CFD Analysis on Capture Efficiency in Commercial Kitchen using Low Radiative Cooking Equipment with Concentrated Exhaust Chimney

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Abstract

In a commercial kitchen, a large ventilation rate is needed and energy consumption can be large because a large amount of effluence of heat and moisture need to be removed. To improve kitchen environment and to save the energy, low radiative cooking equipment with concentrated exhaust chimney was developed. Although a ventilation rate may be decreased by using this equipment, the effluence needs to be captured well. To predict indoor air and thermal environment of commercial kitchen using this equipment, CFD analysis is useful. In the previous study, the capture efficiency of the hood was measured when this new equipment is used. In this paper, CFD simulation was carried out in order to analyze capture efficiency of the equipment with reproducing the measurement. CFD results of various conditions were compared with measured ones. CFD results were agreed well with measured ones for many cases.

Keywords: *Commercial Kitchen Ventilation, CFD Analysis, Capture Efficiency, Combustion Gas, Cooking Effluence*

Introduction

In commercial kitchen, a large amount of heat and moisture are generated and they must be removed. Since the gas cooking equipment involves combustion, a kitchen in which gas cooking equipment is used requires sufficient supply of oxygen for the combustion process. Hence, a large ventilation rate is required to meet the combustion and ventilation requirements resulting in high energy consumption.

A performance of the exhaust hood is important to remove contaminant and keep good air quality. The capture efficiency of hood has been examined previously under various room conditions. For example, Wolbrink and Sarnosky [1] defined capture efficiency as the ratio of moisture captured by the hood to moisture produced by the source. Li et al.[2] proposed new definition of capture efficiency which includes the air exchange between the cooking zone and the room zone in a two-zone mixing model. The capture efficiency of the standard canopy hood for exhaust gas and contaminant generated by cooking above the commercial cooking stoves and fryers were measured on two kinds of heat sources of natural gas and electromagnetic heat by Yamanaka et al.[3]. In addition, Momose et al.[4] investigated the influence of a moving person on the capture efficiency.

Recently, low radiative cooking equipment with concentrated exhaust chimney has been developed to improve the kitchen environment and conserve the HVAC energy requirements. A cross-section of the low radiative equipment is shown in **Fig.1**. The low radiative equipment has two advantages. Firstly, the surface temperature of the equipment is lower than that of the conventional equipment. This reduces radiation heat emission toward workers and room surface. Secondly, generated combustion gas is exhausted effectively by using concentrated exhaust chimney. This reduces the diffusion and overflow of effluences to the room, which also contains the heat and CO2 waste gas from combustion. Consequently, the required exhaust flow rate can be reduced by these advantages. Although a ventilation rate may be decreased by using this equipment, there is no design guideline of ventilation system under operation of this type of equipment. Therefore the purpose of this study is to prove the ventilation performance of these equipments, and build up a design guideline of ventilation system under operation of them. To predict indoor air and thermal environment of commercial kitchen using this equipment, Computational Fluid Dynamics (CFD) analysis is useful. Authors [5] carried out CFD analysis on capture efficiency of the canopy hood for combustion gas and cooking effluence under operation of one kind of equipment operating in a laboratory. However, the simulation accuracy of exhaust plume was not so high suspect. Authors [6] also carried out simplified CFD analysis on indoor thermal environment under operation of three kinds of equipment operating in a room. However, this analysis disagrees with experimental result [5] due to the error in the boundary conditions. In this paper, first we carried out CFD analysis on capture efficiency of the canopy hood under operation of one kind of equipment in a large laboratory. We used measured data of exhaust air [7] and temperature [8] as boundary conditions of the analysis. Comparing with experimental result [5], simulation accuracy is checked. Secondly applying these boundary conditions, we carried out CFD analysis on indoor thermal environment under operation of three kinds of equipment operating in a room which has supply and exhaust air like a real kitchen.

1. CFD Analysis on Capture Efficiency of the Hood in Large Space

1.1 Outline

CFD simulation was carried out in order to analyze the capture efficiency of the hood for combustion gas and cooking effluence under operation of one kind of the low radiative equipment in a laboratory. The laboratory measurements were carried out by Authors [5]. CFD outline is shown in **Table 1**.

1.2 Methods

As an analyzed room, experiment room of the study is simulated. The experimental space is in large of experimental building and the leakage from the hood is exhausted at ceiling height around the hood and it doesn’t capture again. Analyzed room is shown in **Fig.2-Fig.3**. The applications used for this analysis were low radiative range, fryer and kettle. A calculated domain is 4600*4200*3000mm space including a 1200*1200*500mm (2400*1200*500 in the case of kettle) canopy-type exhaust hood in the center. The height of the bottom of the hood is 2000mm. This is common used in the real kitchen. Each application is set under the center of hood. Initial Setting of indoor air temperature is 20 deg.C.

The standard k-ε model (SKE) and RNG k- ε model (RNG) are used as turbulence model. In order to exhaust contaminant from cooking equipment, the hood has a exhaust opening (300*300mm) at the center in the case of range and fryer, and it has two of them in the case of kettle. Assuming that the leakage from the hood is exhausted at ceiling height around the hood, the pressure at ceiling height is fixed as 0 Pa. The air is supplied from the lower part of surroundings walls (from floor to height 800mm). Supply air flow rate is 2 times of exhaust flow rate from exhaust opening at hood. As for the wall boundary condition, the generalized log law was applied for the velocity and adiabatic for thermal condition. Boundary conditions of the room are shown in **Table 2**. This CFD analysis was carried out under five conditions of exhaust flow rate, that is 20KQ (Case1), 30KQ (Case2), 40KQ (Case3), 0.3m/s of the face velocity at the bottom of the hood (Case4) and 0.4m/s of the face velocity (Case5) for each item of equipment. This method conforms to BL method [9] and is authorized as standard measuring method to determine the capture efficiency of a hood in JAPAN. Where, K is the Theoretical combustion gas flow rate per input [m3/(h・KW)] and Q is the gas input[KW]. These conditions are the same as the previous experiment. The analyzed exhaust and supply flow rate are shown in **Table 3**.

1.3 Boundary Conditions of the Equipments

The equipment models are shown in **Fig.4**. Boundary conditions of temperatures of cooking equipment surface, water vapor from the cooking pot and exhaust air from the exhaust opening were applied to the analysis. Since the radiative heat is very small compared to other heat transfer, it is not considered in this analysis. Air flow rate and temperature of combustion gas and ambient air to cool the equipment is based on the measurements. Latent heat of vaporization is calculated based on measured amount of vapor generation rate from the water per hour. Temperatures of cooking equipment surface were based on measured data. These boundary conditions of the equipment were shown in **Table 4-Table 6**.

2. CFD Analysis on Indoor Thermal Environment

2.1 Outline

CFD simulation was carried out in order to analyze indoor thermal environment of the room that three kinds of the low radiative cooking equipments with concentrated exhaust chimney are operated. The laboratory measurements were carried out by Authors [10]. By comparing CFD to Experiment, we validate the accuracy of CFD simulation. CFD outline is shown in **Table 7.**

2.2 Method

As an analyzed room, experimental room of the previous study is simulated. A plan, cross-section and perspective drawing of the analyzed room are shown in **Fig.5**. In the room of 4500*3500*2500mm, a low radiative kettle, range and fryer are installed from the left. Boundary conditions of the each equipment are the same as chapter 1 (see **Table 4-Table 6**). The air is supplied from the three ceiling inlets and exhausted from three exhaust openings (350*350mm) of the hood (900*3500mm).

SKE is used as turbulence model. As for the wall boundary condition, the generalized log law was applied for the velocity and surface temperatures were based on measured data [10]. Simulation conditions of the equipment are shown in **Table 4-Table 6**. This CFD analysis was carried out under five conditions of exhaust flow rate, that is 20KQ (Case1), 30KQ (Case2), 40KQ (Case3) and 0.3m/s of the face velocity at the bottom of the hood (Case4) which is same as the experiment of the previous study TAKANO el at. [10]. The analyzed exhaust and supply flow rate are shown in **Table 8**.

3. Result and Discussion

3.1 Capture Efficiency of the Hood in Large Space

The capture efficiency η is calculated as follows.

$$\eta = \frac{Q_H}{Q_H + Q_c} \quad \text{(Eq.1)}$$

Where

Q_H: Contaminant flow rate exhausted through the hood [kg/s]

Q_c: Contaminant flow rate exhausted at ceiling height around the hood [kg/s]

In order to obtain capture efficiency, passive contaminants are released from a cooking pot as cooking effluence and from exhaust opening of the equipments as combustion gas. The capture efficiency obtained from CFD analysis and experimental is shown in **Fig.6**. With regard to CFD analysis result of both SKE and RNG, the capture efficiency of combustion gas (η_{gas}) and cooking effluence (η_{cook}) in the cases over Case4 of all equipments is 100%. This agrees with the experiment result. In addition, both η_{gas} and η_{cook} of RNG are higher than that of SKE. This is because that as to SKE, an updraft from the pot tends to spread water-vapor into the air. As for η_{cook} of Kettle for Case1-Case3, RNG agrees with the experimental result very well. As for η_{gas} of Kettle for Case1-Case3, however, both SKE and RNG are lower than experimental result. In comparison with SKE, RNG is close to experimental result. In general, SKE overestimates turbulence kinematic energy k around impinging stream [11]. In this simulation of the kettle, SKE overestimates turbulence kinematic energy k around a top panel of the hood. As for η_{gas} and η_{cook} of range for Case1-Case3, SKE and RNG are slightly higher than experimental result, but these can follow the experimental tendency. Flow rate exhausted from exhaust chimney opening may be overestimated. As for η_{gas} and η_{cook} of fryer for Case1-Case3, SKE agrees with the experimental result very well and RNG is slightly higher than experimental result. However, experimental result are not so accurate between Case3 (311m3/h) and Case4 (1512m3/h). This is because that experimental result has no data between them and it is largely-spaced (see **Fig.6**). Further measurements will be needed in the future. If it is assumed that measured data is higher than linearly-interpolated line between them, RNG may agree with experimental result.

In conclusion, some disagreements were seen due to the error in the boundary conditions or the turbulence model, but capture efficiency by CFD were agreed well with measured results for many cases. Thus, it seems that CFD model for each equipment in this section is faithful.

3.2 Indoor thermal environment

The vertical distributions of temperature in A-A', B-B' and C-C' section (see **Fig.5**) of CFD simulation and measure data [10] are shown in **Fig.7**. As for all exhaust flow rates, the larger exhaust rate is, the lower indoor air temperature is and the smaller air temperature difference between the top and the bottom of the room is. These agree with the experimental result very well. This is because that the amount of heat removed from the room by the hood depends on exhaust rate. Especially, as to low exhaust flow rate, room air temperature of upper area is high due to a lot of heat leakage from the hood. This indicates that we can estimate indoor thermal environment in the room accurately. To estimate them accurately, we can use section the data of 3.1 (see **Table 4-Table 6**) for boundary conditions of these equipments.

Experimental measurement point of temperature is shown in **Fig.8** and correlation charts between CFD temperature and experiment temperature are shown in **Fig.9**. As for most points, error is from -2deg.C to +2deg.C, and CFD is broadly consistent with experiment. As for some points of low temperature zone, temperature of CFD is lower than that of experiment. These points are close to the equipments. A minor change in the air movement may have significant effect upon the temperature, so the future researches are needed. **Fig.10** shows the vertical temperature distribution of the room that is the average of the measurement points with the same height. CFD is consistent with experiment well. Although, as to the lower area, temperature of CFD is a slightly lower than that of experiment, this is the same tendency as shown in **Fig.9**.

Conclusions

In this paper, two CFD simulations are carried in order to estimate capture efficiency of the hood and indoor thermal environment in the room operated the low radiative cooking equipments with concentrated exhaust chimney. By comparing the CFD result with the past experimental result, the paper indicates that the CFD conditions of the equipment in this paper are faithful, and we can estimate indoor thermal environment accurately in the room operated the low radiative cooking equipments with concentrated exhaust chimney by using them.

Acknowledgments

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References

1. Wolbrink, D. W., Sarnosky, J. R. Residental Kitchen Ventilation – a guide for the specifying engineer. ,ASHRAE Transactions 98(1), pp.1219-1226, 1992

2. Li, Y., Delsante, A. Derivation of Capture Efficiency of Kitchen Range Hoods in a Confined Space. ,Building and Environment, Vol.31, No. 5, pp. 461-468, 1996

3.Yamanaka, T., Satoh, R., Kotani, H., Momose, T., and Tanaka, R. Capture Efficiency of Exhaust Hood above Cooking Stoves and Fryer under Horizontal Disturbing Airflow in Commercial Kitchen. Proce edings of Healthy Buildings 2000, vol.2:719-724, 2000

4. Momose, T., Satoh, R., Yamanaka, T., and Kotani, H. Influence of Air Current and Movement of A Person on Capture Efficiency of Kitchen Hood. Proceedings of Healthy Buildings 2000, vol.2:713-718E, 2000

5. S. Takano, T. Yamanaka, H. Kotani, K. Sagara, Y. Momoi, and C. Iwasaki , Capture Efficiency of Exhaust Hood for Commercial Kitchen using Low Radiation Cooking Equipment with Concentrated Exhaust, Ventilation 2009, the 9th International Conference on Industrial Ventilation In CD-ROM Paper 1039 2009.10

6. S. Takano, K. Sagara, T. Yamanaka, H. Kotani, Capture Efficiency and Indoor Thermal Environment inside Commercial Kitchen using Low Radiative Cooking Equipment with Concentrated Exhaust Part.2 CFD Analysis on Indoor Thermal Environment, Technical Papers of Annual Meeting, The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, pp.1061-1064, 2008.8 (In Japanese)

7. K. Toyomura, T. Yamanaka, H. Kotani, Y. Momoi, K.Sagara and S. Takano, Indoor Air and Thermal Environment of Commercial Kitchen using Low Radiative Cooking Equipment with Concentrated Exhaust Part 5.Air Flow around exhaust stack for boundary conditions of CFD analysis, Technical Papers of Annual Meeting, Kinki Branch of The

Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, pp.57-60 2010.03 (In Japanese)

8. K. Toyomura, H. Kotani , T. Yamanaka , Y. Momoi, K. Sagara, Capture Efficiency and Indoor Thermal Environment inside Commercial Kitchen using Low Radiative Cooking Equipment with Concentrated Exhaust Part.6 CFD Analysis based on measured data of exhaust air, Technical Papers of Annual Meeting, The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, 2010.9 (Pre-publication, In Japanese)

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

10. S. Takano, K. Sagara, T. Yamanaka, H. Kotani, S. Chihara, Capture Efficiency and Indoor Thermal Environment inside Commercial Kitchen using Low Radiative Cooking Equipment with concentrated Exhaust,Advanced building ventilation and environmental technology for addressing climate change issues, Volume1, pp.171-176,2008.10

11. S. Murakami, A. Mochida, Y. Hayashi, S. Sakamoto, Numerical Study on velocity-pressure field and wind forces for bluff bodies by k-ε, ASM and LES, 8th International Conference on Wind Engineering, 1991.07

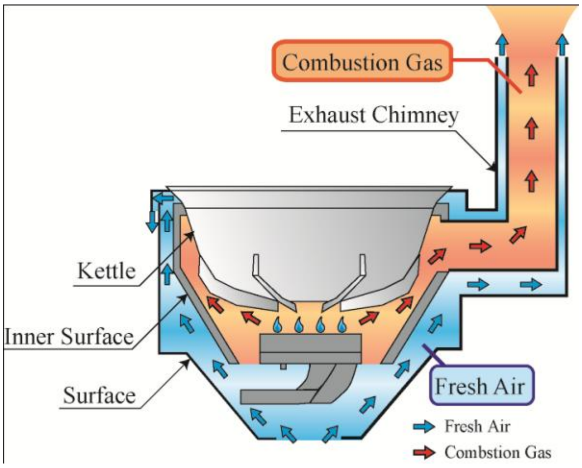


Fig.1 Outline of Low Radiative Cooking Equipment
(Example of Kettle)

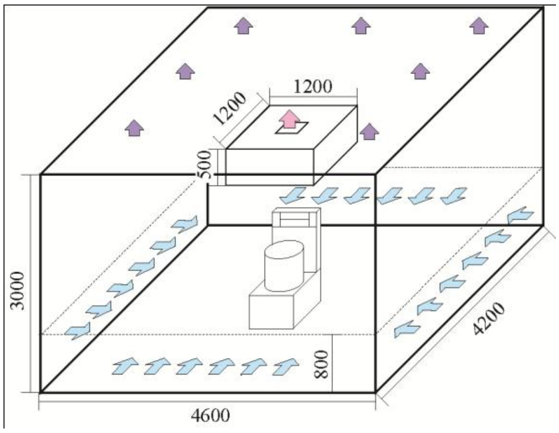


Fig.2 Analysis Room
(Overall View)

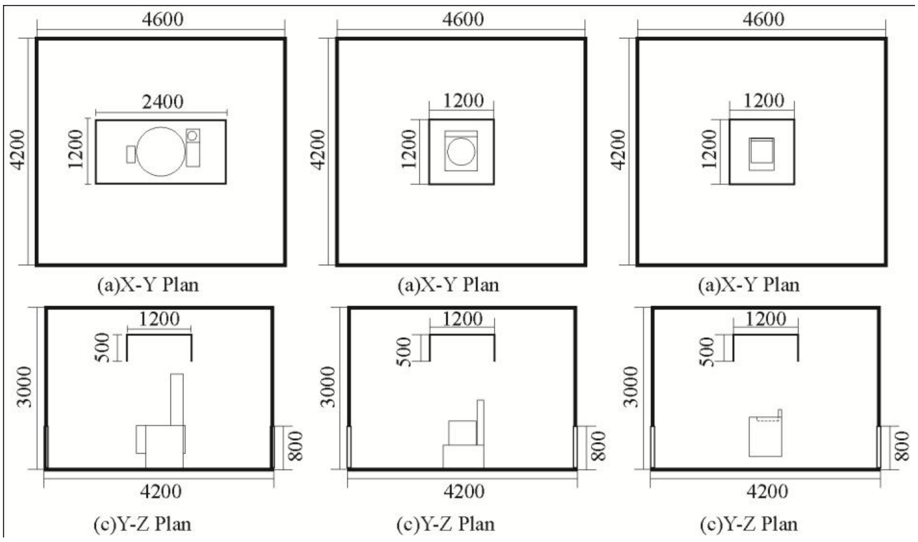
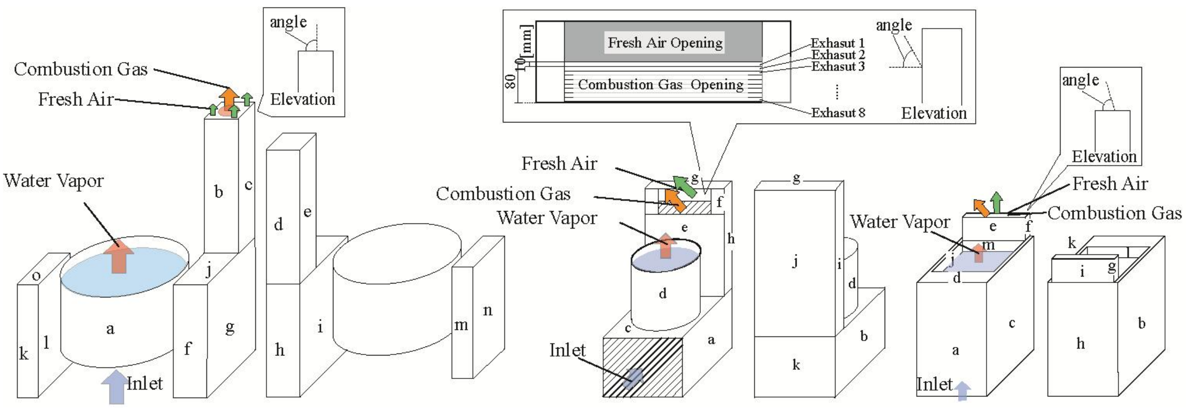


Fig.3 Analysis Room
(Plan and Section)



(a)Kettle (b)Range (c)Fryer

Fig.4 Equipment Conditions

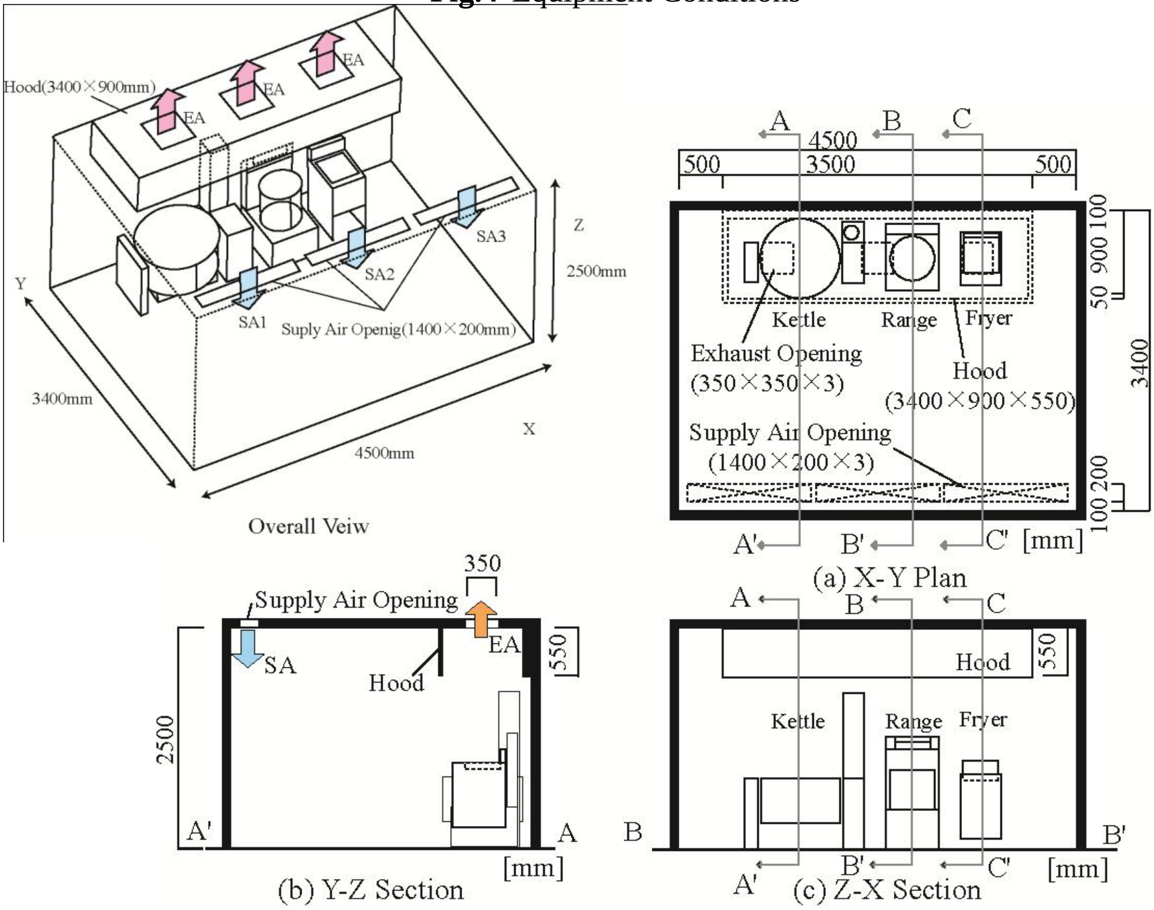


Fig.5 Analysis Room

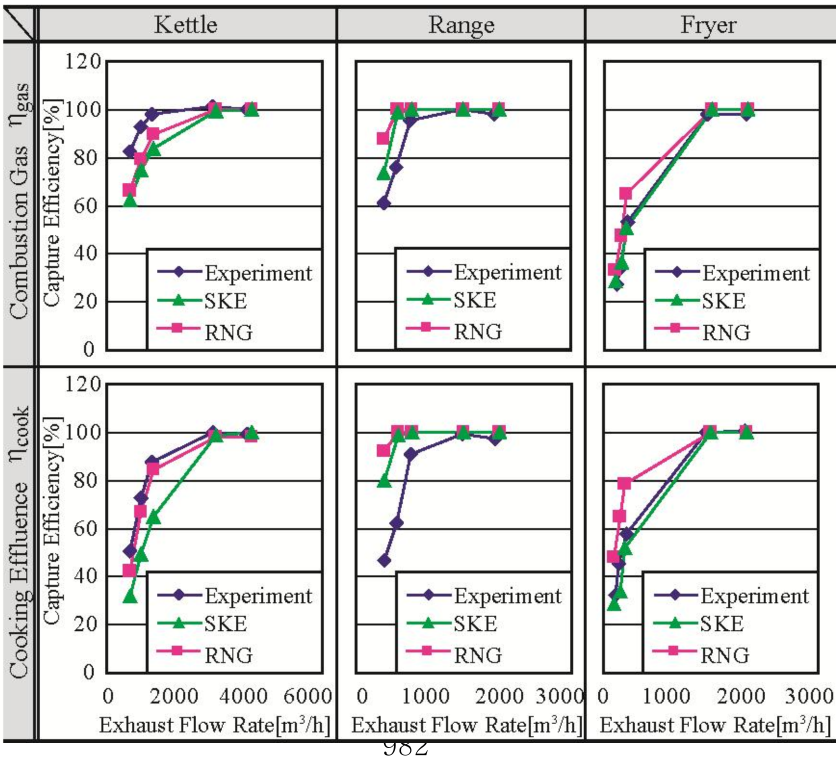


Fig.6 Capture Efficiency
Comparison of CFD Analysis and Experiment

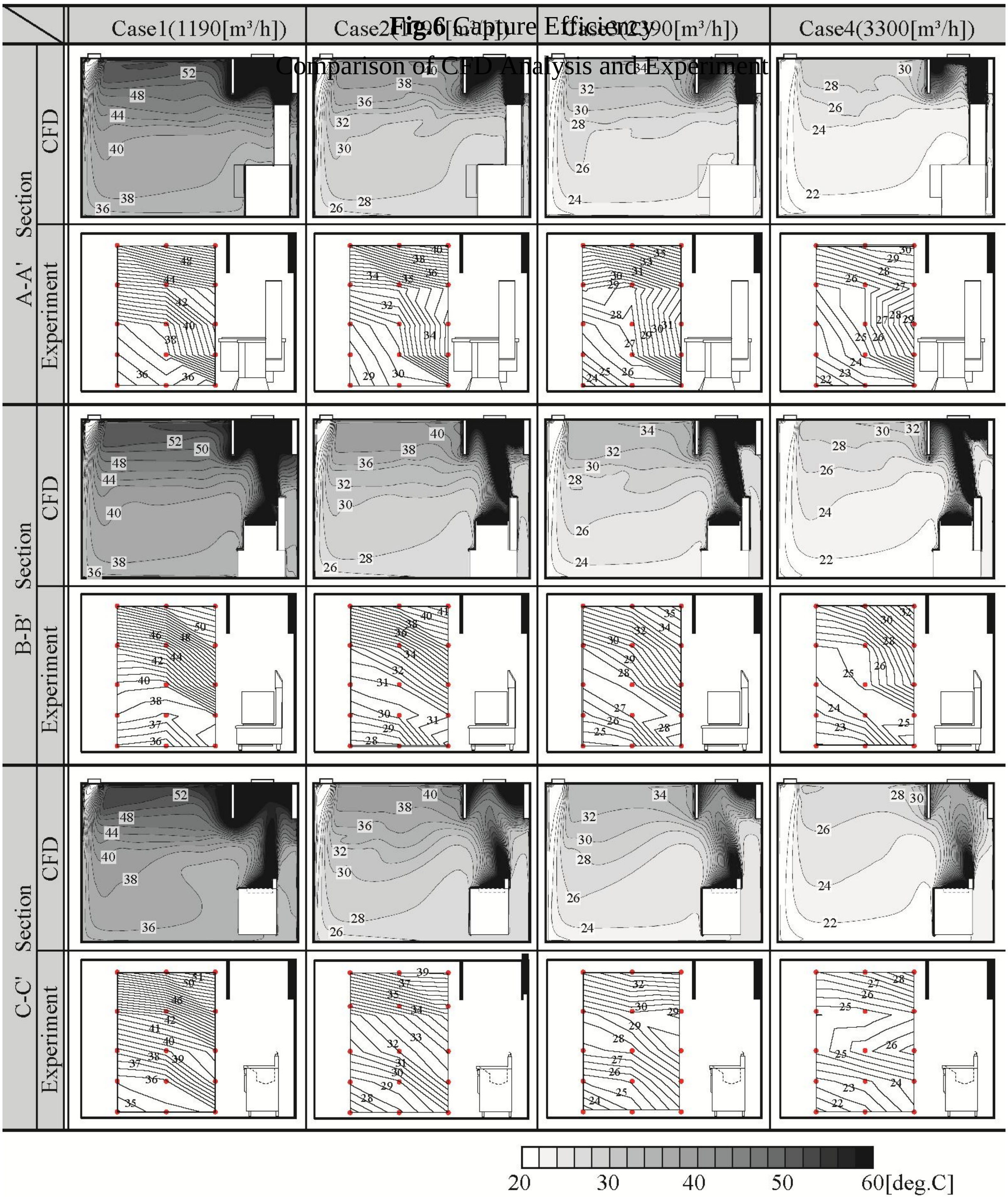


Fig.7 Vertical Distributions of Temperature in A-A', B-B' and C-C' Section
Comparison of CFD Analysis and Experiment

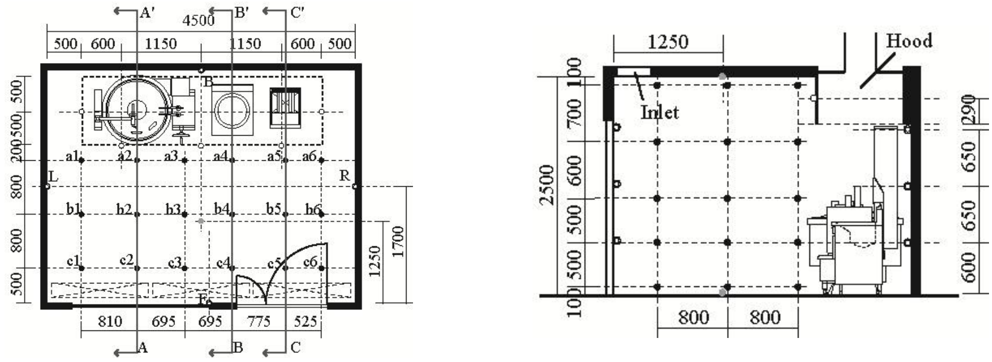


Fig.8 Experimental Measurement Point of Temperature

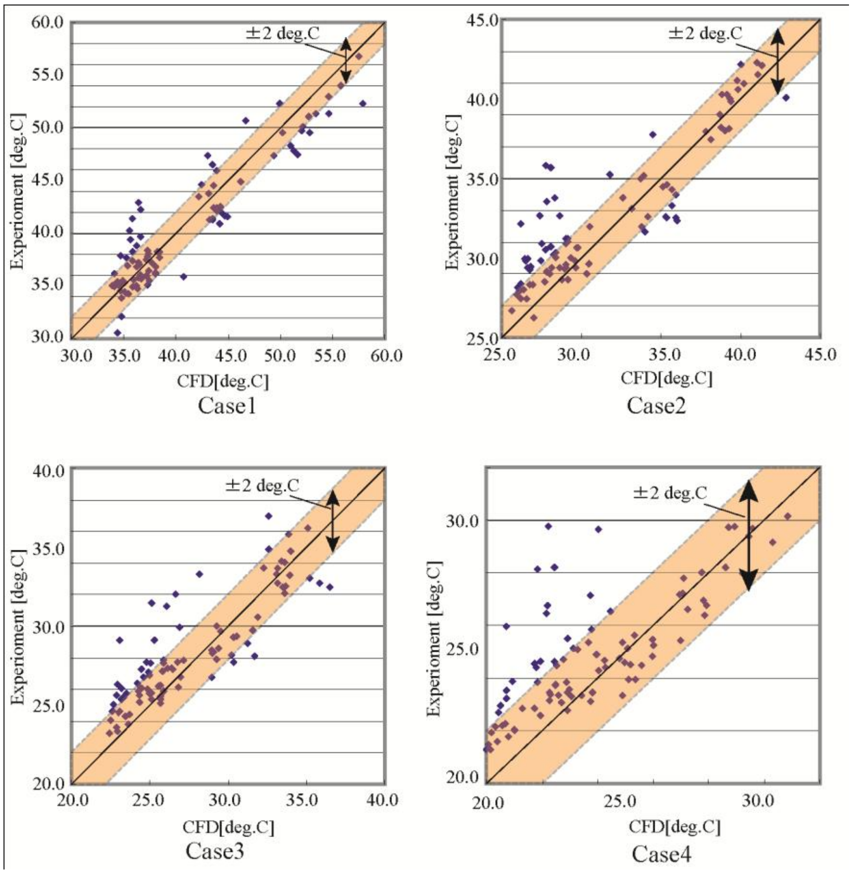


Fig.9 Correlation Chart between CFD and Experiment

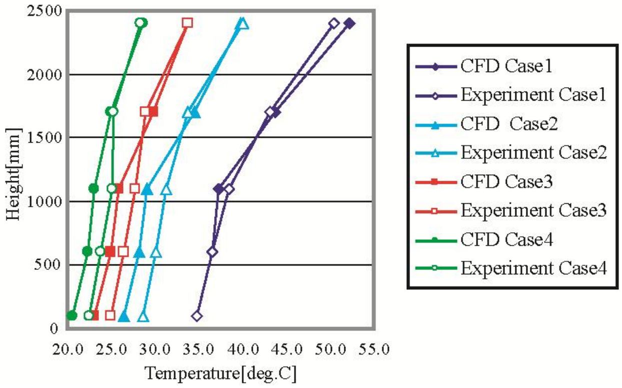


Fig.10 Vertical Temperature Distribution (Plane Measurement Point Average)

Table 1 CFD Outline

CFD code	Fluent 6.3
Turbulence Model	Standard k-ε Model
	RNG k-ε Model
Algolism	SIMPLE
Discretization Scheme	QUICK
Calculated Domain	4600*4200*3000mm

Table 2 Boundary Conditions of Room

Supply and Exhaust Flow	Inlet	θ=293.15[K], See Table 3
	Outlet	See Table 3
	Ceiling	Pressure 0 Pa
Wall		Generalized log law Adiabatic

Table 3 Parameter of Supply and Exhaust Flow Rate

		Exhaust Flow Rate of Hood[m³/h]	Supply Flow Rate[m³/h]
Kettle	Case1-K	649.1	1298.3
	Case2-K	973.7	1947.4
	Case3-K	1298.3	2596.6
	Case4-K	3033.1	6066.1
	Case5-K	4044.1	8088.2
Range	Case1-R	388.7	777.5
	Case2-R	583.1	1166.2
	Case3-R	777.5	1555.0
	Case4-R	1503.8	3007.6
	Case5-R	2005.1	4010.1
Fryer	Case1-F	155.7	311.4
	Case2-F	233.5	467.0
	Case3-F	311.4	622.7
	Case4-F	1503.8	3007.6
	Case5-F	2005.1	4010.1

Table 4 Surface Temperatures of Equipments

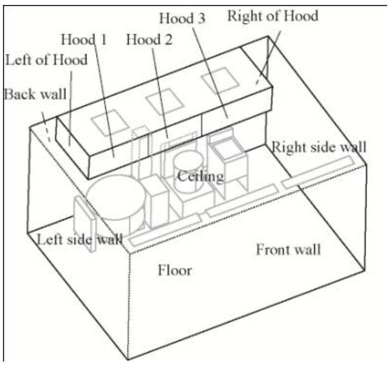
		temperautre[K]
Kettle	a	312.89
	b - e	309.19
	f - o	295.09
Range	a,b	311.26
	c	332.43
	d	372.73
	e	387.16
	f	340.55
	h	321.93
	g	317.80
	i	321.93
	j	308.10
	k	297.97
Fryer	a	309.20
	b,c	313.11
	d	337.36
	e	312.19
	f,g	316.98
	h	298.60
	i	309.98
	j -1	337.04

Table 5 Inlet Conditions of Equipment

		Velocity[m/s]	k[m²/s²]	ε[m²/s³]	Angle[°]	Temperature[K]	Length[m]
Kettle	Combustion Gas	3.07	9.41E-02	8.11E-01	90	662.09	0.08
	Fresh Air	0.68	4.61E-03	2.93E-03	90	339.08	0.24
	Inlet	0.14	1.88E-04	6.42E-06			0.9
	Pot	0.0217	4.72E-06	2.67E-08	90	373.15	0.9
Range	Combustion Gas	※See Table 6			60.00	698.57	0.08
	Fresh Air	0.68	4.62E-03	1.01E-02	54.32	351.92	0.07
	Inlet	0.15	2.18E-04	1.40E-05			0.51
	Pot	0.0224	5.02E-06	5.29E-08	90	373.15	0.5
Fryer	Combustion Gas	0.93	8.68E-03	4.04E-02	57.43	409.87	0.045
	Fresh Air	0.44	1.90E-03	1.25E-02	90	340.57	0.015
	Inlet	0.07	4.93E-05	1.50E-06			0.52
	Pot	0.0233	5.41E-06	7.38E-08	90	373.15	0.4

Table 6 Exhaust Conditions of Range

	Velocity[m/s]	$k[m^2/s^2]$	$\varepsilon[m^2/s^3]$
Exhaust 1	5.04	2.54E-01	3.75E+00
Exhaust 2	3.98	1.58E-01	1.85E+00
Exhaust 3	2.91	8.48E-02	7.24E-01
Exhaust 4	1.83	3.36E-02	1.81E-01
Exhaust 5	0.69	4.70E-03	9.46E-03
Exhaust 6	0	0	0
Exhaust 7	0	0	0
Exhaust 8	0	0	0



Name of the Surface

Table 7 CFD Outline

CFD code	Fluent 6.3
Turbulence Model	Standard k-ε Model
Algolism	SIMPLE
Discretization Scheme	QUICK
Calculated Domain	4500*3400*2500mm

Table 8 Parameter Supply and Exhaust Flow Rate

Supply Air Temperature[deg.C]		18
Exhaust Flow Rate $[m^3/h]$	Case1	1190
	Case2	1790
	Case3	2390
	Case4	4400

Table 9 Surface Temperatures of Room

Wall name	Height	Case1 [deg.C]	Case2 [deg.C]	Case3 [deg.C]	Case4 [deg.C]
Left side wall	1590-2500mm	40.1	31.3	25.6	22.7
	900-1590mm	33.9	26.9	25.1	22.5
	0-900mm	31.7	26.2	24.3	21.9
Right side wall	1590-2500mm	42.5	32.6	28.6	25.7
	900-1590mm	38.3	31.0	27.8	25.1
	0-900mm	35.1	28.9	25.7	23.3
Front wall	1590-2500mm	36.9	28.6	25.2	22.1
	900-1590mm	34.2	27.3	24.5	21.9
	0-900mm	32.9	26.8	24.1	21.5
Back wall	1590-2500mm	48.2	39.4	35.1	32.1
	900-1590mm	40.2	34.8	32.9	29.1
	0-900mm	36.3	31.1	29.7	26.3
Left of Hood		58.6	45.8	40.1	32.1
Hood 1		57.2	44.2	37.9	31.4
Hood 2		66.9	55.8	50.2	44.3
Hood 3		65.8	53.8	46.5	42.6
Right of Hood		68.3	52.8	43.8	37.1
Ceiling		40.7	34.4	31.6	27.6
Floor		28.9	26.4	25.8	24.6