscid flow model and the governed equations are as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho V)}{\partial x} = 0 \tag{1}$$

$$\frac{\partial(\rho V)}{\partial t} + \frac{\partial}{\partial x}(\rho V^2 + p) = 0 \tag{2}$$

$$\frac{\partial}{\partial t}\left[\rho \left(e + \frac{1}{2}V^2\right) \right] + \frac{\partial}{\partial x}\left\{ V \left[\rho\left(e + \frac{1}{2}V^2\right) + p \right]\right\} = 0 \tag{3}$$

Here, ρ is the density of air, being assumed as constant throughout the simulation; V is the instantaneous velocity of air at level x; p is the instantaneous pressure at level x; e is the specific internal energy of ideal gas defined below by equation (4). These three equations are the conservation forms of the continuity, x-momentum and energy equations respectively.

$$e \triangleq c_v T = \frac{p}{(\gamma - 1)\rho} \tag{4}$$

Here, γ is the specific heat ratio. With the aid of equation (4), it can be noticed that equations (1) to (3) contain three dependent variables, namely V, ρ and p.

It is convenient in numerical calculation of non-dimensionalising the dependent variables of the governing equations. Therefore, equations (1) to (3) can further be written in compact non-dimensional forms as shown below:

$$\frac{\partial q}{\partial t} + \frac{\partial F}{\partial x} = 0 \tag{5}$$

$$q = \begin{bmatrix} \rho \\ \rho V \\ \dfrac{p}{(\gamma - 1)} + \dfrac{1}{2}\rho V^2 \end{bmatrix} ; \quad F = \begin{bmatrix} \rho V \\ \rho V^2 + p \\ \left[\dfrac{p\gamma}{\gamma - 1} + \dfrac{1}{2}\rho V^2 \right] V \end{bmatrix} \tag{6}$$

4 BOUNDARY CONDITIONS AND NUMERICAL SCHEME

The field for numerical simulation of aerodynamic problems is the dashed region above the elevator car top, as shown in Figure 1. The inlet boundary conditions are shown below:

$$V_I = V_o + a\,t \quad ; \quad p_I = p_a + \frac{1}{2}\rho V_I^2 \tag{7}$$

Here, V_I is the car top velocity; V_0 is the initial velocity of the elevator car; p_I is the car top pressure; p_a is the atmospheric pressure.

The boundary conditions at the exit opening are based on mass flux conservation law and the principle of flux average distribution by area. Then, at time interval, n, the MacCormarck scheme (MacCormarck 1969, 1981) is applied to equation (5) and the result is shown in equation (8). MacCormarck Scheme is a very effective finte-difference technique which is a two-stage explicit predictor-corrector scheme. This scheme is conceptually similar to Lax-Wendroff Scheme. Since it was first used by MacCormarck, this scheme has become very famous in the computational aerodynamics field and it is very popular in nowadays. One co-author of this paper has been using this scheme for quite a long period of time in studying 3-dimensional viscous and complex air flow problems (Yang 1994, 1996).

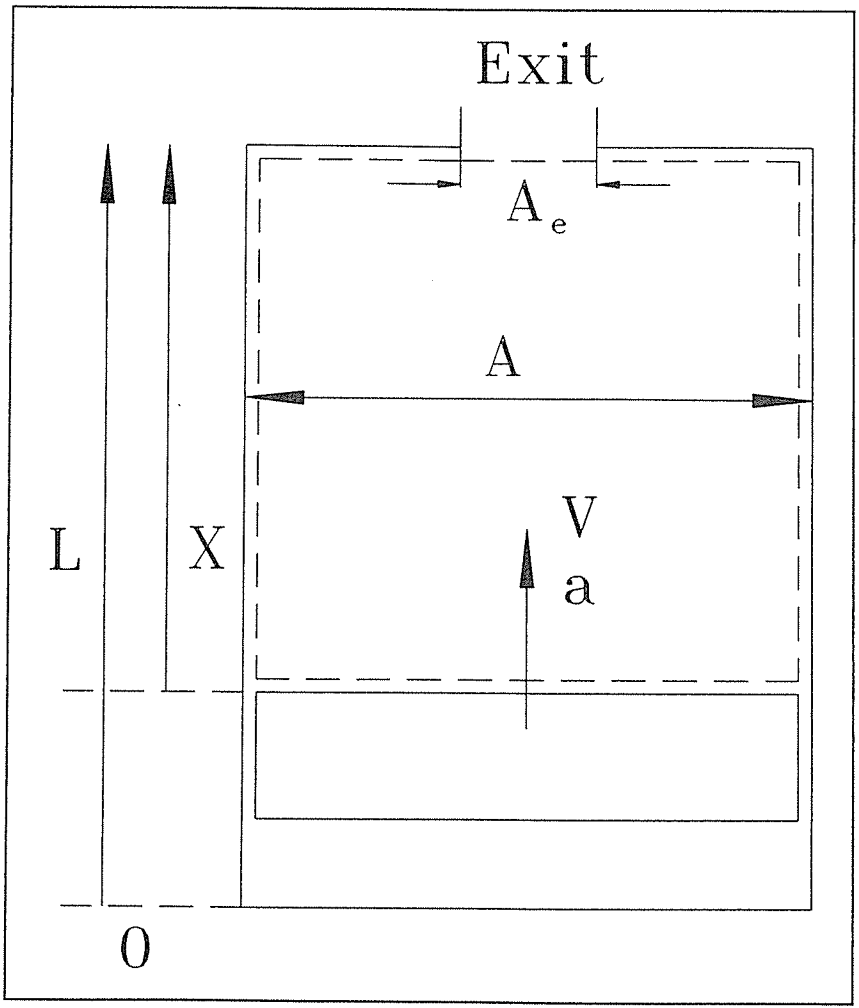

Figure 1 Physical Elevator Model for Simulation

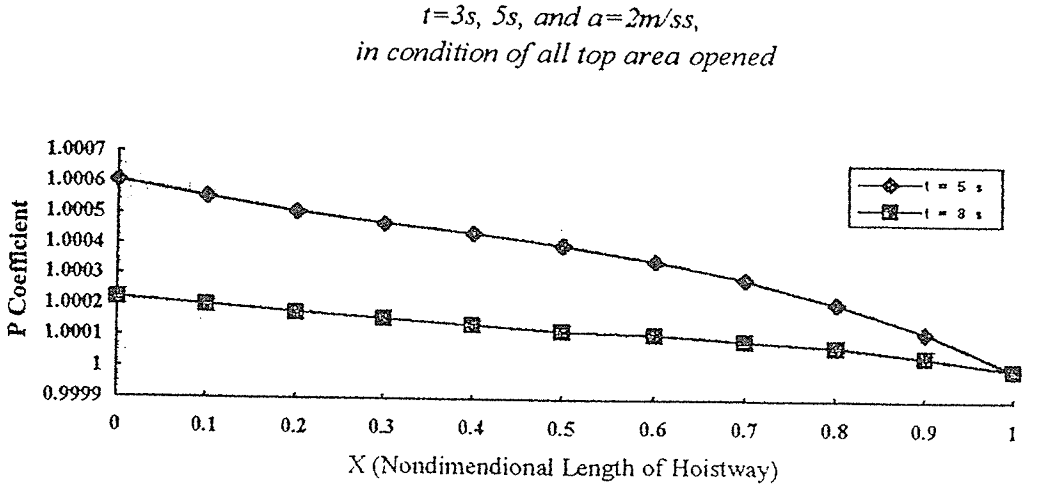

Figure 2 Pressure Distribution for Opened Hoistway, Low Speed, Low Acceleration

$$q_j^* = q_j^n - \frac{\Delta t}{\Delta x} \left(F_{j+1}^n - F_j^n \right) \tag{8}$$

$$q_j^{n+1} = 0.5 \left(q_j^n + q_j^* \right) - 0.5 \frac{\Delta t}{\Delta x} \left(F_j^n - F_{j-1}^n \right) \tag{9}$$

For equation (5) and equation (6), the eigenvalues of the matrix $\mathbf{A} = \partial \mathbf{F}/\partial \mathbf{q}$ are $\lambda = V$ and $V \pm u_s$ where u_s is the sound speed. Consequently, the stability restriction becomes:

$$\left(|V| + u_s \right) \frac{\Delta t}{\Delta x} \leq 1 \tag{10}$$

The artificial viscosity is used in the calculation to eliminate the numerical oscillations. Many numerical algorithms presently used for solutions of N-S equations of aerodynamics may yield oscillatory results in regions containing strong flow gradients, such as weak shocks in the hoistway. In order to avoid production of such oscillatory results, the artificial dissipation term has been added in the governing equations. This kind of technique is also widely used in the computational aerodynamics fields (Dulikravich 1989).

A suitable quadratic formulation can replace equation (5) by the following equation (11).

$$\frac{\partial q}{\partial t} + \frac{\partial F}{\partial x} - k \, \Delta x^2 \left[\, | \, q_x \, | \, q_x \, \right]_x = 0 \tag{11}$$

where k is a constant to be chosen. The artificial viscosity is introduced after a provisional solution at time interval (n+1) has been obtained.

5 SIMULATION RESULTS

First of all, a ratio $A_e/A = 1$ is used, i.e. the whole hoistway has its top fully opened. The pressure profile is shown in Figure 2 at time t = 3 s and 5 s after the car starts to accelerate from a stationery situation with an acceleration = 2 m/s^2. x represents a non-dimensional length of the hoistway measuring from the car top upwards. p coefficient is equal to p/p_a where p is the instantaneous pressure distribution at the centre-line inside the hoistway and p_a is the atmospheric pressure. Two curves are shown for the two time intervals. For this condition, the maximum velocity has been set to 10 m/s. It can be seen that the pressure disturbance caused by the acceleration of the elevator car is propagated to the downstream of the flow field. The pressure is reduced gradually into the atmospheric pressure due to viscosity dissipation. Here, the effect is due to the introduction of artificial viscosity while it is due to the real viscosity of fluid in the real world.

If the height of the hoistway is more than 200 m and the acceleration of the elevator car is increased to more than the gravitation acceleration, i.e. a = 10 m/s^2, the strong

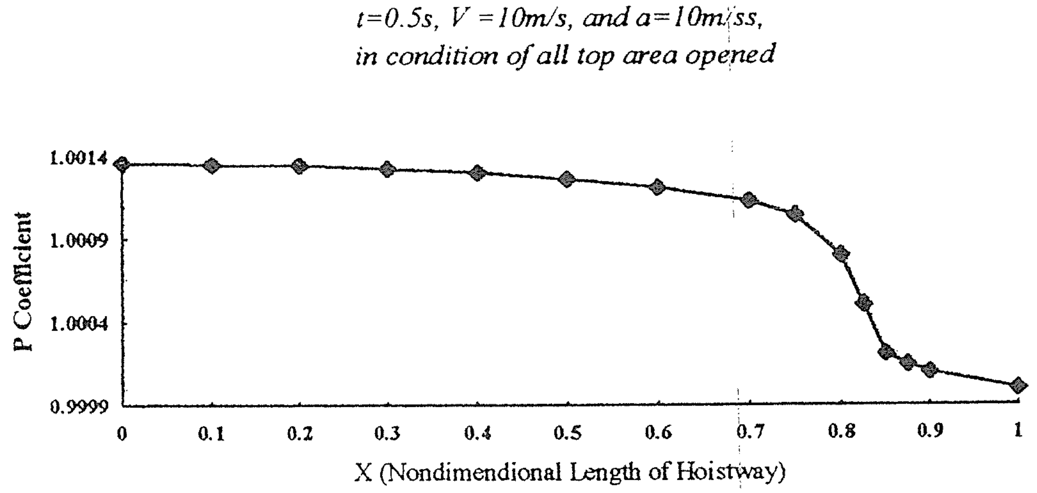

Figure 3 Pressure Distribution for Opened Hoistway, High Speed, High Acceleration

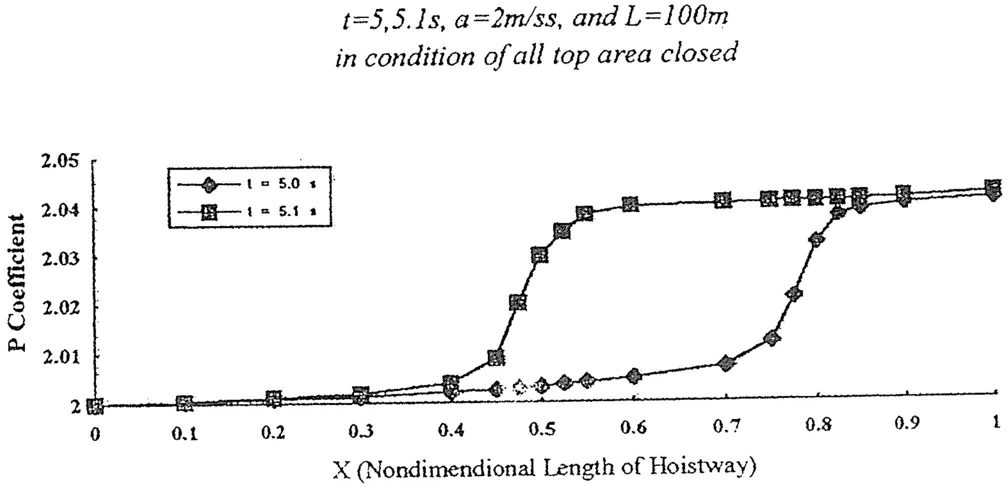

Figure 4 Pressure Distribution for Fully Closed Hoistway

compress waves, i.e. weak shocks, are resulted and captured in the numerical simulation within a time span of 0.6 s. In order to get the result earlier, the initial speed of the elevator car is set to 10 m/s with an acceleration of 10 m/s^2. Such numerical simulation for a full opened hoistway at time t = 0.5 s is shown in Figure 3. In the figure, it can be seen that the strong compress wave (weak shock) can be found clearly at a level x = 0.825. When such kind of compress wave appears, the strong flow oscillation will be generated. Such phenomenon will have a serious impact on the car movement and excessive noise will be produced.

Next, a totally closed hoistway is considered where $A_e/A = 0$. Under this condition, the air flow inside the hoistway cannot be discharged out of the hoistway. Reference is made to Figure 4. The strong compress wave (weak shock) is produced near the top of the hoistway and it moves opposite to the flow direction under a sound speed. This shock wave propagates from the top of the hoistway towards the elevator car top and then back to the top of the hoistway again. Such propagation continuously compresses the air flow so that the pressure inside the hoistway is getting higher and higher. In Figure 4, the initial speed of elevator is 0 m/s with an acceleration of 2 m/s^2. The two curves show the pressure distribution at time t = 5 s and 5.1 s. In the simulation, L is set to 100 m. The maximum pressure in the hoistway is found to be equal to 2.043 p_a.

When the top exit is opened, the air flow can get through the exit and the pressure in the hoistway is being reduced. Figure 5 shows the results under the following conditions: $A_e/A = 0.5$; V_0(initial speed) = 0 m/s; a = 2 m/s^2, t = 5 s and 5.1 s; L = 100 m. It can be seen that the pressure gradient becomes more gentle, indicating that the compress waves are much weaker. In order to study the effect on the maximum pressure produced with respect to the area ratio, A_e/A, several simulations have been carried out and the following parameters have been fixed: t = 5 s; a = 2 m/s^2; L = 100 m, reference being made to Figure 6. Figure 6 shows that the value of maximum pressure inside the hoistway will drop as the ratio A_e/A is getting larger.

6 CONCLUSIONS

The background of the research project has been highlighted has been highlighted. As buildings are getting higher and higher, elevators of higher speed will become mandatory. However, super-high-speed elevators face problems such as excessive vibration and noise. Therefore, special design of the car structure is necessary. The existing approaches to handle the problem experimentally are discussed. However, experimental approaches are expensive and comparatively inflexible for design purposes. Therefore, our belief is that future design must go along with comprehensive and extensive computational fluid dynamics techniques. It is based on this belief we start this research project. As an initial stage, an extremely simplified mathematical model for a hoistway has been developed with only single dimension. Suitable algorithms in numerical methods have been employed and tested so that a more realistic model can be developed in the near future. This paper shows that though a simplified model is employed, several interesting results can be obtained for reference and study. It should also be noted that the accuracy of the model is not so critical because our objective is for computer aided envelop design for reducing noise and vibration instead of accurately modelling the pressure and velocity vector field inside the hoistway.

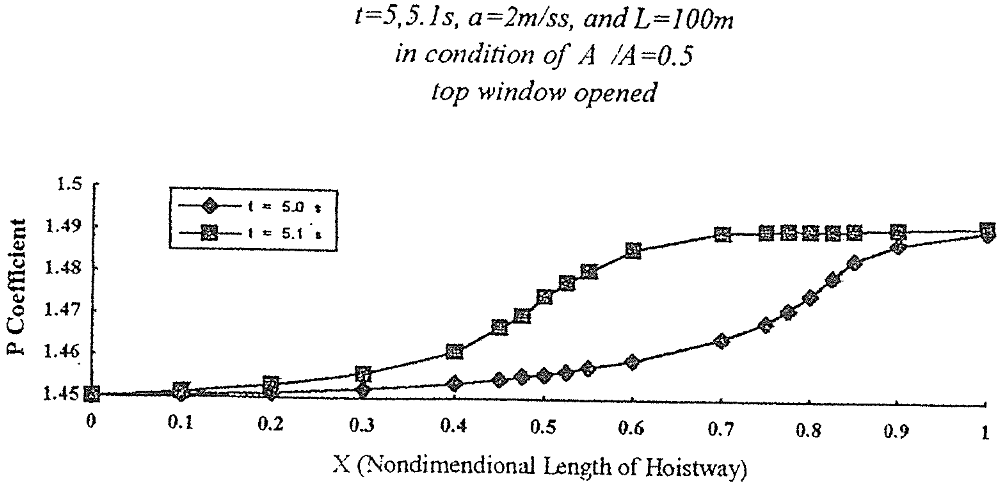

Figure 5 Pressure Distribution for Half-opened Hoistway

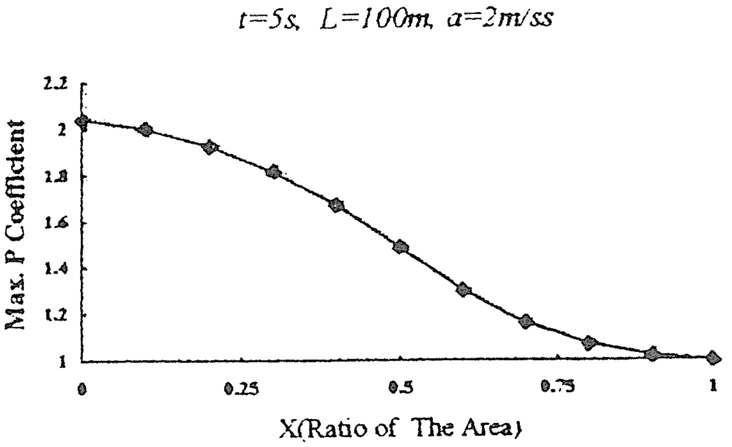

Figure 6 Curves of Maximum Pressure Against Area Ratio

The next version of model will include the display of pressure distribution under the elevator car and also the simulation of leakage of air flow around the elevator car. Irregular shapes of both the hoistway and the elevator car will be taken into account of so that a true 3-dimensional modelling can be carried out. Furthermore, small air-gap openings associated with the landing doors will also be included as well. Experimental approach using PIV will be the final step to verify the design results generated from this CFD approach.

7 ACKNOWLEDGEMENTS

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