Experimental Study on Ventilation Efficiency in Commercial Kitchens

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ABSTRACT

This paper describes the experimental study of ventilation efficiency for commercial kitchens. We investigated an air conditioning and ventilation system which has high efficiency and which can maintain a comfortable environment in the working space with a minimum amount of necessary ventilation air.

The results are as follows:

(1) In the case of outdoor-air being supplied from the hood, 60-70% of the outdoor-air is exhausted by the hood.

(2) Air-flow distribution above the gas range is comparatively stable except in winter, updraft above the gas range flows straight to the exhaust hood when outdoor-air is supplied from the gas range. In winter, updraft above the gas range is strongly effected by the outdoor-air from the hood, and there is dispersion in the updraft direction.

(3) Capture ratio of the combustion gas by the exhaust hood is over 80% except in winter.

Capture ratio is increased when the caloric output of the gas range is larger.

KEYWORDS

Distribution rate of outdoor-air, Capture rate of the combustion gas, Commercial kitchen.

1. INTRODUCTION

It is important to effectively exhaust thermal energy from commercial kitchens, blast furnaces, glass factories and other high temperature heat sources. An air conditioning system is necessary in such places to make a thermally comfortable environment in the working space. When combustion utensils are used, it is necessary to supply oxygen for the combustion of gas. Therefore a large quantity of outdoor-air is required to be brought to the inside, and this influences the thermal and air quality environments of the working space in summer and winter seasons. Furthermore, it causes air conditioning to be less efficient. In spaces like a commercial kitchen where air conditioners have to keep the environment comfortable in spite of a large quantity of ventilation, there are two problems from the viewpoint of comfort and saving energy.

(1) The thermal environment becomes worse if the outdoor-air is supplied directly to the working space without air conditioning, though it saves energy

(2) If temperature controlled outdoor-air is supplied to the working space, loads on the air conditioner increase, though the comfort of the working space improves.

In a commercial kitchen the ventilation and air conditioning systems must not be designed separately. It must be designed in coordinated consideration of the position of the supply outlet of the air conditioner, the position of the outdoor-air supply outlet and the capture efficiency of the exhaust hood.

In this paper, we investigate an air conditioning and ventilation system which has high efficiency and which can maintain a comfortable environment in the working space with a minimum amount of necessary ventilation air. The full-size experiment was carried out using a model of a commercial kitchen, measuring air-flow distribution in the working space and above the gas range, as well as exhaust air capture efficiency. The effectiveness of the ventilation and air conditioning system is examined by this report.

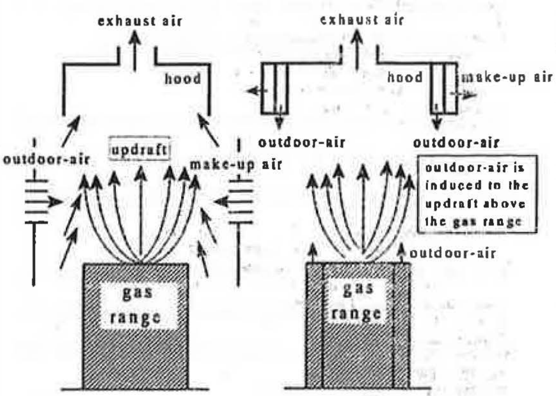
2. RESEARCH OUTLINE

2.1 Ventilation and Air Conditioning System

Figure 1 shows an updraft which appears above the range, and that the amount of air-flow increases with induced indoor air. The greater part of the air which is induced to the updraft is make-up air, which increases air conditioning load and also causes worsening of the indoor environment in usual commercial kitchens. In this research, we developed the ventilation and air conditioning system from the view point of saving energy and producing a comfortable working space environment in which cold or hot outdoor-air is induced to the updraft above the gas range. In this system, the space above the range and the working space are separated by an outdoor-air curtain. In this system, there is a minimum exchange of the heat and air between the gas range and the working space, so the thermal environment of the working space should be comfortable.

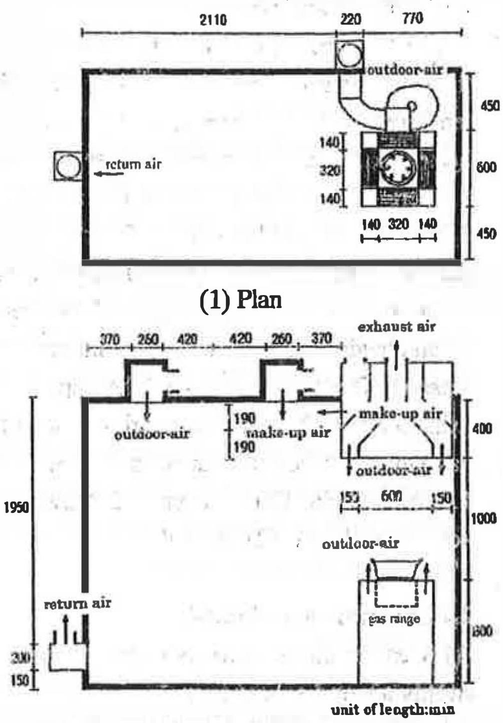
2.2 Model of Kitchen

Figure 2 shows the kitchen model which is in an air-tight experiment chamber with a depth of 3.0m, a width of 1.5m, and a height of 2.2m. This chamber is assumed to be a part of the actual kitchen space. A gas range and an exhaust hood are installed near the wall, to replicate a model commercial kitchen. The inner wall is flat black finish, and the floor,



(1) Usual system (2) Developed system

Figure 1 Outline of developed ventilation system



(2) Section

Figure 2 Plan and section of kitchen model outer wall and ceiling have insulation to reduce internal and external heat exchange. The commercial- use gas range has a maximum calorific value of 14.0kw(12000kcal/h). A JIS standard pot without a lid, having a diameter 28cm with water boiling is used for the measurement. The temperature of outdoor-air and make-up air can be controlled, so it is possible to reproduce thermal conditions of all seasons.

2.3 Experimental Conditions

Table 1 shows the experimental conditions. There are three different experimental conditions. In Exp. 1, outdoor-air is supplied from the hood downward and make-up air is supplied from the hood horizontally to the working space. In Exp. 2, outdoor-air is supplied from the range upward. In Exp. 3 both outdoor-air and make-up air are supplied from the ceiling downward.

The temperature of all of the air supplied to the chamber is controlled by anti-freeze with a temperature of -5 degrees as well as an electric heater, so it can reproduce any season. The temperature of make-up supply air is 15 degrees, with outdoor-air at 30 degrees in summer. The make-up air is 30 degrees, with outdoor-air at 5 degrees in winter. The make-up air and outdoor-air is 20 degrees in intermediate seasons. The total amount of the supply and exhaust air is 400m^3/h. The caloric output of the gas range is made to change in increments of 1.16kw(1,000kcal/h), from 2.32kw(2,000 kcal/h) to 14.0kw(12,000 kcal/h).

2.4 Experimental Method

(1) Measurement methods of the amount of supply air and exhaust air

In advance of the experiment, a duct was installed which was used for air-quantity measurement, and was calibrated with an orifice plate. All fans were controlled by inverters and the maximum air-flow rate was about 500m^3/h.

(2) Measurement method of the distribution rate of the outdoor-air supplied to the test chamber

Tracer gas (C_2H_4) was injected in the outdoor -air, and the concentration of the return air and exhaust air measured in the steady state. The

Table 1 Experimental conditions

Exp. No.	Supply position		Supply temperature		Season
	Outdoor air	Make-up air	Outdoor air	Make-up air	
1-S	Hood	Hood	30℃	15℃	Summer
1-W			5℃	30℃	Winter
1-I			20℃	20℃	Intermediate
2-S	Range	Hood	30℃	15℃	Summer
2-W			5℃	30℃	Winter
2-I			20℃	20℃	Intermediate
3-S	Ceiling	Ceiling	30℃	15℃	Summer
3-W			5℃	30℃	Winter
3-I			20℃	20℃	Intermediate

Table 2 Calculation methods

(1) The distribution rate of outdoor air supplied

$A1 = B1 \cdot C1 \cdot 0.001$ (1)

$A2 = B2 \cdot C2 \cdot 0.001$ (2)

$E1 = A1 / (A1 + A2) \times 100$ (3)

$E2 = A2 / (A1 + A2) \times 100$ (4)

A1: amount of tracer-gas content of return air [liter/hour]
B1: amount of return air [m^3/h]
C1: steady concentration of return air [ppm]
E1: distribution rate of outdoor air of return air [%]
A2: amount of tracer-gas content of exhaust air[liter/hour]
B2: amount of exhaust air[m^3/h]
C2: steady concentration of exhaust air [ppm]
E2: distribution rate of outdoor air in exhaust air [%]

(2) The Combustion gas distribution rate

$F = G \cdot 1.0836$ (5)

$H1 = (I1 - J) \cdot B1 \cdot 0.000001$ (6)

$H2 = (I2 - J) \cdot B2 \cdot 0.000001$ (7)

$L1 = H1 / (H1 + H2) \times 100$ (8)

$L2 = H2 / (H1 + H2) \times 100$ (9)

F: amount of CO_2 produced by gas combustion [m^3/h]
G: amount of combustion gas supplied to the range [m^3/h]
1.0836: amount of CO_2 produced by gas combustion of 1m^3
H1: amount in CO_2 of the return air [m^3/h]
I1: steady concentration of CO_2 in the exhaust air [ppm]
J: concentration of CO_2 in outdoor air [ppm]
H2: amount of CO_2 in the exhaust air [m^3/h]
I2: steady concentration of CO_2 in the exhaust air [ppm]
L1: combustion gas distribution rate of return air [%]
L2: combustion gas distribution rate of exhaust air [%]

(3) Heat balance

$IS = (597.5 + 0.44 \cdot t) \cdot q \cdot \rho \cdot w \cdot 1.163$ (10)

$IA = 0.24 \cdot t \cdot q \cdot \rho \cdot (1.0 - w) \cdot 1.163$ (11)

$Hin = ISin + IAin + K$ (12)

$Hout = ISout + IAout$ (13)

$Ob = K - Sb - Ab$ (14)

IS: latent heat [w] t: temperature[℃] q: air volume [m^3/h]
ρ: air density [kg/kg] w: moisture content [kg/kgDA]
IA: sensible heat [w] K: heat generation rate [w]
Hin: total input heat ISin: inlet latent heat ISout: outlet latent heat
Hout: total output heat IAin: inlet sensible heat IAout: outlet sensible heat
Ob: heat balance [w]

(4) Water vapor balance

$Wi = OW + SW + EV + GW$ (15)

$Wo = RW + FW$ (16)

$Wa = Wi - Wo$ (17)

Wi: amount of inlet water vapor OW: outdoor air water vapor content
SW: make-up air water vapor content EV: amount of evaporation
GW: water vapor content of combustion gas
Wo: amount of inlet water vapor RW: water vapor content of return air
FW: water vapor content of exhaust air Wa: water vapor balance

distribution of outdoor-air in the exhaust air and return air was calculated from the concentration of tracer gas and the amount of air-flow at the return inlet and exhaust hood. Table 2 shows the calculation method. All of the air supplied to and exhausted from the chamber, as well as the temperature and humidity was measured. The heat and water vapor balance were calculated to confirm the precision of the experiment.

(3) Measurement method of the combustion gas distribution rate

CO_2 produced by the gas combustion was used as a tracer gas. The CO_2 concentration was measured in the exhaust air and return air, and the amount of CO_2 included in the combustion gas is calculated by the consumption of gas. The distribution of combustion gas was calculated from the concentration of CO_2 and the amount of air flow at the return inlet and exhaust hood.

(4) Temperature distribution

The temperature in the working space and above the range was measured by thermocouple to evaluate the thermal environment. The temperature was measured every 100 cm^2 in the working space, and every 25cm^2 above the gas range.

(5) Air-flow distribution

A miniature ultrasonic anemometer which can measure a three-dimensional air-flow at the same time (Kaijo Ltd.: type WA390, 5cm span) was used for the measurement of air-flow distribution. Measurement interval of the points was the same as those measuring temperature.

3. MEASUREMENT RESULTS

3.1 Heat and Water Vapor Balance

Table 3 shows the calculation results of the heat and water vapor balance when the caloric output of the gas range is 6.98kw(6000 kcal/h). It shows that about 10%-40 % of the quantity of heat is conducted out from the wall and ceiling of the chamber. Because the water vapor balance is less than 10%, we can conclude that the experiments have been done with suitable precision.

3.2 Outdoor-Air and Combustion Gas Distribution Rate

Figure 3 shows the outdoor-air distribution rate and Figure 4 shows the combustion gas distribution rate.

(1) Exp.1 (Figures 3 and 4 marked ●,○)

In winter and intermediate seasons 60-80% of the outdoor-air supplied from the hood is exhausted by the hood. The distribution rate of outdoor-air that is exhausted by the hood shows a tendency to decrease when the caloric output of the gas range is increased. In summer 50-70% of outdoor-air is exhausted by the hood. When the caloric output of the gas range is over 11.6kw (10000kcal/h), the amount of outdoor-air exhausted by the hood is smaller than the air exhausted by the return outlet. In summer and intermediate seasons, over 90% of the combustion gas is exhausted by the hood. But in winter, the rate that is exhausted by the hood changes due to the increase of the caloric output of the gas range with the rate becoming 30-90%. It is because the temperature of the

Table 3 Results for measurement of heat balance and water vapor balance

Exp. No.	Heat balance			Water vapor		
	Input [kw]	Output [kw]	Balance [kw]	Input [kg/h]	Output [kg/h]	Balance [kg/h]
1-S	16.31	15.18	1.13	8.236	8.928	-0.693
1-W	18.18	15.09	3.09	10.659	10.557	0.102
1-I	15.71	14.96	0.75	8.346	9.032	-0.686
2-S	16.81	15.80	1.01	8.556	8.022	0.535
2-W	17.50	16.49	1.01	10.341	9.823	0.518
2-I	15.79	15.34	0.46	8.320	8.205	0.116
3-S	17.10	15.88	1.31	8.709	9.187	-0.338
3-W	16.72	14.20	2.52	9.376	9.410	-0.036
3-I	16.62	15.77	0.85	9.130	9.334	-0.204

downward outdoor-air from the hood is relatively cold that the downward air-flow velocity increases and influences the updraft above the range.

(2) Exp. 2 (Figures 3 and 4 marked ■,□)

In summer and intermediate seasons 60-80% of the outdoor-air supplied from the hood is exhausted by the hood. The distribution rate of outdoor-air that is exhausted by the hood shows a tendency to decrease when the caloric output of the gas range is increased. In winter, the distribution rate is smaller than the rate in summer and intermediate seasons and reaches only about 70%. When the caloric output of the gas range is less than 9.30kw(8000 kcal/h), the amount of outdoor-air exhausted by the hood increases, but when it is over 9.30kw(8000 kcal/h) the amount of outdoor-air decreases.

In all seasons, over 90% of the combustion gas is exhausted by the hood.

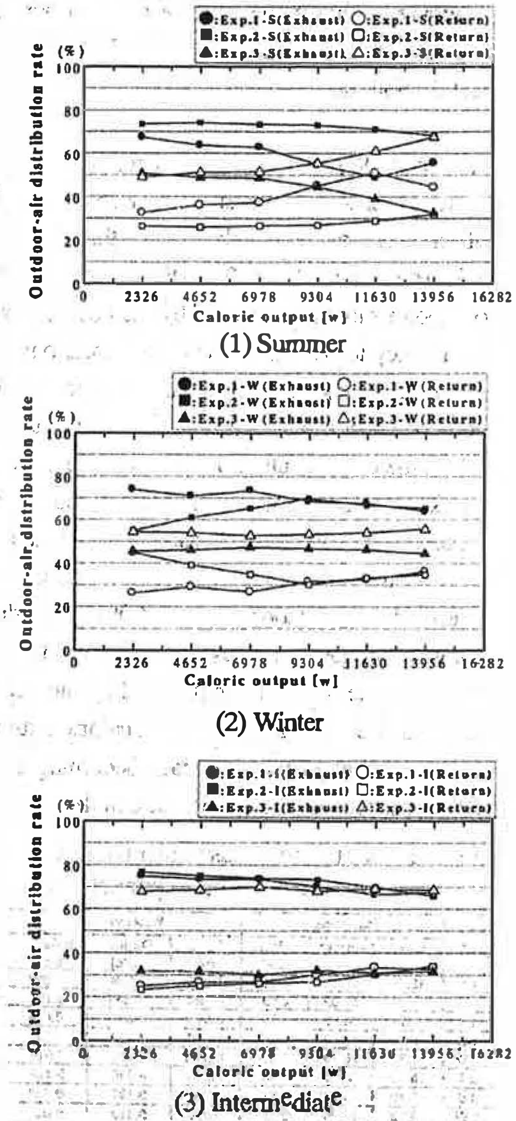


Figure 3 Outdoor-air distribution rate

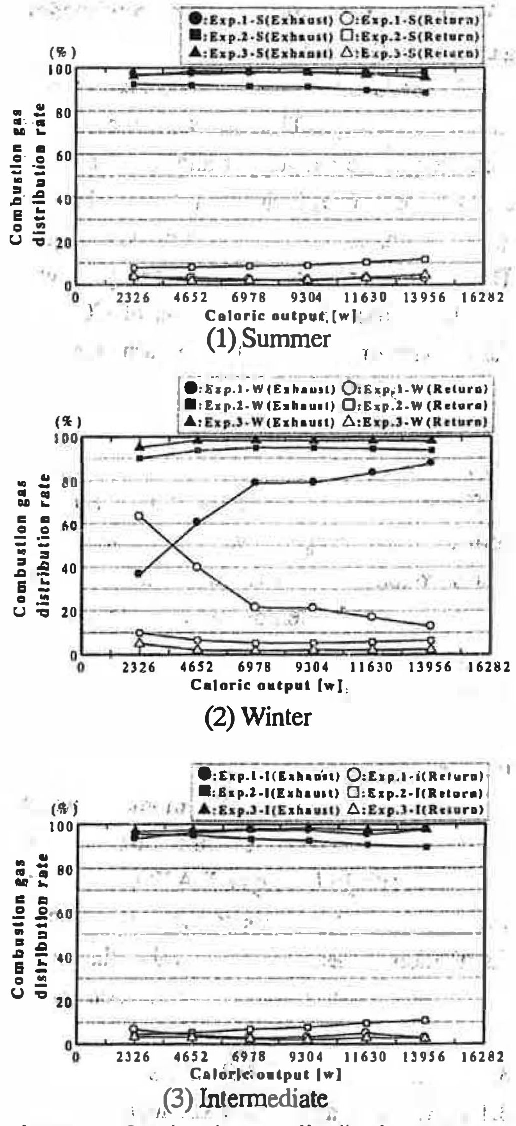


Figure 4 Combustion gas distribution rate

(3) Exp. 3 (Figure 3 and 4 marked ,)

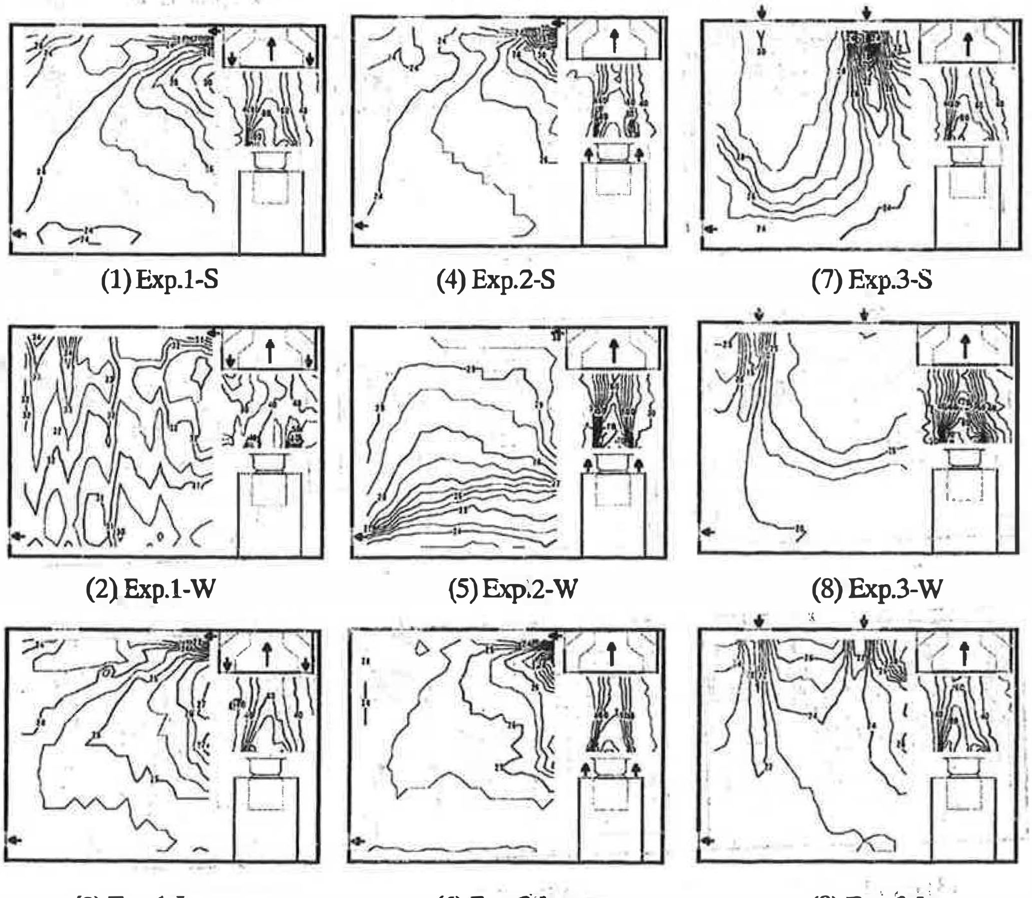
In intermediate seasons, only about 30% of outdoor-air supplied from the ceiling is exhausted by the hood. This is the smallest value of this experiment. In summer 30-40% is exhausted, and in winter 40-50% is exhausted by the hood. When the outdoor-air is supplied from the ceiling, the distribution rate of outdoor-air in the return outlet is larger than that of the exhaust hood. In winter and intermediate seasons, distribution rate of outdoor-air is constant when the caloric output is changed, but in summer the distribution rate to the exhaust hood decreased when the caloric output of the gas range increased. In all seasons, over 90% of the combustion gas is exhausted by the hood, showing that the capture ratio of the hood is excellent in all the experiments 1, 2 and 3.

3.3 Temperature Distribution

Figure 5 shows the measurement results of the temperature distribution in the chamber.

(1) Exp. 1

In summer and intermediate seasons, the distribution of temperature above the range is upward toward the hood. The range of temperature is 60-80 degrees in summer and is distributed widely in comparison with that of intermediate seasons. The range of temperature is 20-40 degrees in the working space, and is distributed



(1) Exp.1-S (4) Exp.2-S (7) Exp.3-S
(2) Exp.1-W (5) Exp.2-W (8) Exp.3-W
(3) Exp.1-I (6) Exp.2-I (9) Exp.3-I

Figure 5 Temperature Distribution

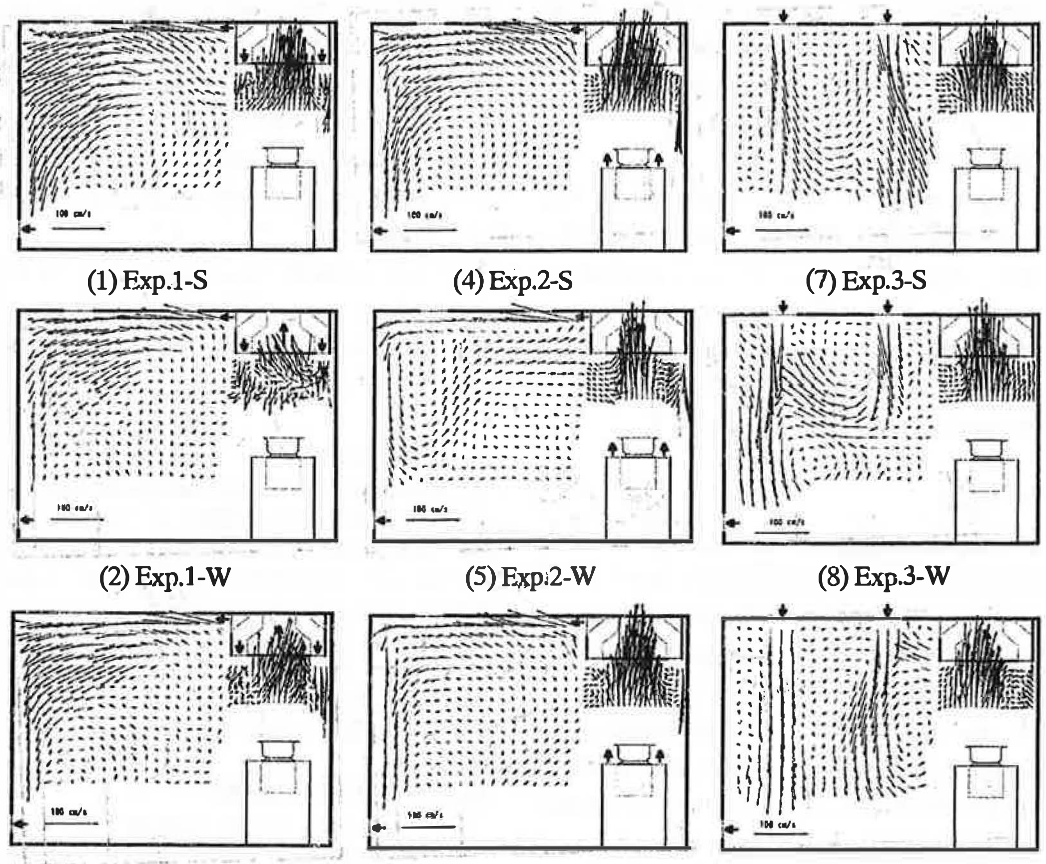
widely especially in winter. The range of temperature is 24-28 degrees in the working space in summer and intermediate seasons. In winter, the temperature under the ceiling is high, because make-up air is accumulating at the top of the chamber.

(2) Exp. 2

In all seasons, the distribution of the temperature above the gas range forms upward toward the hood. The temperature range of over 40 degrees is smaller than when that the outdoor-air flows from the hood. Temperature distribution in the working space is 24-25 degrees in intermediate seasons. In summer, make-up air flows down and causes little temperature distribution. In winter, make-up air can not reach to the lower part of the working space, and the temperature difference between the upper space and the lower space is about 5 degrees.

(3) Exp. 3

In all the experimental conditions it is the same temperature distribution above the gas range. In the working space during an intermediate seasons, the temperature of the make-up air right after the supply outlet near the range rises to a high temperature. In summer , make-up air which has a low temperature spreads out over the whole room, and outdoor-air which has a high temperature is concentrated around the supply outlet. In winter, however, outdoor-air spreads out over the



(1) Exp.1-S (4) Exp.2-S (7) Exp.3-S

(2) Exp.1-W (5) Exp.2-W (8) Exp.3-W

(3) Exp.1-I (6) Exp.2-I (9) Exp.3-I

Figure 6 Air-flow distribution

whole room, and make-up air is concentrated around the supply outlet.

3.4 Air-Flow Distribution

Figure 6 shows the air-flow velocity distribution.

(1) Exp. 1

There is some dispersion of the air-flow distribution above the gas range. Air-flow velocity toward the hood is about 0.5m/s in intermediate seasons, and about 1.1m/s in summer. Outdoor-air from the hood rises together with the updraft above the gas range in summer. In winter, however, only a part of outdoor-air goes to the hood, and there is a tendency not to exhaust from the hood, so air-flow velocity becomes less than 0.5m/s. In all seasons, make-up air from the hood has a circulating flow in the working space.

(2) Exp. 2

Air-flow above the gas range is flowing toward the hood. Air-flow velocity above the gas range is 1.2m/s in all experimental conditions. The air-flow velocity above the gas range increases compared with when outdoor-air flows from the hood. Air-flow velocity in the working space is similar to Exp. 1.

(3) Exp.3

Air-flow velocity above the range is about 1.0m/s, and it flows toward the hood in all experimental conditions. In the intermediate seasons, updraft above the range flows out to the working space and mixes with the make-up air, and has a circulating flow between the working space and the gas range. Both outdoor-air in summer and make-up air in winter create a down draft in the working space.

4. Conclusion

(1) Temperature distribution above the gas range is in a dome-like shape when outdoor-air flows both from the hood and from around the gas range and concentrates toward the center of the exhaust hood.

(2) In the case of the outdoor-air flowing from the hood in winter, fluctuation of air velocity occurs on the center of the gas range. Air-flow above the gas range is distributed straight toward the hood in the case of outdoor-air flowing from the gas range.

(3) In the case of outdoor-air being supplied from the hood, 60-70% of the outdoor-air is exhausted by the hood.

(4) Air-flow distribution above the gas range is comparatively stable except in winter. Especially in summer and intermediate seasons, updraft above the gas range flows straight to the exhaust hood when outdoor-air is supplied from the gas range. In winter, updraft above the gas range is strongly effected by the outdoor-air from the hood, and there is dispersion in the updraft direction.

(5) Capture ratio of the combustion gas by the exhaust hood is over 80% except in winter. Capture ratio is increased when the caloric output of the gas range is larger.

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