FEASIBILITY STUDY OF CFD PREDICTION FOR EVALUATION OF COMMERCIAL KITCHEN ENVIRONMENTS

Takashi Kurabuchi[1], Hitoshi Sosa[1] and Sihwan Lee[1]
[1] Department of Architecture, Tokyo University of Science, Tokyo, Japan

ABSTRACT

A measurement technique was developed on capture efficiency of commercial kitchen ventilation systems affected by disturbance due to HVAC diffusers and movement of kitchen workers. In the process of development, computer simulation using RANS CFD model was applied to evaluate diffusion of gaseous contaminants emitted from commercial kitchen appliances and compared with experiments. CFD results suggested that supply air flow from the displacement ventilation system to make up additional ceiling exhaust exerted little influence on capture efficiency to remove contaminated air which overflowed from the exhaust hood. It also suggested that, when overflowed contaminated air possibly elevated the surrounding concentration, that concentration level could be estimated by extrapolating secondary decay of exhaust air concentration immediately after primary decay when terminating the tracer gas dose. This measurement technique was applied to evaluate appropriate ceiling exhaust flow rate. It was confirmed that the ceiling diffuser of a HVAC system exerted little influence on capture efficiency if air velocity at the bottom front part of the capture hood was restricted to 0.4m/s. The simulated movement of kitchen workers tended to disturb buoyant plumes over the kitchen appliances and markedly lowered the capture efficiency of the hood. Capture efficiency of combustion waste gas was generally higher in low radiation cooking appliance with concentrated exhaust flue than that of the conventional type.

INTRODUCTION

In commercial kitchens, there is a problem with worsening air quality during cooking time from the large amount of heat and steam arising from kitchen appliances including waste gas. In order to deal with that, a large amount of energy is needed for air conditioning and ventilation. In recent years, development of a demand control system for ventiliation and introduction of low radiation and tall exhaust flue type kitchen appliances (hereafter: low radiation appliances) has advanced. Regarding the ventilation flow rate of commercial kitchens, we usually select recommended values based upon the privious ASHRAE criteria of 0.3 m/s hood velocity as per the building guideline set by the Japanese Ministry of Land, Infrastructure, Transport and Tourism Government Buildings Department. In previous study, a hood velocity of 0.3 m/s was found adequate under a calm environment, regardless of whether for open gas burning appliances (hereafter: conventional types), or low radiation appliances are used. However, disturbances from air conditioning flows and kitchen workers' movement have not been considered. Therefore, it is required to measure the actual capture efficiency that indicates the percentage of exhaust gases from appliances that is discharged by the hood in a variety of environments, and to make adequate exhaust flow rate settings. However, in the measurement of capture efficiency in laboratories, overflowing exhaust gases remain inside the room and are recaptured by the hood. In that case, capture efficiencies are overestimated and it is difficult to set adequate flow rates. Hence, there is a need to establish an adequate capture efficiency measuring method in the laboratory.

OBJECTIVE

In this study, we first aim to establish an adequate measurement method of capture efficiency for enclosed spaces such as laboratories. As an establishment procedure, we conducted a comparison of capture efficiency for experiments in a calm space and those of computational fluid dynamics (CFD) to confirm reproduction accuracy of CFD. Next, we examined the non-recapture aritificial environment by setting the concentration outside the hood to zero, and calculated actual capture efficiency not affected by the overflowed contaminant. Then, we developed a method to correct capture efficiency obtained under actual recapture condition by estimating background concentration elevated by overflowed contaminated air. This technique was applied to establish an appropriate test condition for ceiling exhaust flow rate.

Secondly, we installed an air conditioning supply diffuser around the hood and measured the capture efficiency for a simulated disturbance (disturbance with air conditioning flows) and we replicated environments with disturbed airflow due to kitchen worker movement (human disturbance) in order to measure capture efficiency as a funcion of exhaust flow rate of hood, and to examine the effects of disturbance on capture performance.

METHOD

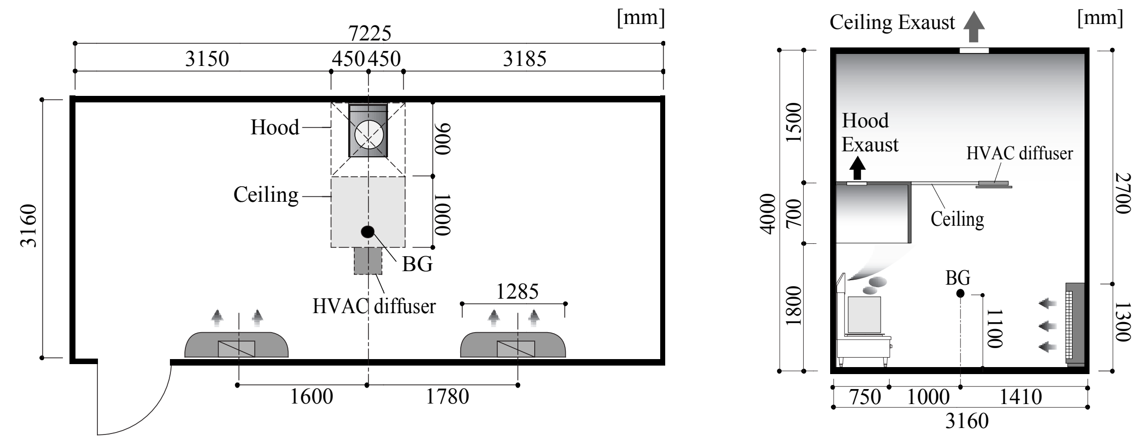
1) Experiment and CFD analysis

The experiment was conducted at the Company T Kitchen Environment Test Lab and capture efficiency was first measured under an undisturbed calm environment. In addition, in conjunction with the experiment, we performed an analysis of the capture efficiency using CFD. The laboratory plan and cross section are shown with supply and exhaust air flow configuration in Figure 1. Fresh air was supplied from the displacement ventilation diffusers to control the disturbance from the test lab air supply. Additionally, we used a ventilation setting that intends to prevent recapturing of overflow by raising the ceiling and creating a space over the top of the hood and attaching a ceiling exhaust opening. We performed measurement of the capture efficiency of waste gas and cooking effluence for six cases: 20 KQ (K: nominal combustion gas flow rate per unit fuel gas consumption rate of 0.93 m^3/kW per h, Q: appliance fuel gas consumption rate converted to heat in kW), 30 KQ, 40 KQ, and hood velocity of 0.3 m/s, 0.4 m/s and 0.5 m/s as indicated in Table 1. From the experiment, the capture efficiency calculation is based upon the method developed in the Better Living laboratory (BL) and provided in Equation (1) below.

$$\mu = \frac{C_e - C_{BG}}{M} \times Q \times 100 \qquad (1)$$

where, μ is the capture efficiency (%), C_e is the exhaust duct concentration, C_{BG} is the background concentration (BG) (-), and M is the generated contaminant quantity (m^3/h), Q is the exhaust flow rate (m^3/h). The capture efficiency measurement deals with the combustion waste gases (Figure 3) from above the appliance and the cooking effluence (Figure 4) from the water surface. For the combustion gases, we calculate the CO_2 emissions from appliance fuel consumption and we consider this the generated contaminant. Additionally, cooking effluence is simulated by SF_6 dosed from piping directly over a water surface.

Next, we will discuss the CFD model. Low radiation appliances are, as demonstrated in Figure 2, those with an exhaust pipe, as well as appliances that reduce surface radiation heat with double layer heat insulation. The Equation (2) for calculating capture



(a) plan *(b) Cross section*

Figure 1 Experimental chamber

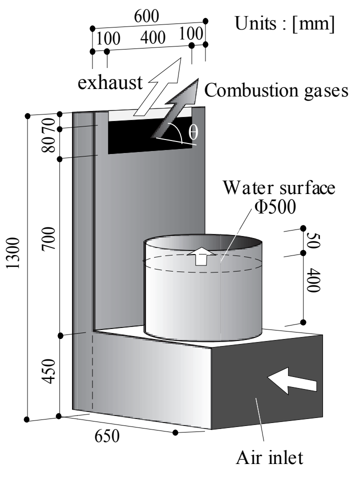


Figure 2 Appliance diagram

Figure 3 Waste gas exhaust

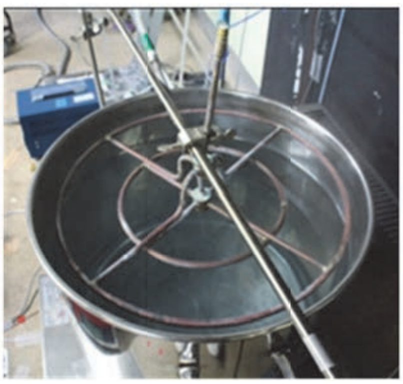


Figure 4 SF_6 dosing tubes

efficiency in CFD is as follows.

$$\mu = \frac{m}{M} \times 100 \qquad (2)$$

where, μ is the capture efficiency (%), m is contaminant removed through exhaust hood (kg/s), and M is the generated contaminant (kg/s).

Additionally, the air flow rate for each case is shown in Table 1. Ceiling exhaust flow rate is set to 1000 m^3/h based on the later discussion, and the flow rate from the hood and that from the ceiling is combined and supplied from the displacement supply diffusers. Next, in Table 2, appliance boundary conditions are shown. Combustion waste gas is exhausted diagonally at high temperature. Insulation air is exhausted just above waste gas exhaust opening.

2) Appropriate ceiling exhaust flow rate examination by CFD analysis

In enclosed spaces like the laboratory used for this study, there is the risk of waste gas overflow being recaptured in the hood and capture efficiency being overestimated. To deal with that, ventilation systems where the air supply from the lower level and exhaust from the ceiling are installed, including ceilings that are high for accumulated gas so as not to be recaptured by the hood. If the ceiling exhaust flow rate is insufficient, there is a risk of accumulated gas reaching the bottom of the hood, and on the other hand, if supply flow rate is too large, induced air flow can disturb capturing of ventilation hood. Because of that, to effectively remove gas overflow and not to disturb ventilation hood capturing, it is necessary to set the ceiling exhaust flow rate appropriately. Therefore, we performed comparative analysis (Table 3) regarding a hood flow rate of 20 KQ and hood velocity of 0.3 m/s for the six case ceiling exhaust flow rates of 400, 600, 800, 1,000, 1,200, and up to 1,400 m^3/h. Additionally, as in Figure 5, with the overflowed contamination for regions outside the hood forced to zero, we examine recapture effect by comparison of resultant capture efficiencies.

3) Estimation of background concentration by extrapolation method of secondary decay in exhaust air through CFD analysis

The extrapolation method of secondary decay is useful to calculate background concentration in order to remove the influence that recapturing exerts on capture efficiency. This method estimates background concentration by analyzing decay in the ventilation food exhaust concentration after termination of tracer gas dose. Typical

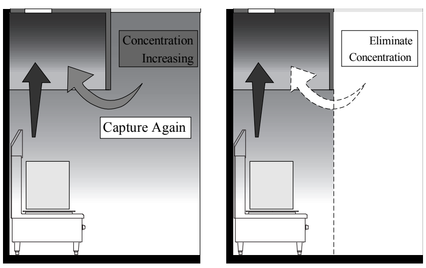
Table 1 Air flow rate for each case

Air volume	Exaust [m^3/h]		Air supply [m^3/h]
	Hood	Ceiling	
20 KQ	324	1,000	1,324
30 KQ	449		1,449
40 KQ	639		1,639
0.3 m/s	884		1,884
0.4 m/s	1,211		2,211
0.5 m/s	1,486		2,486

Table 2 Appliance boundary condition

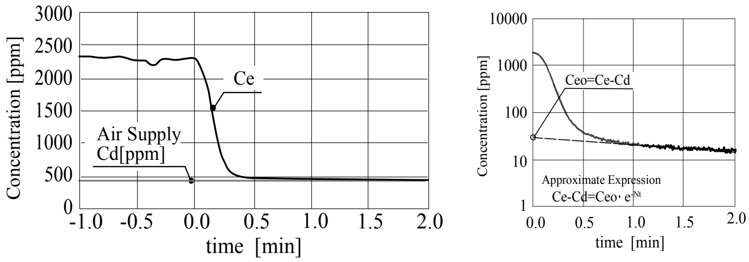
Boundary	Temp [ºC]	*Angle* [º]*	Vel. [m/s]
Waste gas	325	60	1.396
Insulation air	62	54	0.382
Pot water	100	90	0.023
Suction side	-	0	0.105

** Emission angle is set at 0º for horizontal discharge and 90º for vertical discharge*



(a) With recapture (b) Without recapture

Figure 5 Recapture examination



(a) Time history of concentration (b) Log-graph

Figure 6 Concentration decay in exhaust air (Hood exhaust at 30KQ, ceiling exhaust at 1000m^3/h)

Table 3 Case analysis

Examination content	Contents					
Ceiling exhaust [m^3/h]	400	600	800	1,000	1,200	1,400
Hood exhaust	20 KQ, 0.3 m/s	20 KQ, 0.3 m/s	20 KQ, 0.3 m/s	20 KQ, 0.3 m/s	20 KQ, 0.3 m/s	20 KQ, 0.3 m/s
Recapture	Y, N	Y, N	Y, N	Y, N	Y, N	Y, N
Number of cases	24 cases in total					

concentration decay in exhaust air is shown in Figure 6. The measurement process is: first, wait until the concentrations in the exhaust air and background air become stable for the operating conditions. After that, stop appliance operation and tracer gas dose. Focusing on the concentration decay in the exhaust air, we notice that the there is a primary sudden drops of concentration after termination. This is a contribution on the decrease in the direct captured amount of contamination over the appliance. Immediately after this primary decay, then occurs secondary concentration decrease that follows nearly theoretical exponential decay. This is believed because of the decrease in the accumulated contaminants within the room, so we exponentially approximated this decay, and extrapolated the background concentration (C_{eo}) when the appliance has stopped (t = 0). In this study, we estimated actual capture efficiencies applying this technique and compared with values that are for direct capture efficiencies when the surrounding concentration is set to zero. We performed transient analysis regarding concentration decay for a hood exhaust flow rate of 20 KQ and a ceiling exhaust flow rate of 400 m^3/h and 1,000 m^3/h.

4) Comparison of the extrapolation method and BL method using an experiment

In accordance with CFD analysis, we measure the capture efficiencies using the extrapolation method for the experiment and compare to those capture efficiencies obtained using the BL method. The extrapolation method has the advantage in adjustment of capture efficiency when it would suffer from overflowed contaminant. It takes somewhat too long measurement time to evaluate concentration decay after a termination. On the other hand, the BL method can be used to measure accurate capture efficiency in an environment free from elevated background concentration and measurement time is short. Therefore, we performed experiments to compare the capture efficiencies applying the extrapolating method and the BL method for various ceiling exhaust flow rate. If there is no difference in capture efficiencies, we may assume rise in background concentration is effectively suppressed by the ceiling exhaust. In the experiment, we examine 5 cases with a hood exhaust flow rate of 30 KQ and 40 KQ; hood velocity of 0.3 m/s, 0.4 m/s and 0.5 m/s, and ceiling exhaust flow rate of 400 m^3/h and 1000 m^3/h for each case.

5) Disturbances that can affect capture efficiency

We examined disturbance in 3 cases: air conditioning disturbances, human disturbances and non-disturbance. Air conditioning disturbances are supplied by the Anemo type diffuser in a fixed flow rate with horizontal supply angle. The supply air impinges on the hood and becomes a descending air flow and possibly produces disturbances around the hood. The air supply flow rate from the diffuser is fixed to control air speed at the bottom front edge of the hood at approximately 0.4 m/s reference the ASHRAE test standard (Figure 7). Next, we assumed panel movement (Figures 8, 9, and 10) that simulates disturbances involved with kitchen work as stipulated in the Nordtest [Nordtest method VVS-008, BUILDING (1990)]. The panels are 500 mm by 1,000 mm that run back and forth along a 1 m rail in 5 seconds. This simulates the movement of kitchen worker crossing in front of appliances. Table 4 shows the experiment. The used equipment is conventional type range and a low radiation type range.

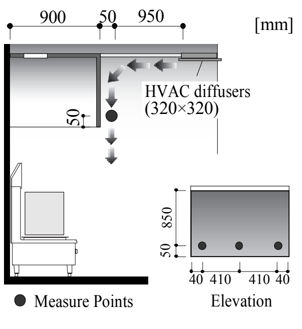


Figure 7 Air conditioning disturbance location

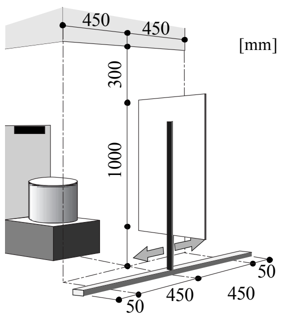


Figure 8 Disturbance generator

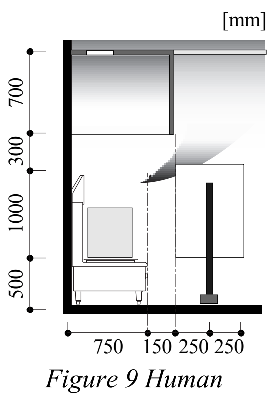


Figure 9 Human disturbance

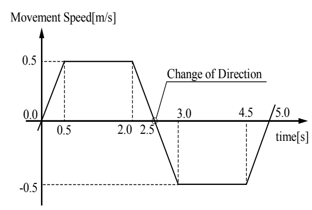


Figure 10 Movement speed

Table 4 Experiment cases

Item	Contents		
Disturbance environment	No disturbance	Air conditioning disturbance	Human disturbance
Appliance type	Conventional, low radiation type	Conventional, low radiation type	Conventional, low radiation type
Number of cases	6 cases in total		

RESULTS AND DISCUSSION

1) Laboratory experiment and CFD analysis

Figures 11 and 12 compare the results of the experiment and analysis. With a hood velocity of over 0.3 m/s, both experiment and analysis capture efficiency is approximately 100%. With a hood velocity under 0.3 m/s, capture efficiency decreases significantly, but waste gas capture efficiency remains considerably high in CFD compared to the experiment. This is probably due to inherent shortcomings of the k-ε turbulence model to underestimate lateral development of buoyant plume. Further study is clearly needed to apply CFD method to precise prediction of capture efficiency. In contrast, the experiment and CFD results tended to coincide well in both waste gas and cooking effluence as far as the general aspects of capture efficiencies are concerned, we decided to apply CFD model carefully to understand flow structure and contaminant dispersion process around commercial kitchen ventilation systems.

2) Examination of adequate ceiling exhaust flow rate through CFD analysis

Figure 13 shows the results. In conditions with the smaller hood exhaust flow rate of 20 KQ, there is a significant overflow. As ceiling exhaust flow rate decreases, capture efficiency appears to rise. This is due to recapture of contaminant overflowed from the hood. In contrast, in a case where the surrounding concentration is set to zero with the same hood exhaust flow rate of 20 KQ, capture efficiency is not affected by ceiling exhaust flow rate. From this, when only the direct capture efficiency is considered, we can see that capture efficiency is stable and is not affected by an increase in flow rate of displacement supply system. Additionally, comparing cases involving recapture and zero surrounding concentration under conditions of ceiling exhaust flow rate from 400 to 800 m^3/h, we see an increase in capture efficiency affected by recapture, but there is little effect on capture efficiency in cases with a ceiling exhaust flow rate over 1000 m^3/h (Figure 13). Also, for cases when hood velocity is 0.3 m/s and

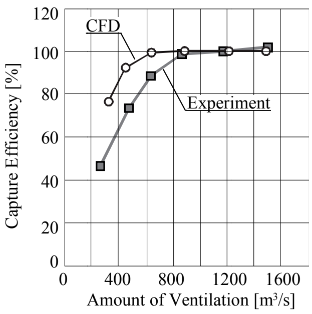


Figure 11 Waste gas capture efficiency without disturbance

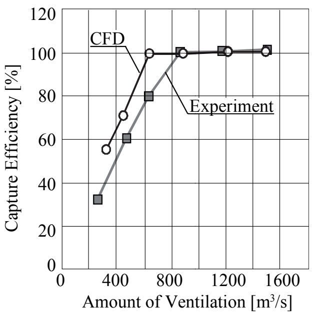
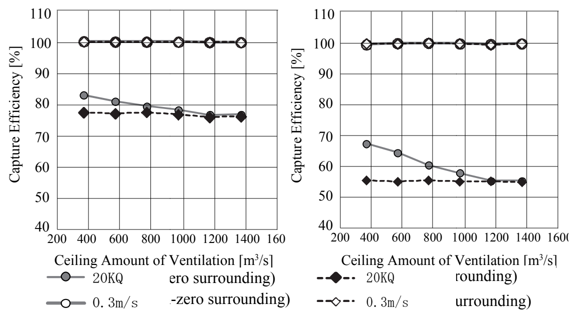
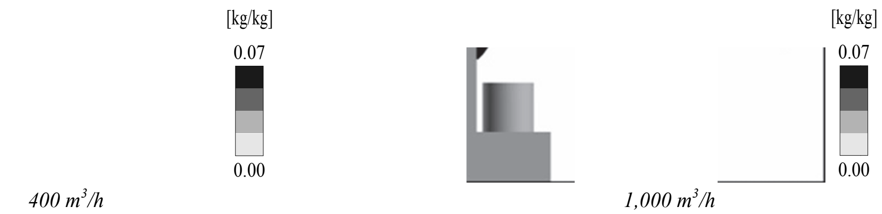


Figure 12 Cooking effluence capture efficiency without disturbance



(a) Waste gas (b) Cooking effluence

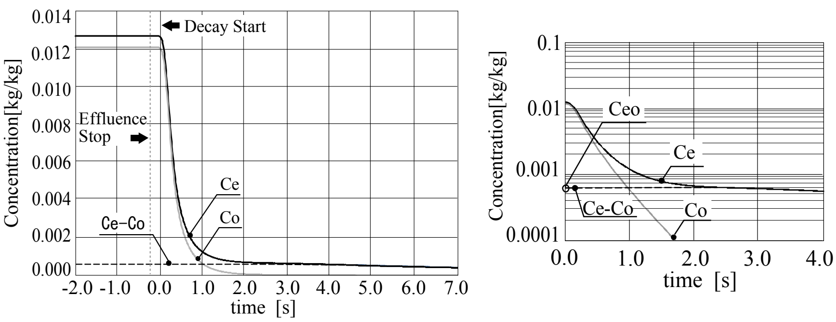
Figure 13 Capture efficiencies with and without surrounding contaminants



(a) Waste gas concentration distribution

(b) Cooking effluence concentration distribution

Figure 14 Contaminant concentration distribution for ceiling exhaust flow rate of 400 and 1,000 m^3/h



(a) Hood exhaust at 20 KQ, ceiling exhaust at 400 m^3/h

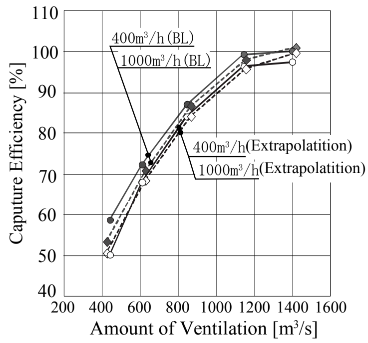
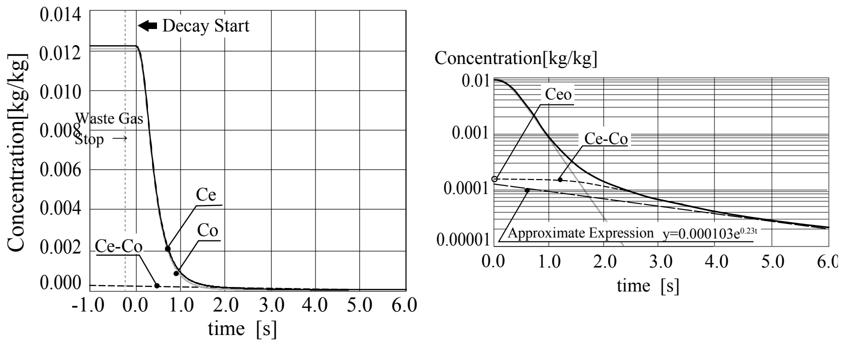


Figure 16 Capture efficiency (BL Method・extrapolating Method)



(b) Hood exhaust at 20KQ, ceiling exhaust at 1,000 m^3/h

Figure 15 Extrapolating method of secondary decay applied to CFD results

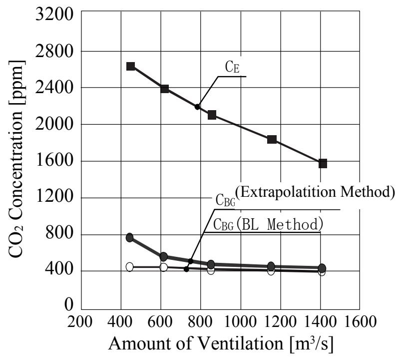


Figure 17 Concentration (Amount of Ventilation 400 m^3/h)

there is little overflow, little difference is seen when comparing to zero surrounding concentration cases. From this, in cases where capture efficiency is high, we cannot see a difference from the ceiling exhaust flow rate. When comparing the concentration distribution with ceiling exhaust flow rate of 1000 m^3/h and 400 m^3/h (Figure 14), we see the elevated concentration below the bottom of the hood for the latter case. These contaminants being recaptured by the hood is thought to be the cause of the rise in capture efficiency. Contrastingly, with a ceiling exhaust flow rate of 1000 m^3/h, we see the surrounding concentration increase is limited. From this, with a ceiling exhaust flow rate of 1000 m^3/h or larger, it is believed that background concentration increases due to overflowed contaminant can be avoided.

3) Extrapolation method of secondary decay applied to CFD results

Figure 15 shows the CFD analysis results, where Ce is the exhaust concentration with normal surrounding condition, Co is the exhaust concentration with zero surrounding condition, and thus Ce-Co is background concentration elevated by the overflowed contaminant. It should be noted that Ceo, which is Ce-Co at the start time of decay, indicates background concentration needed to calculate capture efficiency.

With a ceiling exhaust flow rate of 400 m^3/h, the exhaust concentration drops rapidly and shifts to stable condition for a while. This is due to the capture of contaminant existed in the near zone of the range hood, and dilution effect of supplied air has not yet reached in this region. In that case, the background concentration is kept constant from the beginning to the end of rapid drop of concentration. From this, when exhaust concentration remains nearly constant immediately after rapid drop, we assume this plateau level as the background concentration, which we use to calculate the capture efficiency.

In contrast, with a ceiling exhaust flow rate of 1000 m^3/h, after exhaust concentration decayed rapidly, the decay becomes gradual. This primary rapid decay is from the direct capture of the contaminants over the appliance and the gradual secondary decay is presumed due to the concentration outside the hood region. In regards to the background concentration decay, we see the decay of Ce-Co begins immediately after the stop of contaminant dose. Hence, we calculate the concentration at the beginning of concentration decay by exponential extrapolation of the secondary concentration decay. After estimating these background concentrations at the start time of decay, we see good correspondence of Ceo between actual and estimated values.

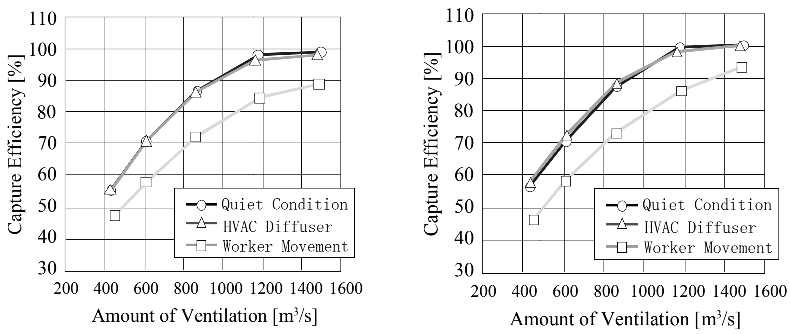
4) Comparison of the extrapolation method and BL method in the experiments

Extrapolation method and BL method capture efficiency measurements are given in Figure 16. In addition, the 400 m^3/h exhaust concentrations, background concentrations, and the assumed background concentrations calculated using the extrapolation method are shown in Figure 16. The capture efficiency obtained using the extrapolation method yielded virtually the same results for ceiling exhaust flow rates of 400 m^3/h and 1000 m^3/h. In case of exhaust flow rate of 400 m^3/h, there is an increase in background concentration due to overflow of contaminant. With the extrapolation method, we are able to calculate an accurate capture efficiency regardless of ceiling exhaust flow rates by estimating rise in background concentration (Figure 17). In contrast, when calculated using the BL method, capture efficiency became up to 9% higher for 400 m^3/h ceiling exhaust flow rate cases. This apparent increase in capture efficiency is due to background concentrations where the ceiling exhaust flow rate is not large enough to avoid overflvow and recapture. For cases where ceiling exhaust flow rate is 1000 m^3/h or above, problems from the use of the BL method are believed to be small because capture efficiency calculation results through the extrapolation method and BL method show little difference. From the above, we used displacement ventilation in the laboratory and we found that it was possible to perform accurate capture efficiency measurements from a ceiling exhaust flow rate set at 1000 m^3/h using capture efficiency measurements from the BL method. And so, for disturbed environment capture efficiency measurement we calculate the capture efficiency based upon 1000 m^3/h and the BL method.

5) Effects of disturbance on exhaust capture capability

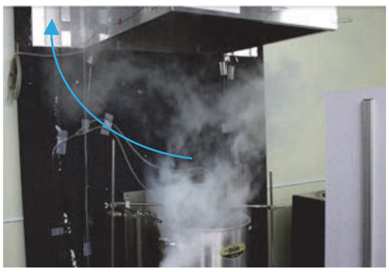
A flow visualization of air conditioning disturbances is shown in Figure 18. While air conditioning air flow forms downward flow after impinging on the hood surface it does not reach beyond the bottom edge of the hood, and does not form downdraft to induce buoyant plume from the appliance. Hence, we find that the air conditioning supply disturbances do not affect hood capture performance. In contrast, flow visualization of human disturbances is shown in Figure 19. The panels move left and right in front of the appliances, inducing hood internal air with them, and we find that the plume flow appeared to overflow at the sides of the hood. Based upon the above results, conventional and low radiation type appliance measurement results are shown in Figures 20 and 21. The capture efficiency from air conditioning disturbances for both conventional and low radiation types show no discrepancy with non-disturbed capture efficiency results. This matches the flow visualization of the observed results, and shows that there is no effect on capture efficiency in this measurement environment. With human disturbances, there is a significant decrease in waste gas capture efficiency and cooking effluence for conventional appliances. This is believed to be because panel movement draws the plume left and right and overflows before it is captured by the hood. In contrast, for low radiation type appliances, the capture efficiency for waste gas does not markedly decrease. This is due to the exhaust of waste gas being concentrated at the upper or

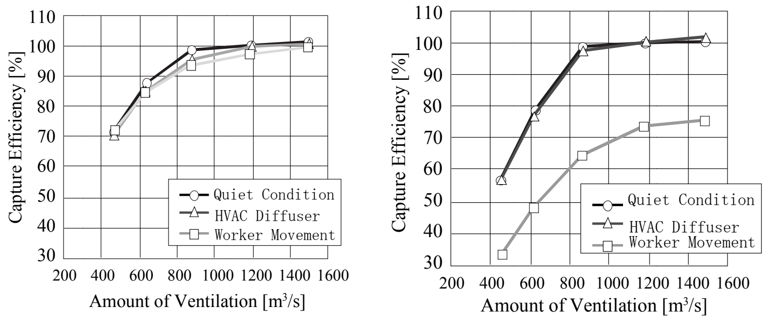
Figure 18 Air conditioning disturbance visualization



(a) Waste gas
(b) Cooking effluence

Figure 20 Capture efficiency-Conventional equipment





(a) Waste gas
(b) Cooking effluence

rear portion of the appliance, and not likely to be easily affected by disturbance. In contrast, cooking effluence capture efficiency from low radiation type appliances decreases considerably. This is because there is no high temperature updraft surrounding cooking effluence in the low radiation type appliances and weak updraft from boiling water surface is easily affected by disturbance.

CONCLUSION

A summary of the general findings of this study is as follows.

- We developed a method to measure capture efficiency of commercial kitchen ventilation system for enclosed space where elevated background concentration is estimated by extrapolation method of secondary decay in hood exhaust air concentration, and the availability of this method was confirmed in both laboratory tests and CFD simulations.
- In the tested laboratory, we undertook displacement ventilation and found that if there is a ceiling exhaust flow rate of 1000m^3/h or greater, there was no significant difference in the results for capture efficiency through the BL method and extrapolation method.
- CFD predictions revealed that actual capture efficiencies are virtually not affected by the flow rate of displacement diffusers in the range that we tested in the experiment, but CFD prediction of capture efficiency was somewhat too high when hood exhaust flow rate was relatively low. Further improvement of CFD is needed.
- Disturbances of 0.4m/s at the bottom of hood induced by anemo type diffuser for air conditioning exerted little influence on capture efficiency both for waste gas and cooking effluence.
- Low radiation type appliance was effective to suppress reductions of capture functions for combustion waste gas through human disturbance due to the concentrated combustion gas flue. On the other hand, capture functions for cooking effluence have greatly reduced for the weak updraft from boiling water surface.

ACKNOWLEDGEMENT

This study was made possible by the financial support received from Tokyo Gas Co., Ltd., Japan. Moreover, we would like to thank the staff of Tokyo Gas Co., Ltd. for their generous cooperation.

REFERENCES

Center for Better Living (2006), Ventilation Units (for Kitchen Use), Methods of Testing Performance of Quality Housing Components, BLT VU-1: 2005 (In Japanese)

Hitoshi. S., Takashi K., Yoshihiro T. and Takeshi. O. : Enhanced Thermal Environment And Energy Saving performance of commercial kitchen with low radiation cooking equipment, Ventilation 2012, Paris, France.

Menter F. R., 1993. Zonal two equation k-ω turbulence models for aerodynamic flows, AIAA Paper 93-2906.

Menter F. R., 1994. Two-equation eddy-viscosity turbulence models for engineering applications, AIAA Journal, vol. 32, no 8. pp. 1598-1605.

Nordtest method VVS-008. BUILDING. 1990. Large scale kitchin rangehoods – hood efficiency and pressure drop.

Toyomura K., Kotani H., Yamanaka T., Momoi Y., Sagara K. and Takano S. : CFD Analysis on Capture Efficiency in Commercial Kitchen using Low Radiative Cooking Equipment with Concentrated Exhaust Chimney, AIVC International Conference 2010, D-3, 2010.10, Seoul, Korea.