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AN ANALYSIS OF THE INFLUENCE OF PISTON EFFECT ON ELEVATOR SMOKE CONTROL

John H. Klote

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

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Abstract

This paper is part of a joint project between the United States and Canada to evaluate the feasibility of using elevators for the evacuation of the handicapped during a fire. The transient pressures produced when an elevator car moves in a shaft are a potential problem for elevator smoke control. Such piston effect can pull smoke into a normally pressurized elevator lobby. This paper presents an analysis of an elevator smoke control system emphasizing the influence of piston effect on system performance. For most elevators the problem can be overcome by designs that prevent smoke from being pulled into lobbies, and equations for the amount of pressurization air to accomplish this are developed for *two* arrangements of supply air outlets. Where this approach is not feasible, the methods of analysis presented in this paper can be used to determine smoke infiltration for a hazard analysis.

Key words: elevators (lifts), hazard analysis, piston effect, pressurization, smoke, smoke control.

1. INTRODUCTION

The problem of fire evacuation of the handicapped has become a topic of concern within the fire protection community. One solution would be the use of elevators. Logistics of evacuation, reliability of electrical power, elevator door jamming, and fire and smoke protection are long-standing obstacles to the use of elevators for fire evacuation. All of these obstacles except smoke protection can be addressed by existing technology as discussed by Klote [1].

The National Bureau of Standards (NBS) in the United States and the National Research Council of Canada (NRCC) are engaged in a joint project to develop smoke control technology for elevators. The initial report [2] of this project was a concept study evaluating several elevator smoke control systems by computer analysis using the NBS program for analysis of smoke control systems[3]. The transient pressures due to 'piston effect' when an elevator car moves is a concern of building designers relative to elevator smoke control. The second report [4] of this project developed an analysis of the pressures due to piston effect in a building without smoke control and evaluates piston effect in light of that analysis. This paper presents an analysis of piston effect incorporating elevator smoke control, and addresses the problem based on this analysis.

2. SMOKE CONTROL SYSTEM

The term 'smoke control' is used in this report to mean the limiting of smoke movement by pressurization produced by mechanical fans. This meaning has attained some level of acceptance in North America. Ideally, an elevator smoke control system should protect the elevator shaft and the elevator lobbies such that smoke contamination in these areas does not present a hazard.

Most elevator doors have large gaps around them [5]. Such large leakage areas around the doors result in lobby and shaft pressures that are nearly equal under most conditions. Thus if pressurization air is supplied to the elevator shaft, the lobbies will be pressurized indirectly to almost the same pressure as the shaft. A concern with such systems is that a few open doors might result in significant loss of pressurization. The first paper [2] of this project demonstrates that this problem can be overcome by use of a system with feedback control. The flow rate of air into the shaft is controlled by a differential pressure sensor to maintain a constant pressure difference across the elevator lobby door on the fire floor. One method of varying the flow rate is a fan bypass system. It may be possible to develop other systems that can also solve the pressure loss problem. Because the elevator smoke control

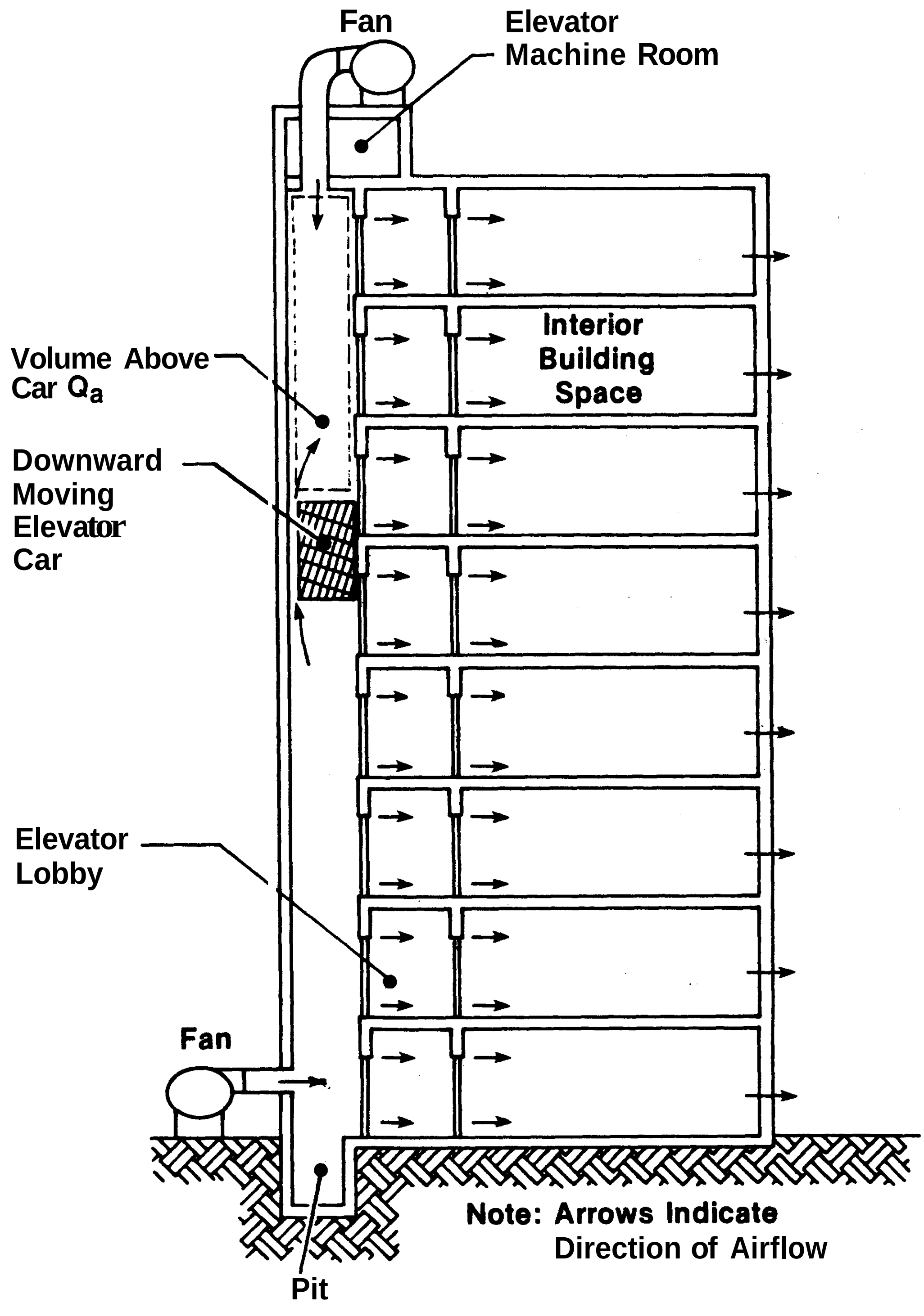

Figure 1. Airflow due to shaft pressurization and car motion

system discussed above can deal with this problem, it is the basis of the analysis and discussions that follow.

3. ANALYSIS

The direction of airflow illustrated in figure 1 is that which would result from shaft pressurization. When an elevator car moves downward, piston effect tends to increase the pressure below the car and to reduce the pressure above the car. In extreme cases the reduction of pressure could overcome a shaft pressurization system and result in smoke infiltration of the elevator lobby or shaft. For the sake of simplicity, buoyancy, wind, stack effect, and the heating and ventilating system have been omitted from this analysis.' Omitting stack effect is equivalent to stipulating that the building air temperature and the outside air temperature are equal. Because these temperatures are the same, the gravity effects on air density and pressure are negligible. For this analysis elevator car motion is limited to a single car moving in a single car shaft or in a multiple car shaft. The analysis is for a downward-moving elevator car (as illustrated in figure 1), however the problem of an upward-moving one is same mathematically. Thus the equations developed can be extended for an upward-moving car by reversing subscripts a (above the car) and b (below the car).

3.1 Equations for Conservation of Mass

The law of conservation of mass can be written for the volume, Q_a, above the car

$$\left[\begin{array}{c}\text{Net mass flow}\\ \text{into volume } Q_a\end{array}\right] = \left[\begin{array}{c}\text{Rate of mass change}\\ \text{within volume } Q_a\end{array}\right] \tag{1}$$

$$\dot{m}_{pa} + \dot{m}_{ba} - \dot{m}_{ao} = \frac{d}{dt}(\rho Q_a)$$

where

$\dot{m}_{pa}$ = mass flow rate of pressurization air to the shaft space above the car
$\dot{m}_{ba}$ = mass flow rate from below the elevator car, Q_b , to volume, Q_a
$\dot{m}_{ao}$ = mass flow rate from volume, Q_a , to the outside
ρ = air density within the shaft.

For a downward moving car velocity, V, and a cross-sectional area of the shaft, A,, the derivative of the volume, Q_a , can be expressed as

$$\frac{d\,Q_a}{dt} = A_s V \qquad (2)$$

The air density is essentially constant within the shaft. Therefore, Substituting equation (2) into equation (1) yields

$$\dot{m}_{pa} + \dot{m}_{ba} - \dot{m}_{ao} = \rho\, A_s V \qquad (1a)$$

The conservation of mass equation for the entire shaft is

$$<_a + \dot{m}_{pb} - mao - \dot{m}_{bo} = 0 \qquad (3)$$

Where $\dot{m}_{pb}$ is the mass flow rate of pressurization air to the shaft below the car.

3.2 Equations for Mass Flow

To expedite the analysis, the flow areas are chosen sucn that they are the same for each floor of the building and that the only vertical airflow in the building is within the elevator shaft. The flow from Q_a to the outside is

$$\dot{m}_{ao} = N_a C\, A_e S_a \sqrt{2\rho\, |\, P_a\, |} \qquad (4)$$

where

N_a = number of floors above the car

C = flow coefficient

A_e = effective flow area per floor between the shaft and the outside

P_a = pressure of the air in Q_a relative to the outside

S_a = the sign of P_a.

The absolute value signs and S_a are included in equation (4) to allow for pressurization failure above the downward moving car. The outside pressure is not explicitly incorporated in equation (4), because P_a is a gage pressure which is the difference between the absolute pressure and the atmospheric pressure outside the building. The effective flow area, A_e, is the area that results in the same flow as the system of flow areas from the building to the outside when A_e is subjected to the same pressure difference as the system. The system of flow areas can consist of areas in parallel with one another, in series, or a combination of both parallel and series. The ASHRAE smoke control manual [6] presents a detailed discussion of effective flow areas, and an example evaluation of A_e for a system of flow paths is presented later in this paper.

The flow rate from Q_b to the outside is

$$\dot{m}_{bo} = N_b C A_e \sqrt{2\rho P_b} \qquad (5)$$

where

N_b = number of floors below the car

P_b = pressure of the air in Q_b relative to the outside.

If the car were standing still, $\dot{m}_{bo}$ would be positive. A downward-moving car only increases the positive pressurization below the car. Thus the analysis only accounts for positive pressurization of the shaft below the car as can be observed from equation (5). Neglecting hydrostatic pressure difference, the mass flow rate from below the car to above it can be expressed as

$$\dot{m}_{ba} = C_c A_f S_{ba} \sqrt{2\rho \, | P_b - P_a |} \qquad (6)$$

where

A_f = free flow area in the shaft around the car
C_c = flow coefficient for flow around the car
S_{ba} = sign of $(P_b - P_a)$.

Equation (6) includes the absolute value signs and S_{ba} to allow for flow from above the car to below it. This can occur when the pressurization air, $\dot{m}_{pa}$, above the car is very large. Tests were conducted to evaluate C_c on a twelve-story elevator shaft at the NBS administration building [4]. For one car traveling in a two car shaft, the flow coefficient was .94, and for two cars traveling side-by-side together the flow coefficient was .83. The case of the two cars moving together was measured to obtain an approximation of a car moving in a single car shaft.

3.3 Equations for P_a and P_b

Substituting equations (4) and (5) into equation (3), and solving for P_b yields

$$P_b = (c - b \sqrt{| P_a |})^2 \qquad (7)$$

where

$c = (\dot{m}_{pa} + \dot{m}_{pb})/K_{bo}$
$b = S_a N_a / N_b$
$K_{bo} = N_b C A_e \sqrt{2 \rho}$

Combining equations (1a),(4),(5),(6) and (7) yields

$$\dot{m}_{pa} + K_{ba} S_{ba} \sqrt{\left| \left[c - b\sqrt{|P_a|} \right]^2 - P_a \right|} - K_{ao} S_a \sqrt{|P_a|} - \rho A_s V = 0 \qquad (8)$$

where

$$K_{ba} = A_f C_c \sqrt{2 \rho}$$

$$K_{ao} = N_a C A_e \sqrt{2 \rho}$$

As might be expected, for $\dot{m}_{pa} = \dot{m}_{pb} = 0$, equation (8) reduces to equation (7) from the earlier paper [3] on piston effect without shaft pressurization (note that the sign convention for P_a is opposite in the two papers).

4. MOTION OF CAR

For this paper three phases of elevator car motion are considered: constant acceleration, transitional and constant velocity motion. A car starting from rest accelerates at a constant rate, a, until the transitional velocity, V_t, is reached. The time, t_t, to reach this velocity is

$$t_t = \frac{V_t}{a} \qquad (9)$$

The distance, X_t, the car travels in this time is

$$X_t = \frac{V_t^2}{2a} \qquad (10)$$

During the transitional phase the acceleration decreases until full operational velocity, V_p, is reached. Strakosch [7] uses the following approximate relations for this phase:

$$t_p = \frac{V_p^2 - V_t^2}{2\,a\,V_t} \tag{11}$$

and

$$X_p = \frac{1}{3\,a}\left[\frac{V_p^3}{V_t} - V_t^2\right] + X_t \tag{12}$$

where X_p is the distance the car travels before it reaches full operational velocity at time t_p from the start of motion. These equations leave the motion between X_t and X_p undefined. Motion in this region is not necessary for evaluation of piston effect in the context of this paper as is demonstrated by the example in the following section.

5. PRESSURE DIFFERENCE ACROSS LOBBY DOORS

For fire evacuation by elevators, the pressure difference, ΔP_{il}, across the elevator lobby doors is of major importance. If AP„ is positive, the resulting airflow from the lobby to the building will act to prevent smoke infiltration of the lobby. This pressure difference can be evaluated by examination of the effective flow area. For the system of three series flow paths from the shaft to the outside illustrated in Figure 1, the effective flow area per floor is

$$A_e = \left|\frac{1}{A_{ls}^2} + \frac{1}{A_{il}^2} + \frac{1}{A_{oi}^2}\right|^{-\frac{1}{2}} \tag{13}$$

where

A„ = leakage area between the lobby and the shaft

A_{il} = leakage area between the building and the lobby

A_{oi} = leakage area between the outside and the building.

For paths in series the pressure difference across one path equals the pressure difference across the system times the square of the ratio of the effective area of the system to the flow area of the path in question. Thus for flows above the elevator car, ΔP_{il} can be expressed as

$$\Delta P_{il} = P_a (A_e / A_{il})^2 \tag{14}$$

This equation is general in that it applies to any system of flow paths not just those shown in figure 1, provided that A_e is evaluated for that particular system, This analysis does not include the effects of other shafts such as stairwells and dumbwaiters. Provided that the leakage of these other shafts is relatively small compared to A_{oi}, equation (13) is appropriate for evaluation of A_e for buildings with open floor plans. The configuration of figure 1 was selected because many buildings are constructed with open floor plans and because evaluation of this system may provide some understanding of more complicated systems with interior partitions. The complicated flow path systems probably require case by case evaluation which can be done by using the effective area techniques presented in the ASHRAE smoke control manual [6].

A computer program was developed which solved equation (8) for P_a by the method of bisection [8] using the car velocities and displacements of equations (9) through (12). Equations (13) and (14) were used to obtain ΔP_{il}. In the preceding analysis, the number of floors, N_a, above the car might be thought of as an integer, however, a real number value for N_a was used for the computer program to allow calculations when the car is not located exactly at a floor. This occurs at the points where transitional acceleration begins and ends. The real number approach assumes that at each floor the leakage area, A_{il}, is uniformly distributed over the floor height. Even though it is obvious that leakage areas in buildings are not uniform, it is believed that the errors due to this assumption are insignificant.

Table 1. Flow Areas of Eleven Story Elevator Shaft for Example Piston Effect Analysis

	m^2	ft^2
For Single Car Shaft		
A,,, area between lobby and shaft	0.167	1.80
A,,, area between building and lobby	0.0390	0.42
A_{oi}, area between outside and building	0.0502	0.54
A,, cross-sectional area of shaft	5.61	60.4
A,, free flow area around car	1.80	19.4
For Double Car Shaft		
A,,, area between lobby and shaft	0.0836	0.90
A,,, area between building and lobby	0.0390	0.42
A_{oi}, area between outside and building	0.0502	0.54
A_s, cross-sectional area of shaft	11.22	120.8
A,, free flow area around car	7.41	79.8

Note: For the single car shaft a value of C_c = 0.83 was used, and for the double car shaft a value of C_c = 0.94 was used. The flow coefficient was C = 0.65. Pressurization air was $\dot{m}_{pa}$ = 0 and $\dot{m}_{pb}$ = 2.160 kg/s (3810 standard cfm at 68 °F and one atmosphere). Car acceleration was 1.22 m/s^2 (4 ft/sec^2), and V_t at 60 % of V_p.

Figure 2. shows computer calculated values of AP,, for a single and a double car shaft for two values of V,. The flow areas for these examples are listed in table 1. These flow areas are based on the measured values of A, and A, from tests of the NBS administration building [4] and average leakage values from Appendix C of the ASHRAE smoke control manual for a building with a floor size of 14.0 m x 67.7 m (46.0 ft x 222 ft) and 3.099 m (10.17 ft) between floors. Pressurization air was supplied below the car and at a rate such that ΔP_{il} was 25 Pa (0.10 in H_2O) when the cars were still.

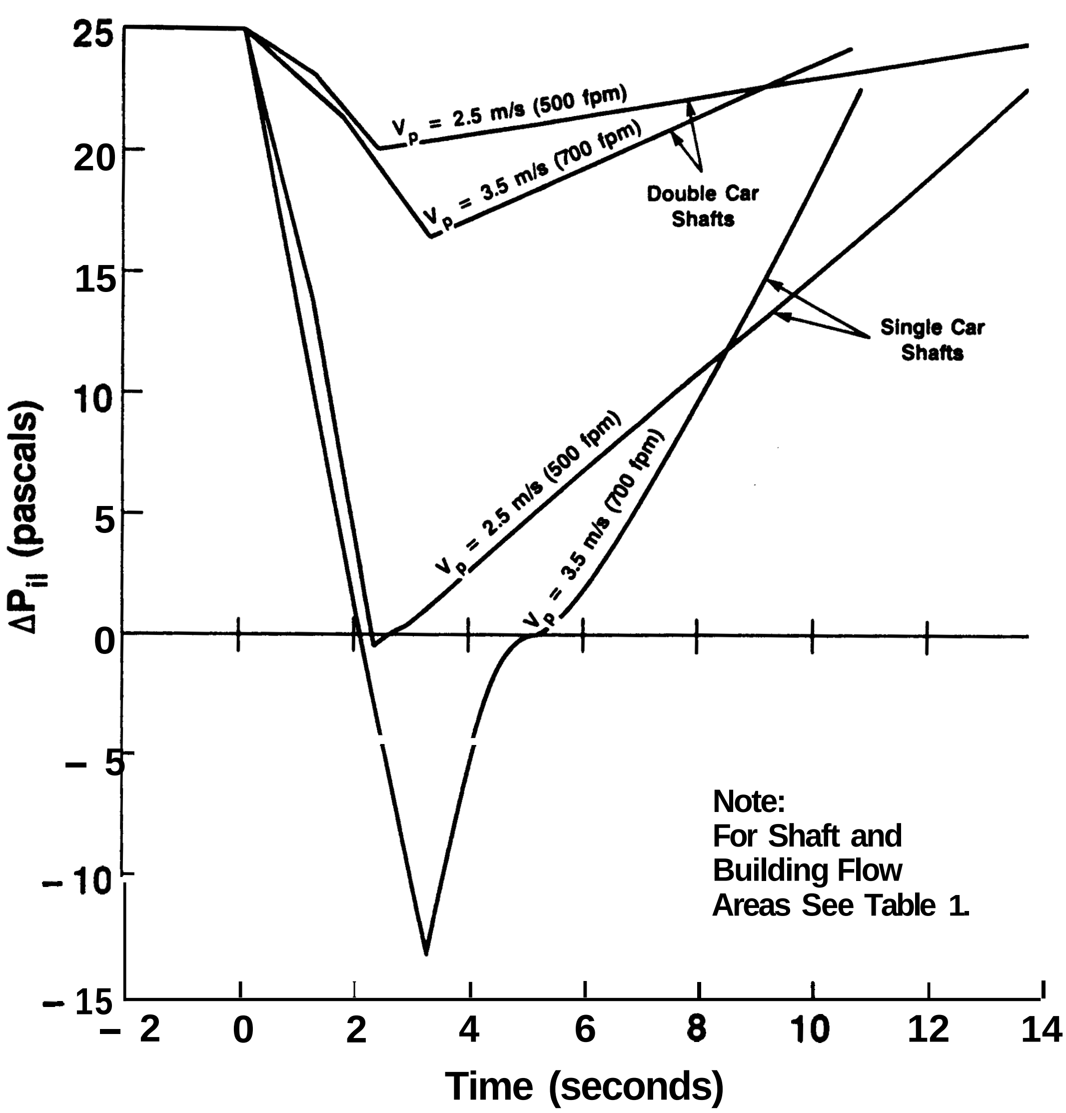

Figure 2. Calculated pressure differences across elevator lobby doors due *to* piston effect of a single car moving in an eleven story shaft

As expected figure 2 illustrates that piston effect is more pronounced for greater car velocities and for single car shafts. For the double car shaft of this example, piston effect does not adversely effect lobby pressurization. This is because the free flow area, A_a, around the car is so large that there is little resistance to air flow around the car. Because A_a is large for all multiple car shafts, piston effect in these shafts will probably not have an adverse effect on lobby pressurization except at high car velocities.

For the example single car shaft at V_p = 3.5 m/s (700 fpm), piston effect caused a flow from the building to the lobby for a duration of about 3 seconds. In a fire situation this could result in smoke being pulled into the lobby. The severity of such a situation would depend on the speed of the car, the size of the lobby, the toxicity of the smoke and the number of times the car passes the floor. Modern elevators operate at speeds up to 10 m/s (2000 fpm). At these high speeds piston effect is much more significant. Fortunately such high speeds are not common for single car shafts.

6. HAZARD ANALYSIS

One approach to the piston effect problem is an analysis determining the quantity of toxic gases pulled into an elevator lobby by piston action and determining the resulting hazard to life. The mass, m, of smoke laden air pulled into the elevator lobby during the decent of a car is

$$m = -\int_{t_1}^{t_2} \dot{m}_{ao}\, dt$$

where the smoke and air mixture is pulled into the lobby during the time interval from t_1 to t_2. The mass flow rate can be obtained from equation *(4)* using the pressures as defined by equation **(8)**. The mass of gases pulled into a lobby due to an upward moving car can be determined by a similar approach.

An evaluation of the resulting hazard must include considerations of mixing of air and smoke within the lobby, an estimate of the number of times a car passes the floor of concern and an analysis of the effects of the toxic gases on people waiting in the lobby. Such an analysis is beyond the scope of this paper. An alternate approach is to design elevator systems such that piston effect does not cause any smoke infiltration of elevator lobbies. This approach is developed in the following section.

7. CRITICAL PRESSURIZATION RATE

For an unpressurized shaft Klote and Tamura *[4]* developed an expression for the limit of the extent of piston effect, and this limit was obtained for the conditions of the elevator car being at the top ($N_i = 0$) of the shaft and a car velocity of V_p. Similarly, a limit or minimum value of P_a can be obtained for a pressurized shaft using the same conditions. Observation of figure 2 reveals that once the car reaches V_p, ΔP_{il} increases with time or with distance from the top of the shaft. If the car were traveling at V_p over all its decent, ΔP_{il} would increase with distance traveled from the top of the shaft. Obviously for the above conditions, equation (8) yields a value of P_a which is less than that resulting from realistic car motion starting at rest. For a pressurized shaft, setting N_i to zero results in equation *(4)* becoming $\dot{m}_{ao} = 0$ and by definition b = 0. Equation (8) becomes

$$(P_a)_{min} = \frac{1}{2\,\rho}\left[\left(\frac{\dot{m}_{pa} + \dot{m}_{pb}}{N_{tot} C\, A_e}\right)^2 - \left(\frac{\rho\, A_s V_p - \dot{m}_{pa}}{A_f C_c}\right)^2\right] \qquad (15)$$

where

$(P_a)_{min}$ = minimum level of pressurization above a downward moving elevator car

N_{tot} = total number of floors.

A negative value of $(P_a)_{min}$ indicates a failure of pressurization due to piston effect. The velocity V_p was used in equation (15) because this is the maximum speed at which the car can travel making the resulting pressure a limit below which the pressure P_a would not fall.

A value of $(P_a)_{min} = 0$ means that elevator pressurization remains positive throughout the car's descent. The total mass flow rate to achieve this condition is referred to as the critical pressurization rate, $\dot{m}_{crit}$. A common situation is to supply all of the air at one point. If all the air is supplied below the car ($\dot{m}_{pa} = 0$), the critical mass flow rate is

$$\dot{m}_{crit} = \rho A_s V_p \frac{N_{tot} A_e C}{A_f C_c} \qquad (16)$$

If pressurization air is supplied at this rate or greater to the space below a downward moving elevator car, piston effect will not result in loss of shaft pressurization. It is obvious that equation (16) also applies to an upward-moving car with all the air supplied above the car. Thus it can be stated in general that equation (16) defines the critical mass flow rate for a shaft with an air pressurization inlet at only one location.

For pressurization air supplied evenly at the top and bottom of the shaft ($\dot{m}_{pa} = \dot{m}_{pb} = \dot{m}_{crit}/2$), the critical mass flow rate is

$$\dot{m}_{crit} = \frac{2 \rho A_s V_p}{1 + \dfrac{2 A_f C_c}{N_{tot} A_e C}} \qquad (17)$$

If at least half this amount of pressurization air is supplied above the car and an equal amount below it, piston effect will not result in loss of shaft pressurization. Equations (16) and (17) can be used to check during smoke control design to assure that piston effect does not result in loss of shaft pressurization. Table 2 lists critical mass flow rates calculated from these equations for shafts of the previous example. An elevator smoke control system may need a much greater supply rate of pressurization air in order to produce the pressure differences desired for smoke control as discussed in previous reports [1,2]. It can be observed from table 2 that $\dot{m}_{crit}$ is larger when air is supplied at only one location as opposed to being supplied both at the top and bottom of the shaft. Obviously, injecting air into the shaft above the car reduces piston effect for a downward moving car. It can also be observed from table 2 that a double car shaft has a much lower $\dot{m}_{crit}$ than a similar single car shaft. This supports the belief that generally piston effect would not be a problem for multiple car shafts.

Table 2. Critical mass flow rates calculated from equations (16) and (17) for example shafts

	Single Car Shafts		Double Car Shafts	
	kg/s	Standard cfm	kg/s	Standard cfm
FOR V_p = 2.5 m/s (500 ft/min)				
Pressurization air supplied at one point	2.44	4310	1.00	1770
Pressurization air evenly divided between top and bottom of shaft	2.27	4010	0.96	1700
FOR V_p = 3.5 m/s (700 ft/min)				
Pressurization air supplied at one point	3.42	6040	1.40	2470
Pressurization air evenly divided between top and bottom of shaft	3.18	5620	1.35	2380

Note: For areas and flow coefficients see table 1. Standard cfm is at 68 °F and one atmosphere.

8. FUTURE EFFORT

Elevator smoke control tests are being conducted by the NRCC at the Fire Zesearch Tower near Ottawa to evaluate various system concepts under full scale fire conditions. Tests will be conducted by the NRCC on an existing building with a pressurized elevator shaft in an attempt to verify the analysis presented in this paper. The final effort planned for this project will be for NRCC and NBS to jointly develop practical engineering design information for elevator smoke control based on this research.

9. CONCLUSIONS

1. For most elevators, especially those in multiple car shafts, it is feasible to deal with the piston effect problem by designing so as to prevent smoke from being pulled into the elevator lobby by piston effect.

2. For an elevator shaft with only one pressurization air inlet, piston effect will not result in loss of shaft pressurization provided the mass flow rate of pressurization air is at least as great as the critical mass flow rate determined from equation (16).

3. For an elevator shaft with equal amounts of pressurization air supplied evenly at the top and bottom of the shaft, piston effect will not result in loss of shaft pressurization provided the mass flow rate of pressurization air is at least as great as the critical mass flow rate determined from equation (17).

4. For single car shafts with high velocities or multiple car shafts with very high velocities the approach of 1 above may not be feasible. For such cases a hazard analysis may provide useful information, and the methods of analysis presented in this paper can be used for the fluid flow portion of such a hazard analysis.

10. NOMENCLATURE

A	area
a	acceleration
b	$S_a N_a / N_b$
C	flow coefficient
c	$(\dot{m}_{pa} + \dot{m}_{pb}) / K_{bo}$
K	coefficient
m	mass
m	mass flow rate
N	number of floors
P	pressure
Q	volume
t	time
V	elevator car velocity
X	distance of car travel
p	density
AP	pressure difference

Subscripts

a	above elevator car
b	below elevator car
c	elevator car
crit	critical
e	effective
f	free flow around
i	building
1	lobby
min	minimum
o	outside
s	shaft
P	full operational
t	transitional
tot	total

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