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Numerical Study for Influence of Crossdraft Directions and Magnitudes on Push-Pull Ventilation Systems

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푸시풀 후드시스템의 방해기류 방향 및 세기의 영향에 관한 수치적 연구

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푸쉬-풀 환기시스템은 도금조와 같이 흡인해야 할 거리가 상대적으로 긴 경우에 많이 사용되고 있다. 그러나, 창문이나 출입문을 통한 방해기류가 푸쉬-풀 환기시스템의 오염물질 제어효율을 심각하게 훼손시키고 있다고 추측하고 있으나 이에 대한 세부적인 연구가 부족한 상태에 있다. 따라서, 본 연구에서는 전산유체역학(Computational fluid dynamics)을 이용하여 푸쉬-풀 환기시스템에서의 방해기류의 방향과 세기가 흡인효율에 어떠한 영향을 미치는지에 대해 평가해 보았다. 선형흡인효율(Linear capture efficiency) 방법을 이용하여 푸쉬-풀 환기시스템에서 가상의 개방조에서 발생한 오염물질이 푸쉬-풀 시스템에 의하여 포집되지 못하고 누출되는 구역이 어딘지를 찾아낼 수 있었다. 전산유체역학 컴퓨터시뮬레이션은 AIRPAK2.1 (FLUENT CODE) 소프트웨어를 사용하였다. 푸쉬-풀 후드시스템에 방해기류가 강하게 작용하면 상대적으로 강한 와류가 발생하는데, 일반적인 난류모델인 κ-ε 모델은 와류현상을 충분히 보여주지 못한 반면에 RNG 모델을 사용했을 때 실험결과를 적절히 모사해낼 수 있었다. RNG 모델을 이용하여 세가지 방향, 즉 푸쉬에서 풀 방향으로, 풀에서 푸쉬 방향으로 그리고 그에 수직되는 방향으로 방해기류가 있을 때의 푸쉬-풀 환기시스템의 흡인효율을 분석하였다. 방해기류가 0.25m/s이하일 때에는 흡인효율이 거의 떨어지지 않았으나, 방해기류가 0.6m/s에서 흡인효율이 40-70%로 떨어짐을 알 수 있었다. 따라서, 방해기류를 감소시킬 수 있는 방안에 대해서도 연구를 해야 되겠지만, 방해기류 존재하에서 충분한 흡인 효율을 유지할 수 있는 푸쉬-풀 후드 설계기준에 대한 연구도 필요할 것으로 판단된다.

Key Words : CFD, push-pull ventilation systems, capture efficiency, crossdraft velocity, turbulence modeling

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Ⅰ. INTRODUCTION

Malin (1945) reported the earliest study on the push-pull ventilation system. Investigators have studied the key parameters of push-pull ventilation systems. Battista (1947), Ega and Silverman (1950), and Hama (1957) investigated the influence of push flow rate on push-pull ventilation system. During the 1980s, US NIOSH published a series of papers of push-pull ventilation systems. Hughes and Huebener (1982, 1985) reported the required minimum flow speed for both push nozzle and pull hood for different sizes of tank based on experimental conditions.

So far, detailed design guidelines for push-pull ventilation system designers have been recommended by ACGIH (2004). In the recommendation, the push airflow rate per unit width of the tank is determined by width of tank, and the pull airflow rate is recommended as2.10-2.52m3/min. But relative studies (Robinson & Ingham, 1996 and 2003; Marzal et al., 2003 Chern & Ma, 2007) proved that many factors significantly affected the flow field and capture efficiency of push-pull ventilation systems. For instance, the offset encloses the gas in a small region; the push flow can carry the contaminant to the pull side to prevent contaminant dispersion; the flanges determine the flow pattern; push and pull flows depend on the length of the tank. The last study was focused to compare the push-pull and exhaust fume cupboards, in which airflow motions and associated pollutant distributions in fume hoods was investigated (Chern & Cheng, 2007).

Some practices and experiments have proved that more contaminant escape from the push-pull ventilation system with crossdrafts. However, the influence of the crossdraft has not gotten profound study.

Furthermore, the mean crossdraft velocity of 0.6 *m/s* and maximum velocity of *m/s* 3 in Korean industry were described by Song (2005) which induced that the push-pull ventilation system could not efficiently run. An efficient push-pull ventilation system should get more than capture efficiency of 90% for contaminant. Rota et al. (2001) reported the capture efficiency was higher than 90% in case the crossdraft velocity from the pull side to the push side in push-pull system was lower than 0.3 m/s), whereas for the higher crossdraft velocity, the capture efficiency decreased rapidly. Song (2005) experimentally studied the effects of two different crossdraft velocities which were from the push side to the pull side and vise versa in push pull ventilation system, and reported that the loss zone of contaminant would be spread with increasing crossdraft velocities.

The validity of CFD simulation on push-pull ventilation system design has been proved in some studies (Kulmala, 1994; Conroy et. al., 2000; Robinson & Ingham, 1996; Flynn et. al., 1995). The simulation model can correctly reproduce the characteristics of push-pull ventilation systems through comparing the predictions of CFD model with some available experimental data. Therefore, the CFD simulation has been widely used to develop the push-pull ventilation system (Rota, 2001 Chern & Chen, 2007). In present investigation, Preliminary study shows the comparisons between previous experimental (Song, 2005) and present CFD results on capture efficiency of push-pull ventilation systems with different crossdraft velocities. The objectives of the present study are numerical analysis for influences of directions and magnitudes of crossdraft on capture efficiency in typical push-pull ventilation systems recommended by ACGIH (2004). The linear capture efficiency is used to determine the loss zone of gas contaminant.

Ⅱ. METHODS

A. Numerical Models

Numerical model is employed to investigate push-pull ventilation systems. The air flow is assumed to be steady, isothermal and incompressible. The governing equations include Mass conservation and the momentum equation in this study:

$$\nabla \cdot \vec{u} = 0 \tag{1}$$

$$\rho u_i \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{\partial}{\partial x_j}(\rho u_i' u_j'), \tag{2}$$

Where is a mean velocity vector; the components of the velocity vector of x_i and x_j directions are respectively u_i and u_j , p is air density; p is air pressure(식 1, 2에 P가 없네요, 이럴 경우 생략); μ is dynamic viscosity. It has been difficult to obtain a universal turbulence model for all types of airflow (Chen, 1995). Two classical and in common used turbulence models are analyzed in following section.

- Standard κ-ε model;

- Renormalization group (RNG) κ-ε model

Combining κ-ε models with equation (1) and (2), in κ-ε models, the Reynolds stresses are determined using Boussinesq approximation:

$$-u_i'u_j' = \mu(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}) - \frac{2}{3}\delta_{ij}k \quad (3)$$

Where δ_{ij} is the Kronecker Delta. The local turbulence viscosity μ is related to the turbulence kinetic energy κ and the dissipation rate of the turbulence kinetic energy ε, which is shown as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (4)$$

To κ and ε, the standard κ-ε model and RNG κ-ε model have identical form on equation. The differences between them are produced on equation. Comparing to the standard κ-ε model, the RNG κ-ε model has an additional source term,R_ε, this term improves flow prediction for regions with large strain rates, and this term is always negligible Therefore, the model can better predict separate and swirl flows, which have been proved by Loomans (1998). In present study, we will compare the applications of these two models on study of capture efficiency of push-pull ventilation systems.

B. Linear Capture Efficiency

Contaminants released from opening surface tank could not be completely captured by pull hood. To study the capture characteristics and loss zones of push-pull ventilation systems without crossdraft, Marzal (2002) divided the releasing surface of tank into four aerodynamics zones, which were (1) semi-free flow zone, (2) impact zone, (3) wall jet reorganization zone, and (4) wall jet zone, and pointed out that the main loss of contaminants was occurred in impact region. The later study, Song (2005) experimentally proved the four aerodynamics zones using other size tank without any crossdraft. The two results had good agreement on visualization aerodynamics each other, these two results are shown in Fig. 1. Figs.1a and b show experimental and hand-drawn visualization aerodynamics, respectively.

According to Marzal (2001)study, Marzal (2003) applied linear capture efficiency methodology in detail for determining total capture efficiency E_T in push-pull ventilation systems:

$$E_T = \int_0^L \frac{E_l}{L} dl \quad (5)$$

Where: E_T is linear capture efficiency, L is the total length of the tank and l is the distance measured in the tank from diffuser tube to the push element. The linear capture efficiency is determined as equation (6):

$$E_l = C_a / C_{aT} \quad (6)$$

Where: C_a is the concentration of measured contaminant in the pull hood when the contaminant is released from the diffuser tube placed over the surface tank, C_{aT} is the concentration in pull hood when the contaminant is introduced directly into the pull hood.

Ⅲ. NUMERICAL SIMULATIONS

Fig.2 shows the simulated push-pull ventilation systems in this study. The length and width of open surface tank are 0.8m and 1.2m, respectively. The height of freeboard is 0.15m. The heights of push and pull hood are 0.005m and 0.05m, respectively. In the simulation process, we put 12 tubes with 0.1 m intervals on the surface of

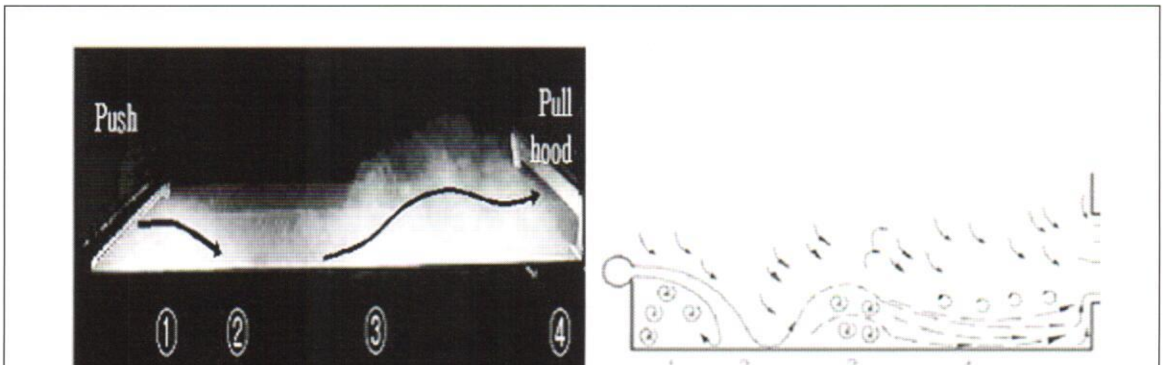

Fig.1.experimental and hand-drawn visualization aerodynamics of push-pull ventilation systems

treatment tank. The tube is slotted with 10 mm diameter, through which the contaminant emerged uniformly. The contaminant evaporation velocity considered is 0.3 *m/s*. The relative parameters include: push velocity of 7.8 *m/s* and pull velocity of 9.97(ACGIH, 2004)

The crossdraft velocities of 0.20, 0.40, 0.60, 0.80, 1.00, and 1.20 *m/s* are used in simulation process to observe the capture efficiency as a function of the crossdraft velocity in detail. A static pressure is at free stream boundaries. The non-uniform calculation grids are used with grids of 128×84×34 cells to obtain grid independent result. The cases are solved with a finite-volume based on AIRPAK2.1 (FLUENT) computer code.

Ⅳ. VALIDATION OF TURBULENT MODELS

In the Fig.3, the linear capture efficiencies are affected by crossdraft from pull to push hood. As what has been analyzed above, the linear capture efficiency decreases to minimum value in the impact zone which because the swirling flow is produced in this region where more gas contaminant is lost. The standard κ-ε model completely fails to predict the swirl flow field and capture efficiency which dues to Standard κ-ε model over predicts the kinetic energy in the swirl flow field (Chen, 2001)

The results from the RNG κ-ε model are slightly better than

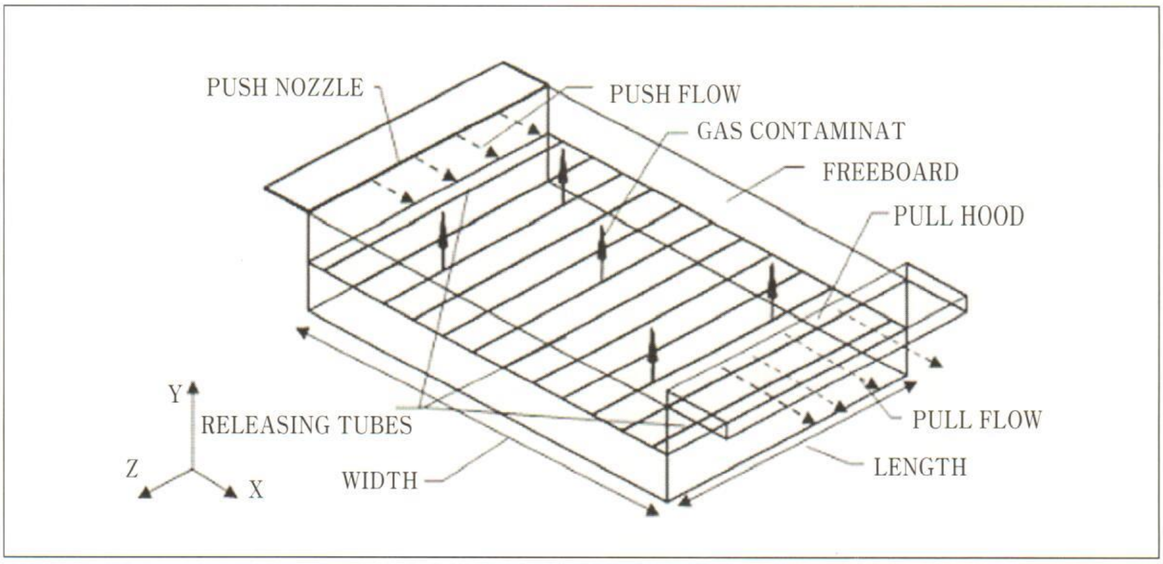

Fig.2. Sketch of push-pull ventilation system for studied open surface tank (open suface tank study)

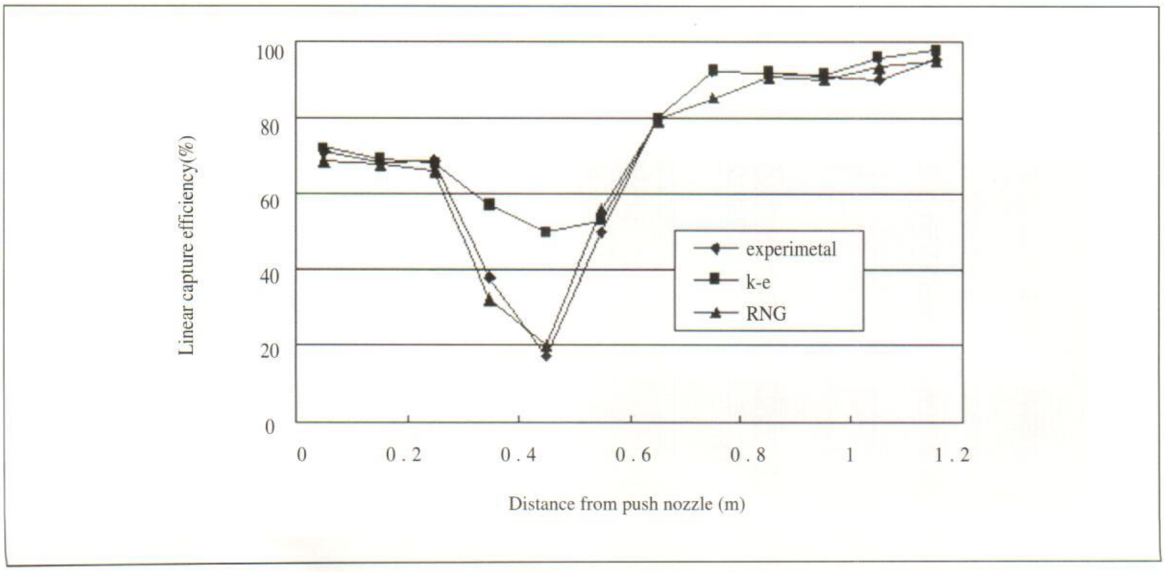

Fig.3. linear capture efficiencies with crossdraft from pull to push hood.

standard κ-ε model simulation results. RNG κ-ε model is employed to predict the influence of crossdraft magnitudes and directions on capture efficiency in this study.

V. RESULTS AND DISCUSSION

The total capture efficiencies are estimated for the three different configurations (of crossdraft flow) including (from the pull) to push hood, (from the push) to pull hood, and perpendicular to side freeboard, respectively.

A. Total Capture Efficiencies

Fig.4 summarizes the simulation predictions for influences of different crossdraft velocity directions and magnitudes on total capture efficiencies. It can be seen that at low crossdraft velocity, the system keeps high capture efficiency which is 90%, whereas for higher crossdraft velocities the capture efficiencies decrease very rapidly.

The average value of 0.6 *m/s* is typical crossdraft velocity of many industrial workplaces in Korea. Therefore, it should be noted that the all three total capture efficiencies decrease to 70% below when crossdraft velocity is 0.6 *m/s*, which means that more than 30% gas contaminant emits into workplace. The recommended push-pull ventilation systems(ACGIH, 2004) would not be able to reach the real workplace requirements in Korean industries.

B. Linear Capture Efficiency Analysis for Loss Zones of Push–pull Ventilation Systems

The recommended push-pull ventilation systems are used in the workplace with crossdraft. It has predicted that the crossdraft velocities with varied directions, which have different influence levels on capture efficiency. The linear capture efficiency was carried out using crossdraft velocities of 0.2 and 0.8 *m/s* to observe the loss zones.

Fig.5 shows linear capture efficiency as a function of the crossdraft velocities from push to pull hood. When the crossdraft velocity is 0.2 *m/s*, the loss zone disappears. Main loss zone spreads to the region from 0 to about 0.85 *m* when the crossdraft velocity is to 0.8 *m/s*, and the linear capture efficiencies are reduced with decreasing distance from push hood to diffuser tube. Especially in the short range closer to pull hood, the linear capture efficiencies are very high which because almost all gas contaminant emitted from the wall jet zone is captured by the pull hood (Marzal. et al., 2002).

Comparing with Fig.5, significant differences of linear capture efficiency are observed in Fig.6 in which the direction of crossdraft is from pull to push hood. With lower crossdraft velocity of 0.2 *m/s*,

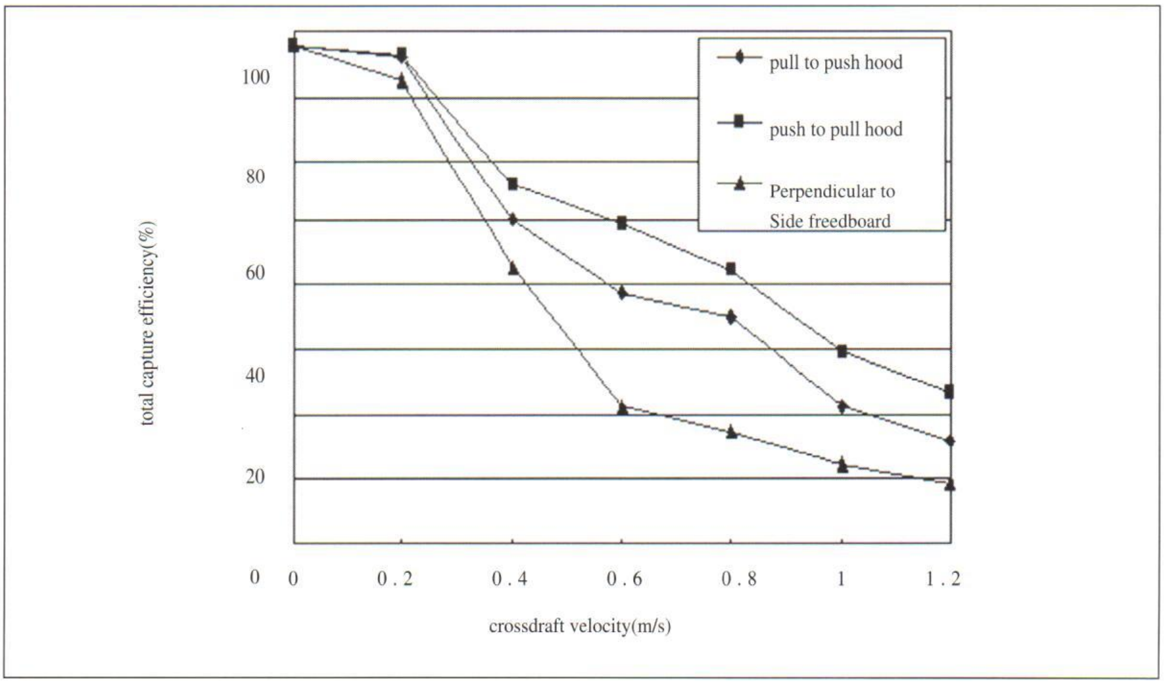

Fig.4.Total capture efficiency as a function of the crossdraft velocity directions and magnitudes

almost all gas contaminant was driven into pull hood. A hollow is clearly observed when crossdraft velocity of 0.8 *m/s*. The loss spreads to larger range from 0 to 1 *m*.the larger range can be predicted that was due to increased impact zone.

From all the simulations applied in this study, we verified that it was the worst condition that the crossdraft blows in the direction of perpendicular to side freeboard. It can be seen in Fig.7 that, although at crossdraft velocity of 0.2 *m/s*, some gas contaminant escapes from the region of 0.4 to 0.6m. When crossdraft velocity increases to 0.8 *m/s*, the linear capture efficiencies are lower than 20% in the region between 0 and 0.6 m. In the following region, linear capture efficiency rapidly increases with decreasing distance between the diffuser tubes and pull hood.

C. Velocity Fields Analysis for Loss Zones of Push-pull Ventilation Systems

The effects of crossdraft velocity on push-pull ventilation systems can be clearly deduced from the air velocity field. Some differences are carried out between the three phases. It may be observed the airflows from the push hood to the pull hood are broken by the crossdrafts.

Firstly, we compare the velocity fields with crossdraft from push to pull hood and pull to push hood, oppositely. In Fig.8a and Fig.8b, the semi-free flow zones are clearly shown in interior surface of the just front push hood where the recirculating regions are produced. That is because the curtain on the tank formed two airflows: the main one, later forming the wall jet, and the other, under the push hood, which returns toward the origin with a circular movement, which defeat the push flow. Moreover, with the crossdraft from push to pull hood, emitted gas containments are close to the tank surface. The one escapes from pull hood above which is due to the same direction between crossdraft and push flow. Whereas when the

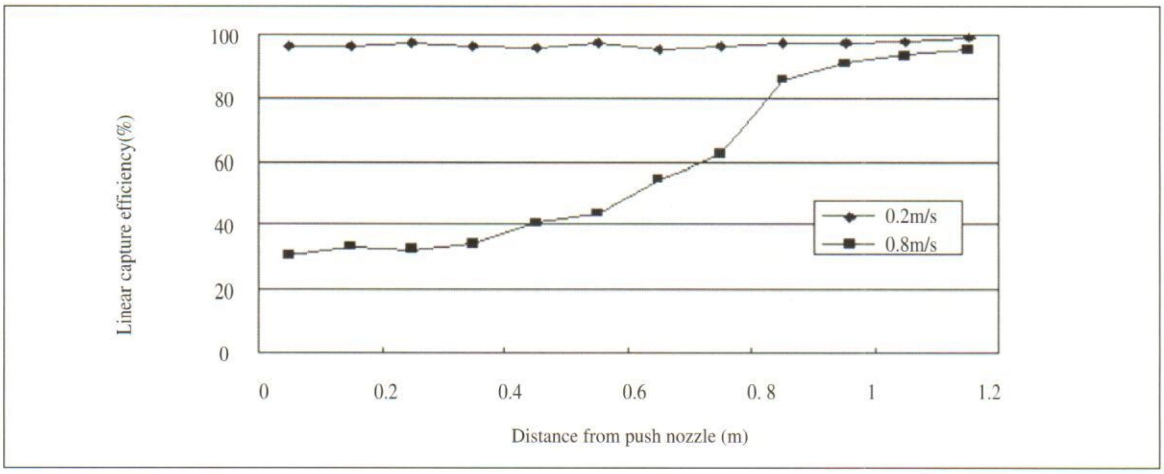

Fig.5.Linear capture efficiency as a function of the crossdraft velocities from push to pull hood

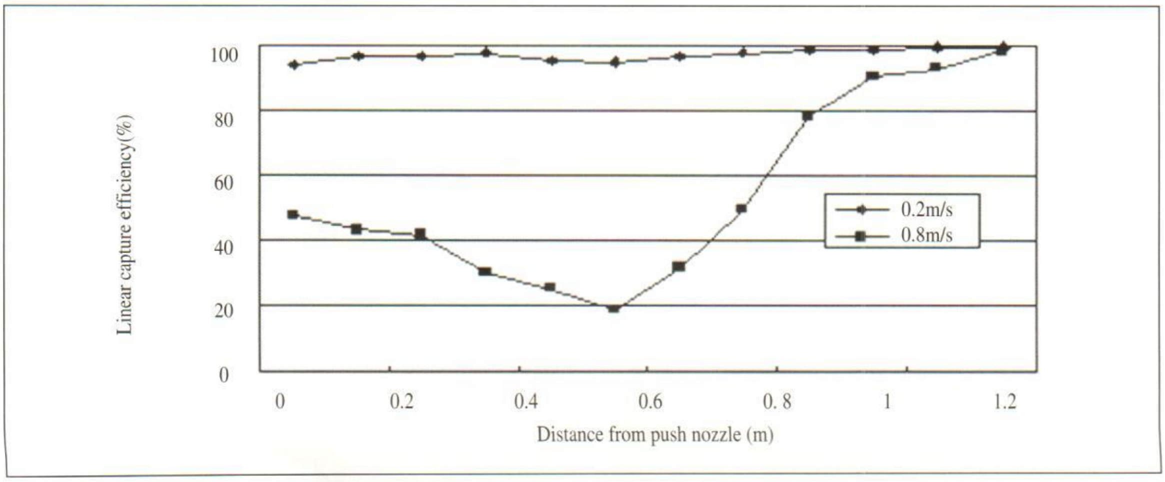

Fig.6. Linear capture efficiency as a function of the crossdraft velocities from pull to push hood

crossdraft from pull to push hood, the aerodynamics behavior of airflow become more complicated. In Fig 8b, a recalculating zone is produced in the region of superior surface of the just front push side, which results from the convection between push and crossdraft airflows. Due to this convection, some of gas contaminant emitted in semi-free flow zone does not suffer loss in the region, but reaches to the wall jet zone and that is captured by the pull hood. In impact zone, the force of swirl airflow drives gas contaminant far away the system. Therefore, in principle, as the crossdraft magnitude increases so did the impact, and the higher emissions are to be expected.

Secondly, for the case of crossdraft of perpendicular to side freeboard, the velocity fields in Figs.9a, b and c show the front views of velocity field in the three different planes (they are, 0.2, 0.6, and 1.0m in front of the push hood, respectively). It can be predicted in the Figs.9a and b that emitted gas contaminant is mixed with crossdraft airflow and then is driven out from the system. Only the

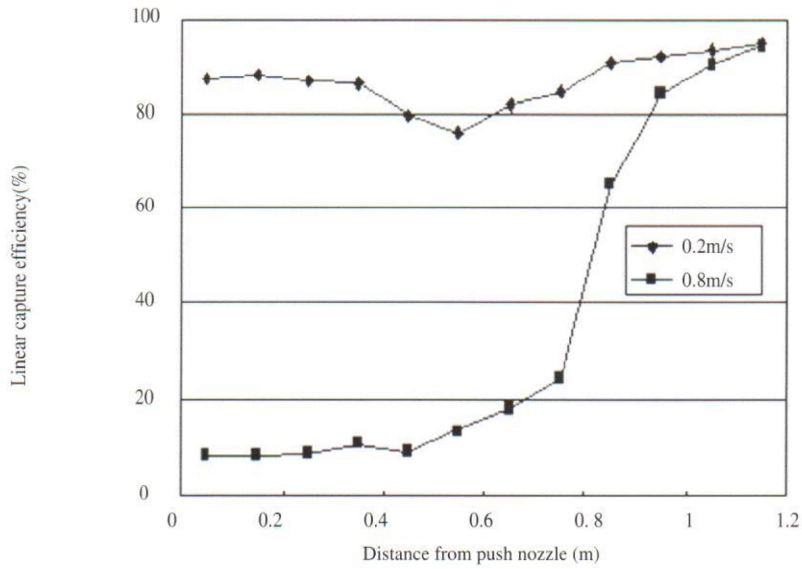

Fig.7.Linear capture efficiency as a function of the crossdraft velocities of perpendicular to side freeboard

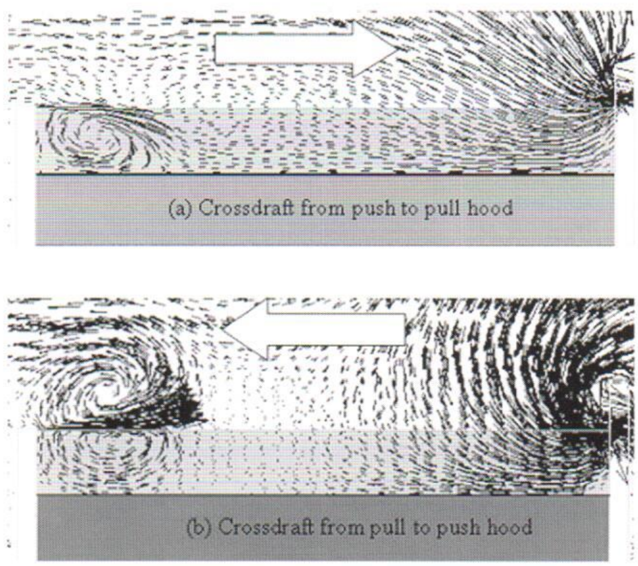

Fig.8. Velocity fields in the symmetry vertical plane of the tank

contaminant emitted from the range of very near to pull hood is captured, which is shown in Fig.9c. Above behaviors provide the effect distance of pull airflow is very short. Therefore, as soon as emitted from the tank the gas contaminant goes toward downstream. The Fig.11d shows the vertical view of velocity field in the symmetry section of the tank. The crossdraft of perpendicular to side freeboard is a difficult eliminating factor for increasing total capture efficiency of push-pull ventilation systems.

Ⅵ. CONCLUSIONS

Linear capture efficiency methodology was useful to analyze the loss zones of push-pull ventilation systems. Using this methodology, the loss zones can be clearly observed. The loss zone of the systems was produced in impact zone without crossdraft surrounds the systems. Both the standard and RNG κ-ε turbulence models can predict the capture efficiency of push-pull ventilation systems when no crossdraft or the crossdraft direction from push to pull hood.

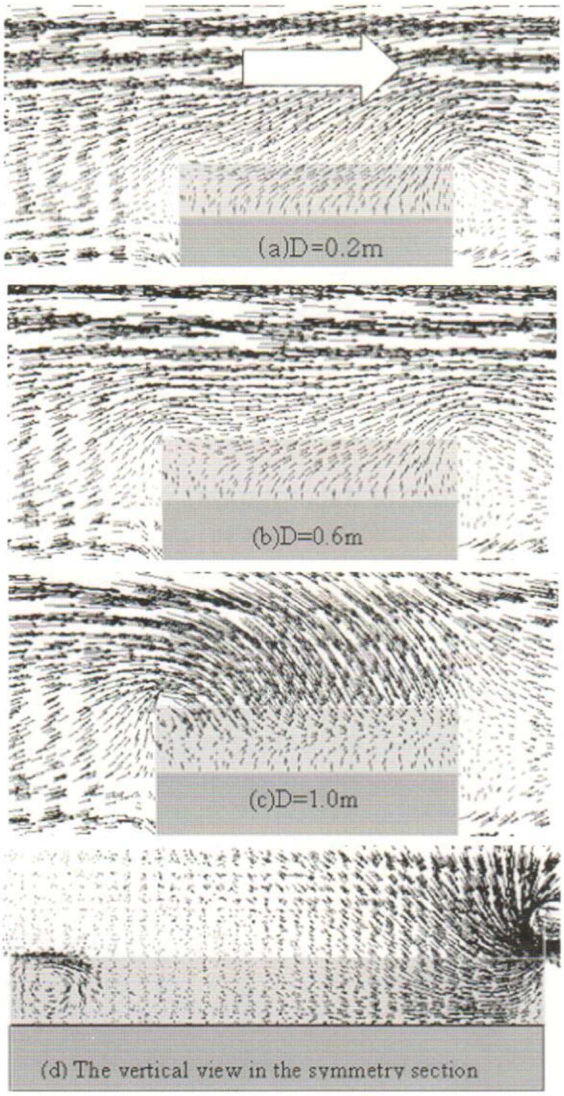

Fig.9. the velocity fields in the four different planes of the tank with crossdraft of perpendicular to side freeboard

With crossdraft from pull to push, the standard κ-ε model failed to predict the capture efficiency which was due to swirling airflow in impact zone. The RNG κ-ε model was successful to predict the capture efficiency under the three directions of crossdraft. The pull velocity of 9.97 *m/s* was recommendation value (ACGIH, 2004), and was used in industry without crossdraft. Also this recommended push-pull ventilation systems can well run when the crossdraft velocity lower than 0.25 *m/s*, whereas, for higher crossdraft velocity the capture efficiency decreases almost rapidly. The capture efficiencies are reduced to below 70% when crossdraft velocity is 0.6 *m/s* in Korean industrial environment. On the basis of the results of several simulations in this study, new design guidelines should be developed for the condition when crossdraft velocity is higher than 0.25m/s.

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REFERENCES

ACGIH. American Conference of Governmental Industrial Hygienists. Industrial Ventilation -A Manual of Recommended Practice (25th ed.) ISBN 1-882417-52-6.; 2004

Battista WP. Semi-lateral tank ventilation hood controls contaminant, cut costs. Heat. Piping Air Condition. v.19. 1947: 85-89

Chen Q. : Comparison of different k-e models for indoor airflow computation.

Numerical Heat Transfer, Part B, Fundamentals, v.28. 1995: 353-369.

Chen Q. : Simplified diffuser boundary conditions for numerical room airflow models. Repor ASHRAE 1791 Tullie Circle, NE Atlanta.2001: 30329-2305.

Chern and Ma Chen-Hsuan : Numerical investigation and recommendations for push-pull ventilation systems. Journal of Occupational and Environmental Hygiene, v.4.2007: 184?197.

Conroy LM. et al, : An analytical, numerical, and experimental comparison of the fluid velocity in the vicinity of an open tank with one and two lateral exhaust slot hoods and a uniform crossdraft. Ann. Occup. Hyg., Vol. 44, No. 6, 2000: pp. 407-419.

Ega and Silverman L. : Design of push-pull exhaust systems.Heat Ventil. v.10.1950: 73-78.

Flynn MR. et al : Three dimensional finite-element simulation of a turbulent push-pull ventilation system. Ann Occup Hyg; 39.1995: 573-589.

Hama GM. : Supply and exhaust ventilation for metal picking operations. Air Cond. Heat Ventil.54.1957: 61-63

Hughes RT. and Huebener, D.J. : Development of push-pull ventilation criteria. Division of Physical Sciences and Engineering, National Institute for Occupational Safety and Health, Cincinnati, Ohio.1982.

Huebener DJ. and Hughes R.T. : Development of push-pull ventilation. Am.ind.Hyg.AssJ.46. 1985:262-267

Kulmala Ilpo. : Numerical simulation of a local ventilation unit. Ann.Occup.Hyg.,

Vol.38, No.4, 1994:pp.337-349.

Kulmala Ilpo. : Numerical calculation of the capture efficiency of an unflanged circular exhaust opening. Ventilation 94, Proceedings of the 4thInternational Symposium on Ventilationfor Contaminant Control. Solna: Arbete och18.1994:.pp.339-334.

Loomans. M. : The measurement and simulation of indoor air flow. Ph.D.

Dissertation, Eindhoven University of Technology, the Netherlands.1998

Malin BS. : Practical pointers on industrial exhaust system. Heat Ventil. 42. 1945: 75- 82.

Marzal F. et al. : Methodologies for determining capture efficiencies in surfacetreatment tanks. AIHA Journal 64.2003:604-608

Marzal F. et al. : Determination and interpretation of total and transversal linear efficiencies in push-pull ventilation systems for open surface tanks. Ann. Occup. Hyg. Vol. 46, No. 7,2002: pp. 629-635

Robinson M. and Ingham DB.: Recommendations for the design of push-pull ventilation systems for open surface tank. *Ann.occup.Hyg.*, Vol.40, No.6,1996a: pp.693-704.

Robinson M and Ingham DB. . Numerical modeling of the flow patterns induced by a push-pull ventilation system. Ann Occup Hyg; Vol.40, No.6, 1996b: pp. 293?310.

Robinson,M, and Ingham DB. : Design and operating parameters for push-pull ventilation of open surface tanks. *Int.J.Energy* Res. 27. 2003: 757-770.

Rota R. et al. : Design guidelines for push-pull ventilation systems through computational fluid dynamics modeling. AIHAJ.62,2001:141-148

Song Se-Wook .et al : Evaluation of capture efficiencies of push-pull hood systems by crossdraft directions and velocities using smoking visualization technique. Korean Soc Occup Environ Hyg 15(1). 2005 ::36-44.

Song Se-Wook. : The evaluation of capture efficiencies of push-pull ventilation systems under crossdraft Ph.D.Dissertation, Department of Environmental Engineering, Changwon National University, Korea.2005