터널과 지하공간, 한국암반공학회지
제13권 제4호, 2003년 8월, pp. 287~293

TUNNEL & UNDERGROUND SPACE, Vol. 13, No. 4, 2003, pp. 287-293
Journal of Korean Society for Rock Mechanics

Modeling of Smoke Dispersion through a Long Vertical Duct

Sung-Wook Yoon[1)]*

장대(長大) 수직 환기구를 통한 매연 확산의 모델링 연구

윤성욱

Abstract A long vertical duct is an essential installation for extracting smoke to the ground level when a fire occurs in an underground space. Due to the limitations of its basic assumptions, the existing two-layer zone model is unsuitable to model smoke dispersion through a long vertical duct. Therefore, an assessment was made to investigate the applicability of the field model, which is based on the computational fluid dynamics (CFD). A similar configuration to the published experimental work was modeled to test the validity. It is clear that under a consistent decision criterion based on the mass fraction, the field model (CFD) is able to predict that the diffusion front progresses up the shaft with exactly the same rate as that in the empirical correlation equation. This result is far better than the mathematically obtained equations in previously published research. Therefore, it can be said that the field model is an excellent option to predict the smoke dispersion through the long vertical shaft.

KeyWords: long vertical duct, fire, smoke, CFD, underground space, modeling

초 록 장대(長大) 수직 환기구는 지하공간에서 화재 발생시 매연을 지상으로 배출해 내기 위한 필수적 설치물이다. 현재 널리 사용되는 이층(二層) 존(zone) 모델은 기본 가정이 제한적임으로 인해 장대 수직 환기구에서의 매연유동을 해석하는데 부적합하다. 그러므로, 그 대안으로서 전산유체역학에 기초한 필드 모델의 적용성이 검토되었다. 전산모델의 유효성을 조사하기 위해 이미 발표된 기존의 실험과 유사한 구조를 선택하여 모델링 하였고 그 결과를 서로 비교하였다. 모델링에서 일정한 기준의 질량분율을 일관되게 적용하여 얻어진 매연의 확산 상단면은 실험결과를 바탕으로 구한 매연확산의 경험적 상관관계식과 거의 유사한 속도로 환기구내에서 상승함이 관측되었다. 이것은 다른 연구자들이 수학적 이론으로부터 구한 상관관계식의 결과보다 더 우수한 결과이며 전산유체역학에 기초한 수치모델이 장대형 수직 환기구를 통한 매연확산 연구에 효과적인 도구가 될 수 있음을 보여준다.

핵심어: 장대 수직 환기구, 화재, 매연, 전산유체역학, 지하공간, 모델링

1. Introduction

When an underground fire occurs, venting of hot gases through a long vertical duct as well as horizontal ducts is crucial. Therefore, the overall numerical fire research for underground spaces should be accompanied by numerical research on smoke dispersion through a long vertical duct. Regarding this matter, Cooper (1994) recognized that it is not reasonable to apply a traditional, two-layer, zone-type, fire modeling approach to a vertical duct or shaft type space where the characteristic height is much greater than the horizontal span. This is because the basic assumptions of zone modeling become invalid. As the plume rises and spreads in the vertical duct, its volume eventually becomes significant and it starts to fill a large fraction of the section of the duct. Furthermore, it is not reasonable to expect that the characteristic mixing times in the shaft will be short compared to the characteristic times of interest, and there are no grounds to justify a uniform, two-layer approximation to the density and temperature distributions. Therefore, different modeling approaches, such as CFD, should

---

[1)] 정회원, 범창종합기술 설계1팀 차장
*교신저자(Corresponding Author): swyoon@hotmail.com
접수일: 2003년 4월 4일
심사 완료일: 2003년 8월 19일

be taken for the simulation of vertical smoke dispersion.

2. Physics and Theories

Consider a flow through the long vertical duct where there is no mass addition along the length of the shaft $\overline{V_z}$ and can be negligible, turbulent mass balance equation can be written as

$$\partial\bar{\rho}/\partial t + \partial(\overline{V_z'\rho'})/\partial z = 0 \qquad (1)$$

Here, z is the same direction as the axis of the duct

Defining D as the eddy diffusivity for buoyancy-driven turbulence, $\overline{V_z'\rho'}$ the term in equation (1) can be modeled as equation (10):

$$\overline{V_z'\rho'} = -D\,\partial\bar{\rho}/\partial z \qquad (2)$$

Cannon and Zukoski (1975) suggested that the turbulent diffusivity, D, is given by the product of a velocity fluctuation, w' and a characteristic length scale, λ. The value for w' is determined from an energy balance based on the potential energy released when a mass of heavy fluid (ρ_u) with a vertical scale Δz moves downward in the duct and displaces a mass with the same scale but a lighter fluid (ρ_l) Fig. 1 provides a sketch showing notations of the model. The value of w' is then calculated using the idea that the change in potential energy between the two configurations appears as the kinetic energy of the fluctuations:

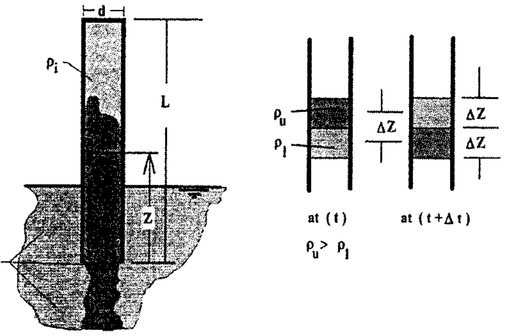


Fig. 1. A sketch showing the notations used to analyse the physical model of the ventilation shaft (after Zukoski, 1994).

$$\rho(w')^2 \propto (\rho_u - \rho)g\Delta z \text{ and } (\rho_u - \rho_l) \approx (\partial\rho/\partial z)\Delta z \qquad (3)$$

Thus,

$$w' \propto \sqrt{\frac{1}{\rho}\left(\frac{\partial\rho}{\partial z}\right)g(\Delta z)^2} \qquad (4)$$

Here, g is gravitational acceleration.

The turbulent diffusivity is then estimated from the product of w' and an appropriate scale length, λ, to give

$$D \equiv w'\lambda \propto \sqrt{\frac{1}{\rho}\left(\frac{\partial\rho}{\partial z}\right)g(\Delta z)\lambda} \qquad (5)$$

The most natural selection for Δz and λ is the shaft diameter, d. The final approximation involves the Boussinesq approximation, which allows the density that appears in the denominator of equation (5) to be approximated by the density of the lighter fluid (ρ_l) in the reservoir. This approximation works well if the density difference is small but may cause problems when there are considerable density differences.

Therefore, the equation can be written as:

$$D = K\sqrt{\frac{1}{\rho_l}\left(\frac{\partial\rho}{\partial z}\right)gd^2} \qquad (6)$$

where K is a constant.

To determine K, Gardner (1977) considered the particular problem of quasi-steady turbulent diffusion in a long shaft connecting two relatively large vessels of incompressible fluids, with the density of the fluid in the top higher than that in the lower vessel. Gardner used the experimental data of Mercer and Thompson (1975) with salt-water/freshwater systems and circular shafts of diameter d, and determined K as:

$$K = K_G = 0.56 \qquad (7)$$

In contrast to this, Baird and Rice (1975) analyzed the literature on rising bubble columns and related systems where gas flow rates are large enough for the bubble wakes to interact strongly and to generate turbulence in the opposing fluid motion. For such systems they determined K as:

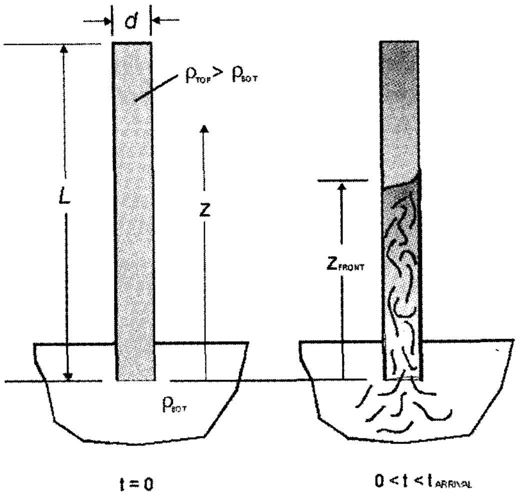


Fig. 2. Sketch of simulated experiments (after Cannon and Zukoski, 1975).

$$K = K_{BR} = 0.21 \tag{8}$$

The unsteady-state experiments of Cannon and Zukoski (1975) included the configuration of Fig. 2. This involved a tube of length L, closed at the upper end, $z = L$, and inserted into a relatively large vessel of density ρ_{BOT}. The tube (shaft) was initially filled with a fluid of density $\rho_{TOP} > \rho_{BOT}$. The experiments were initiated by allowing the fluid in the tube to mix with the fluid in the lower vessel. A diffusion front at elevation $z = z_{FRONT}(t)$, which is 0 at the start ($t = 0$), rises in the tube and stops when it reaches the top. The diffusion front was visualized by dying either the salt-water initially in the transparent tube or the ambient water. The experiment is completed at time t_{ARRIVA}, when the diffusion front reaches the top of the vessel.

Assuming that $\Delta\rho / \rho_{BOT}$ is very small (as with salt water/fresh water), Cooper (1994) simplified the analytical equation of Cannon and Zukoski (1975) based on equations (1), (2) and (6) as

$$z_{FRONT} / d = 3.35\left\{K\left[(g/d)(\Delta\rho/\rho_{BOT})\right]^{1/2} t\right\}^{2/5} \tag{9}$$

Cooper also suggested K value as

$$K = K_C = 0.438 \tag{10}$$

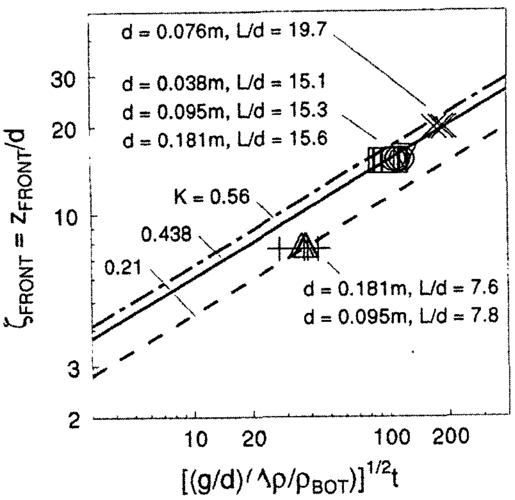


Fig. 3. Position of the diffusion front: Graphs of equation (19) for different values of K and values measured in the salt-water/fresh-water experiments of Cannon and Zukoski (1975) (after Cooper, 1994).

Cooper then compared his correlating K value with those of Gardner (1977), Baird and Rice (1975) and the data set of Cannon and Zukoski (1975), by calculating the resulting positions of the diffusion front with the equation (9). The results are plotted in Fig. 3.

In 1994, Zukoski reinvestigated his experimental data (also plotted on Fig. 3) and suggested a power of 0.57 for $\left[(g/d)(\Delta\rho/\rho_{BOT})\right]^{1/2} t$, which is higher than that of Cooper's analytical equation. He then formulated the following revised empirical equation as

$$z_{FRONT} / d = 0.97\left\{\left[(g/d)(\Delta\rho/\rho_{BOT})\right]^{1/2} t\right\}^{0.57} \tag{11}$$

It is apparent that the key parameters in equation (9), which are based on the theoretical model, are the same as those in the empirical equation (11), although the powers of the right hand side of each equation differ (0.4 and 0.57 respectively).

3. Modeling Methodology

In the simulation, oxygen was chosen to form the heavier top fluid ($\rho_{TOP} = \rho_{oxygen}$) while nitrogen comprised the lighter bottom fluid ($\rho_{BOT} = \rho_{nitrogen}$). At a temperature of 293 K and pressure of 1 atm,

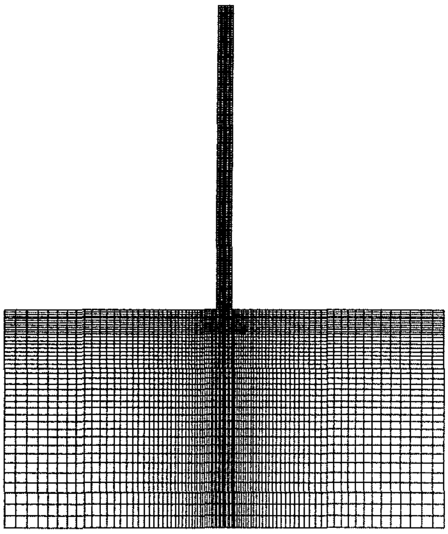


Fig. 4. Grid generated for the simulation of smoke dispersion through a long vertical duct.

the density of oxygen (ρ_{oxygen}) and nitrogen ($\rho_{nitrogen}$) were calculated to be 1.354 and 1.185 kg m^{-3}, respectively. These two fluids were chosen for use in this study because

1) They satisfy the basic assumption of equation (9), which demands that $\Delta\rho/\rho_{BOT} = 0.143 \ll 1.$
2) The value of $\Delta\rho/\rho_{BOT}$=0.143 falls into the range of values for the fresh water/salt water experiments of Cannon and Zukoski (1975), which typically vary between 0.035 and 0.190. Selecting another fluid set whose $\Delta\rho/\rho_{BOT}$ value is outside this range is inappropriate here because the empirical equation (11) was obtained from the data whose $\Delta\rho/\rho_{BOT}$ values are inside it, and it cannot be guaranteed that equation (11) would work for other values at this stage.

One of the geometries of the experimental set up of Cannon and Zukoski (1975), where the geometric ratio *L/d* is 19.7 and *d* is 0.0762 m, was adopted as the geometry for the numerical simulation. The experimental set up and procedure is sketched on the Fig. 2.

CFX, a commercial CFD code based on the finite volume method was utilized for the computation. The code was run on the workstation from Digital Equipment.

In the code, transport equations were disceretised with the hybrid differential scheme, which combines central and upwind schemes depending on the relative strength of convection and diffusion as judged by the Pecklet number. SIMPLEC algorithm was used for pressure correction.

Fig. 4 shows the two-dimensional grid of the model. Inside the shaft, 150 × 8 uniform grid cells were generated for the shaft, which is located above the level surface of the reservoir. For the bottom reservoir, 88 × 40 geometrically progressive grid cells were generated.

At the level surface of the reservoir, the atmospheric pressure boundary condition was applied, and wall boundary conditions were imposed on all the other boundaries.

For the simulation, it was assumed that the elevation of the turbulent diffusion front $k-\varepsilon$ model was used. No heat transfer was considered and the ambient temperature was assumed to be 293 K.

A time dependent (transient) model was used, with each time step fixed at 0.3 seconds. A maximum of 100 iterations were carried out for the convergence of each variable at each time step.

For the turbulence model, the buoyancy modified (z_{FRONT}) coincided with the height at which the mass fraction of bottom fluid (nitrogen) reached either 0.5% or 10% of the mixed fluid. It is not a straightforward task to relate the diffusion front detected by human eye in the previous experiments conducted by researchers such as Cannon and Zukoski (1975) to the mass fraction of the bottom fluid inside the cell. Using a mass fraction of 0.5% as the decision criteria implies that the human eye is so sensitive that it can detect a mere 0.5% change in the cells. Alternatively, specifying a mass fraction of 10% means that the mass fraction of the fluid of interest should take up at least 10% of the cell. This should allow a relatively straightforward observation procedure. The use of both decision criteria was therefore investigated in this study.

4. Results and Discussion

Around 108 seconds were taken for the turbulent diffusion front, z_{FRONT}, to reach the top of the vertical shaft. Fig. 5 shows the fluid movement inside the

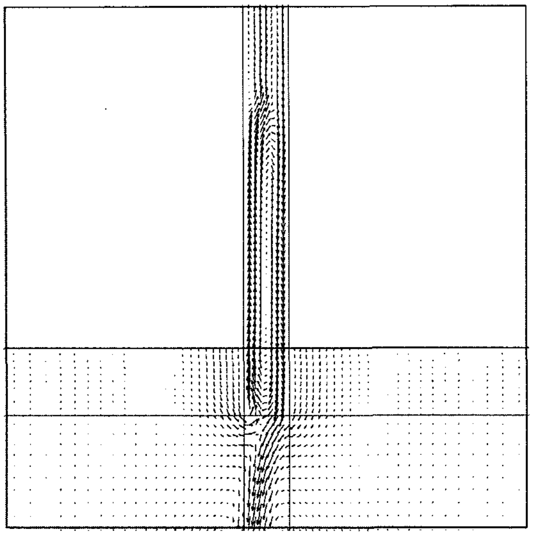


Fig. 5. Fluid movement inside the shaft and reservoir.

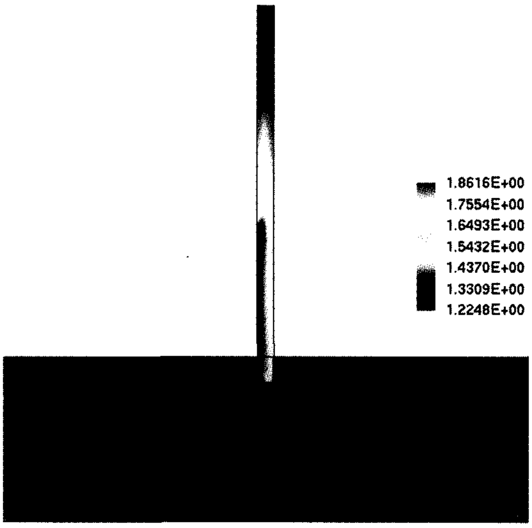


Fig. 6. Simulated density (kg m^{-3}) profile after 74.5 seconds.

shaft and reservoir. When the simulation commenced, the bottom fluid did not penetrate upwards through the middle of the shaft but instead moved up on one side of the tube, with a corresponding downwards movement of the top fluid on the other side. However, this convective behavior did not persist for long. The two fluids appeared to mix with each other vigorously (due to diffusion) at the center of the shaft near the end of the diffusion front. It is believed that this simulated phenomenon is similar to the observation of Zukoski (1994), who reported that, "fingers of mixed fluid frequently moved several diameters up one side of the shaft and then fell back to completely fill the tube with mixed fluid". Fig. 6 shows the density change of the fluid after 74.5 seconds.

Using the simulated data, the progression of the turbulent diffusion front through time has been drawn on Fig. 7. This has been done in the same manner as Fig. 3 drawn by Cooper (1994), to facilitate a comparison.

From Fig. 3 and Fig. 7, it can be seen that the simulated data are well correlated with the measurements. For the case where the 0.5% decision criterion was used, the simulated data are scattered above the solid line that represents the correlation equation (19) of Zukoski (1994), which is believed to be the best fit to the measured data. For the 10% decision criterion scenario, the estimated data are located very close to the solid line. The following empirical equations have been fitted to the simulated data points, as plotted in Fig. 8.

For the 0.5% criteria:

$$z_{FRONT}/d = 1.25\left\{\left[(g/d)(\Delta\rho/\rho_{BOT})\right]^{1/2} t\right\}^{0.57} \qquad (12)$$

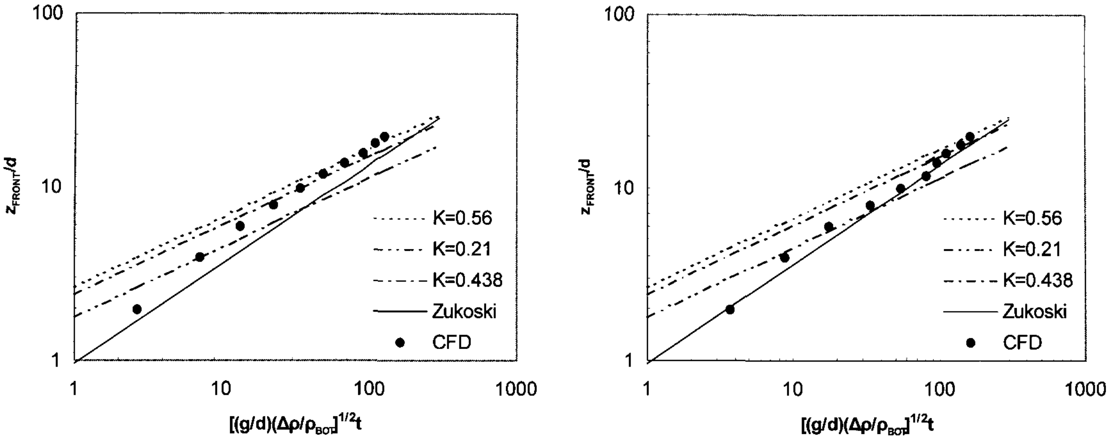
For the 10% criteria,

$$z_{FRONT}/d = 1.03\left\{\left[(g/d)(\Delta\rho/\rho_{BOT})\right]^{1/2} t\right\}^{0.57} \qquad (13)$$

Comparing equations (12) and (13) with equation (11), the following conclusions were reached.

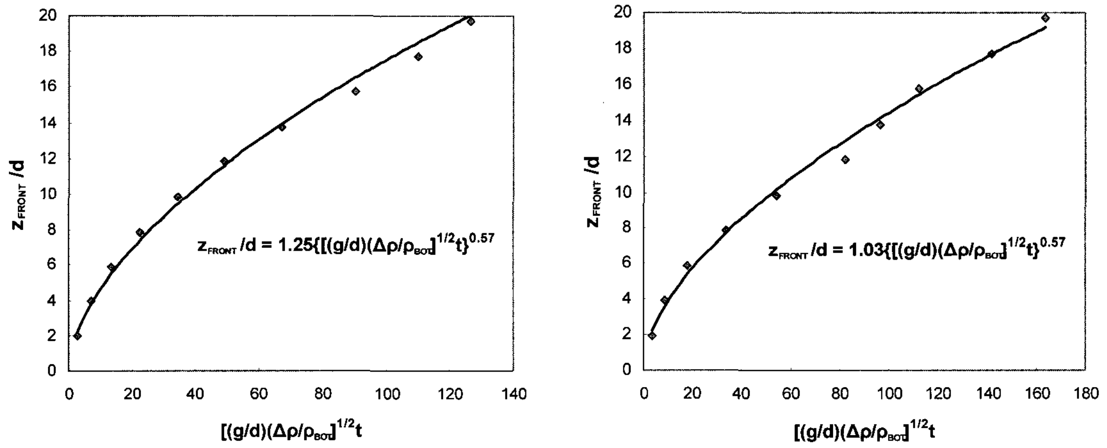
With the 0.5% decision criterion, which requires that the human eye is so sensitive that it can detect a mass change of 0.5% in the cells, the simulation predicted exactly 0.57 as the power on the right hand side of equation (19). However, this criterion would appear to be slightly over-sensitive, as the estimated data are scattered above the plotted line of Zukoski (1994). As a result, the proportionality coefficient of 1.25 in formula (20) is higher than the coefficient of 0.97 in equation (19).

With the 10% decision criterion, both the power (0.57) and the proportionality coefficient (1.03) in equation (21) closely matched the corresponding values in equation (19).



(a) Mass fraction of N_2 (bottom light fluid): 0.5% in the cells (b) Mass fraction of N_2 (bottom light fluid): 10% in the cells

Fig. 7. Elevation of the front as a function of time.



(a) Mass fraction of N_2 (bottom light fluid): 0.5% in the cells (b) Mass fraction of N_2 (bottom light fluid): 10% in the cells

Fig. 8. Trend lines calculated for the cases of 0.5% and 10% mass fraction of N_2 (bottom light fluid).

However, it is still too early to conclude that a 10% mass fraction of bottom fluid in the mixed fluid is equivalent to the diffusion front witnessed by the human eye. Further research regarding this matter could be problematic because visually-based decision making involves a degree of subjectivity. However, it is clear that under a consistent decision criterion based on the mass fraction, CFD is able to predict that the diffusion front progresses up the shaft with a rate proportional to the power of 0.57. This result is far better than the analytical equations obtained in previously published research, such as equation (9), which determined the power to be 0.40.

5. Conclusion

The study focused on the numerical simulation of smoke dispersion through a long vertical duct.

From the observations, the following conclusion can be made;

1) It is clear that under a consistent decision criterion based on the mass fraction, the field model (CFD) is able to predict that the diffusion front progresses up the shaft with exactly the same rate as that in Zukoskis empirical equation. This result is far better than the mathematical equations obtained in

previously published research. Therefore, it can be said that the field model is an excellent option to predict the smoke dispersion through the long vertical shaft.

2) The proportionality constant of Zukoski's empirical equation is closely related to the subjectivity in choosing the mass fraction criteria for the diffusion front. The 10% mass fraction of bottom fluid in the mixed fluid shows a good match with the diffusion front witnessed by human eyes. Hence, it could be inferred that the 10% mass fraction criteria corresponds to the visual progression of the smoke through the long vertical shaft. However, further researches are needed excluding the visually-based decision that can involves a degree of subjectivity.

References

1. Cannon, J. B. and E. E. Zukoski, 1975, Turbulent mixing in vertical shafts under conditions applicable to fires in high-rise buildings. Tech. Fire Report 1 to the National Science Foundation, California Institute of Technology.
2. Cooper, L. Y., 1994, Simulating smoke-movement through long vertical shaft in zone-type compartment fire models. Technical report NISTIR5526, BFRL, National Institute of Standard and Technology, Gaithersburg, USA.
3. Gardner, G. C., 1977, Motion of miscible and immiscible fluids in closed horizontal and vertical ducts. Int. J. Multiphase Flow, 3, 305-318.
4. Baird, M. H. I. and R. G. Rice, 1975, Axial dispersion in large unbaffled columns, Chemical Engineering, 9, 171-174.
5. Zukoski, E. E., 1994, Review of flows driven by natural convection in adiabatic shafts. Technical report NIST-GCR-95-679, National Institute of Standard and Technology, Gaithersburg, USA.

윤성욱
1993년 서울대학교 공과대학 자원공학과 공학사
1997년 서울대학교 대학원 자원공학과 공학석사
2003년 Imperial College 환경공학과 공학박사
Tel: 02-568-1571
E-mail: swyoon@hotmail.com
현재 범창종합기술 설계1팀 차장