Ventilation Planning for Mid-sized Japanese Commercial Kitchens and Calculation Method of Ventilation Rate Using Building Information Modeling

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ABSTRACT

In the design of a commercial kitchen ventilation system, it is very important to maintain the capture efficiency of exhaust hoods and ensure smooth removal of heat, moisture, and odor. The capture efficiency is affected by the kitchen ventilation system and the cooking appliance usage condition. To identify an appropriate ventilation system design method for commercial kitchens in Japan, surveys were conducted as follows.

The first survey was conducted on kitchen hoods, cooking appliances, and air supply openings in 35 mid-sized commercial electrical kitchens in Japan. In this survey, design drawings were collected, and field inspections were conducted. It is important to know the usage conditions and load factors of cooking appliances, which influence the capture efficiency. Therefore, the second survey was conducted to determine how cooking appliances were used. The load factors were studied based on the electricity consumption data of various cooking appliances used in ten mid-sized commercial kitchens in Japan.

The design load factors are utilized to determine the conditions of the standard test method for the capture efficiency of exhaust hood and are the basic data for calculate cooling loads in kitchens. The proposed design method using the load factor can be referred to as smart kitchen ventilation.

This study also demonstrates the application of Building Information Modeling (hereafter BIM) technology in commercial kitchens. Information on the cooking appliance and exhaust hood included in the BIM can be used to calculate the ventilation rate. This method can improve the design efficiency and reduce human error. The ventilation designer can compare the ventilation rate of several design methods, such as the conventional and proposed methods. In this study, an example procedure for ventilation rate calculation with BIM is demonstrated. Further, the scope for futures studies are discussed.

KEYWORDS

Electrical Commercial Kitchen, Actual Survey, Electricity Consumption, Design Load Factor, BIM

1 INTRODUCTION

In commercial kitchens, a large amount of heat, water vapor, and oil mist are generated because of the cooking operation. The energy consumed in ventilation/air conditioning to remove them is very large [Kondo, Y. et al. 2001]. It is very important to improve the capture efficiency of the exhaust hoods to maintain a healthy work environment for the kitchen staff.

In Japan, the ventilation standard [MLIT, 2015] of commercial kitchens has been based on the average velocity of the exhaust hood. While the standard is very simple, it may cause the overestimation of the ventilation rate. However, the circumstances of commercial kitchens have changed, such as diversification of cooking equipment and ventilation/air-conditioning systems. For these reasons, it is desirable to establish a standard test method for hood capture efficiency that reflects the actual condition of commercial kitchens. Ventilation/air conditioning systems should be designed based on these data.

In this research, a ground situation survey was conducted to obtain basic data for appropriate conditions to be used in the standard test method of hood capture efficiency [JTCCM, 2015]. The hood capture efficiencies determined using the standard test method can be used to realize healthy and comfortable work conditions with moderate ventilation rate. It is a smart ventilation method that considers the actual condition of the cooking operation and the HVAC system. In addition, the ventilation rate calculation tool using BIM can improve the design efficiency and reduce human error.

2 SURVEY METHOD

2.1 Ventilation system

Survey items regarding kitchen specifications are shown in Table 1. A mid-sized kitchen of the company cafeteria was surveyed, in which 200 to 800 meals are served during one mealtime. When sufficient design data could not be obtained, pictures of the air supply opening and the air conditioner were collected to understand the situation inside the kitchen. Figure 1 shows the location of 35 commercial electric kitchens in Japan.

Table 1: Survey item of ventilation system
(Survey period 2012.11–2013.2)

Item		Sub Item	Contents
Kitchen size		Floor space	Cooking area
		Ceiling height	Ceiling height
Exhaust	Hood	Size	Width, depth, height
		Type	Island, wall-mounted
		Overhang	Width, depth
		Heating equipment	Cooking appliance type and arrangement
	Ceiling	Type	VHS, BL, etc.
		Installation position	Plan/elevation position
		Number/Air volume	Number of outlets, air volume
Air supply		Type	PK, VHS, ceiling PAC, etc.
		Outside air	Air conditioning
		Installation position	Plan/elevation position
		Number/Air volume	Number of air inlets, air volume

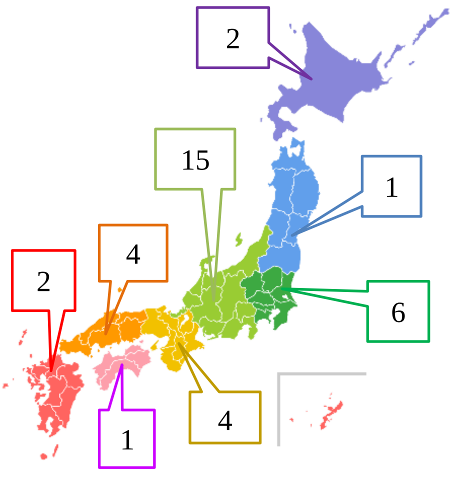


Figure 1: Survey location

2.2 Load factor of cooking appliances

The load factor of various cooking appliances was surveyed in ten mid-sized commercial electric kitchens. Table 2 shows the outline of the surveyed kitchens. The measurement in winter was conducted for two weeks, while the power consumption data of the watthour meter installed in the appliances for ten days was examined. The electric power was measured at intervals of one second, and the average value for one minute was recorded.

Table 2: Outlines of ten kitchens for the load factor study (Survey period 2012.11–2013.2)

Kitchen		A	B	C	D	E	F	G	H	I	J
Prefecture		Hokkaido	Kanagawa	Toyama	Shizuoka	Aichi	Aichi	Aichi	Aichi	Osaka	Okinawa
Floor space [m²]		129	163	113	72	73	72	135	96	88	94
Ceiling height [m]		2.4	2.3	3.6	2.6	2.4	2.4	2.4	2.3	2.5	2.6
Number of meals	Design	600	800	250	200	200	200	200	400	200	150
	Operation	500	200	100	100	190	100	180	310	130	150
Operating time		7:30–16:00	6:30–17:00	6:00–14:30	6:30–14:30	8:00–14:00	8:00–15:00	8:00–14:30	6:30–14:30	6:00–15:00	6:30–15:30
Measurement	Year	2012	2012	2012	2010	2012	2013	2012	2012	2012	2012
	Start	12/11	12/5	11/19	12/6	11/10	1/9	11/28	12/13	11/5	12/13
	End	12/25	12/18	12/7	12/28	11/26	1/24	12/10	12/27	11/16	12/27
Number of operations		10	10	14	15	10	11	10	10	10	10
Cooking appliances [Total rated power [Number]]	Noodle boiler	42.0 kW(3)	18.0 kW(2)	23.1 kW(2)	6.1 kW(1)	5.0 kW(1)	8.0 kW(1)	12.0 kW(3)	11.3 kW(1)	11.3 kW(3)	9.3 kW(1)
	Flyer	15.0 kW(1)	12.0 kW(2)	7.0 kW(1)	6.0 kW(1)	12.3 kW(1)	5.3 kW(1)	23.2 kW(4)	14.6 kW(2)	12.8 kW(2)	6.0 kW(1)
	Rice cooker	32.4 kW(2)			15.3 kW(1)	16.2 kW(1)	21.0 kW(1)	15.3 kW(1)	30.0 kW(2)	30.0 kW(2)	
	IH cooktop	16.0 kW(1)	30.0 kW(6)	26.6 kW(1)	8.0 kW(2)	26.0 kW(2)	13.0 kW(3)	15.0 kW(1)	23.6 kW(3)	20.0 kW(6)	10.0 kW(1)
	Low range	10.2 kW(1)		10.0 kW(1)			5.5 kW(1)	10.0 kW(2)	4.0 kW(1)	10.0 kW(2)	5.0 kW(1)
	Tilting pan	13.0 kW(1)	18.0 kW(2)	9.0 kW(1)		9.0 kW(1)	12.0 kW(1)	12.0 kW(1)	20.0 kW(2)		
	Steam convection	9.5 kW(1)	29.0 kW(2)	10.3 kW(1)	10.1 kW(1)	18.5 kW(1)	18.5 kW(1)	18.5 kW(1)	5.9 kW(1)	9.3 kW(1)	
	Warmer table	4.5 kW(1)			4.5 kW(1)	9.0 kW(1)	3.6 kW(1)				
	Dish washer	10.5 kW(1)		14.4 kW(1)	8.0 kW(1)	3.1 kW(1)	11.9 kW(1)	5.6 kW(1)	22.8 kW(1)	6.7 kW(1)	
	Chinese range	6.0 kW(1)									10.0 kW(1)
	Soup kettle	15.0 kW(1)		12.0 kW(2)							
	Griddle							11.7 kW(1)			10.0 kW(1)

※The measurements were conducted during lunch time on weekdays.

3 SURVEY RESULTS OF THE VENTILATION SYSTEM

3.1 Kitchen Size

The ceiling heights of the 35 kitchens are shown in Figure 2. These varied from 2.4 m to 2.5 m. The average height, without considering the uncommon height of over 3.1 m was 2.45 m. Figure 3 shows areas of preparation, cooking, pantry, washing, and others in the kitchen. The cooking area covers 56% of the entire kitchen. The preparation area and the washing area covers approximately 20% each. The floor area of the entire kitchen ranges from 50 m^2 to 200 m^2, with an average value of 104.2 m^2.

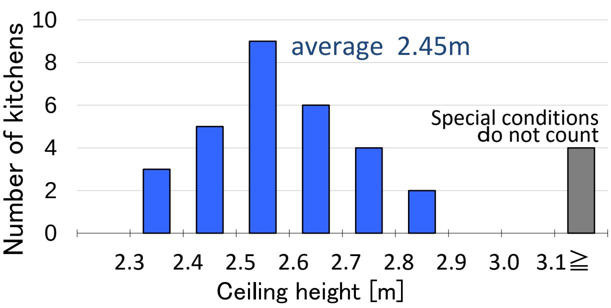


Figure 2: Ceiling height of the kitchens

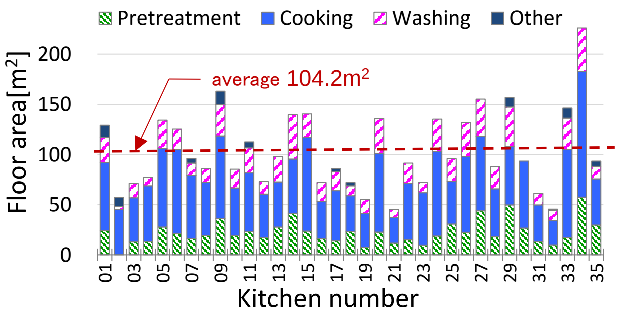
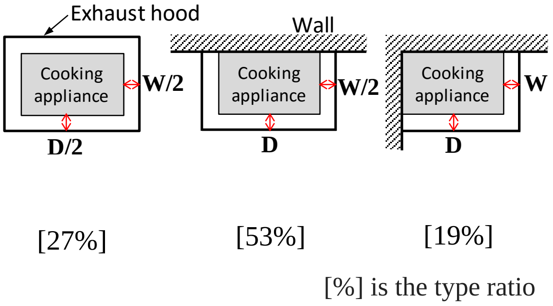
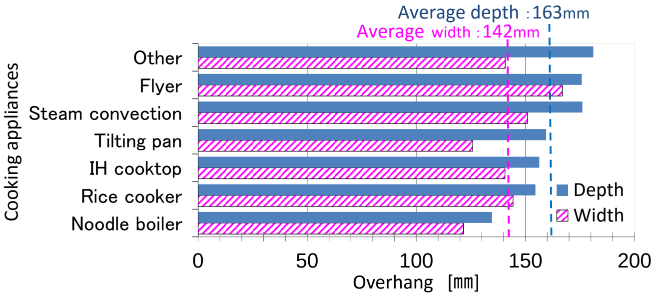


Figure 3: Kitchen work area

3.2 Overhang of Exhaust Hood

The overhang size of exhaust hoods was calculated as shown in Figure 4 (a). The average size of the overhang, excluding irregular, cases is shown in Figure 4 (b). The mean size of the overhang for each cooking appliance ranges from 120 to 180 mm. However, in the survey carried out by ASHRAE [ASHRAE, 2011] for U.S. kitchens, the overhang size was 230 to 460 mm, which is much larger than the results in Japan.



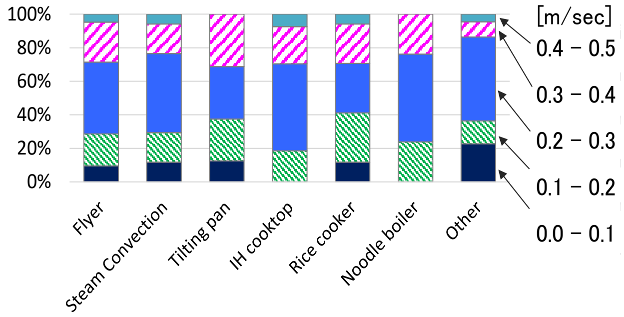


(a) Definitions of overhang size (b) Results of overhang size for appliances

Figure 4: Survey of Overhang of Exhaust Hoods

3.3 Exhaust Air Volume

Information on the exhaust air volume for the exhaust hood was obtained for 21 kitchens. Figure 5 shows the average velocity of exhaust hoods for each cooking appliance. The mean value of the average velocity of exhaust hood was 0.25 m/s. In many cases, the average velocity was within a range of 0.2 m/s to 0.3 m/s. Figure 6 shows the air change rate of 31 kitchens. The air change per hour was within the range of 30 to 40 ACH for 26% of the kitchens. The average air volume of the ceiling exhaust was 16.3% of the total exhaust air volume.



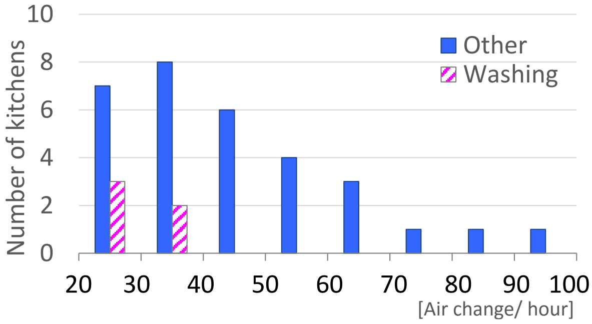


Figure 5: Average Velocity of Exhaust Hood

Figure 6: Air Change Rate of Kitchens

3.4 Type of Supply Opening and Supplied Air Temperature

Figure 7 shows the type of supply openings. The universal type opening (hereafter VHS) was applied to 52% of the kitchens, while punker louver type (hereafter PK) was applied to 45% of kitchens. Packaged air conditioning mounted on the ceiling and PK are likely to cause air disturbance for the exhaust hood. They were installed in 22 kitchens, which is 63% of the whole. In 20 kitchens, which is approximately 60% of the whole, outside air was supplied without temperature control. This worsens the thermal condition.

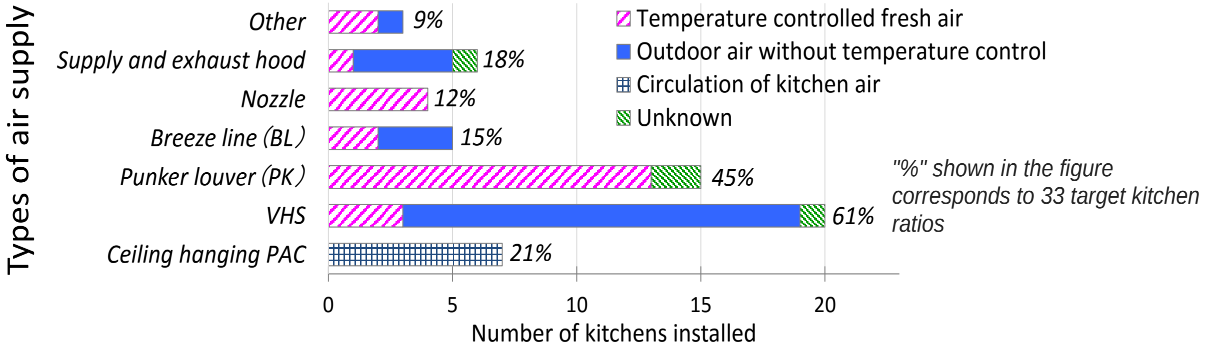


Figure 7: Type of Supply Openings

4 SURVEY RESULTS OF LOAD FACTOR

4.1 Averaging Time for Load Factor

The load factors with three averaging times, i.e., 1-min, 5-min, and 10-min are shown in Figure 8. The 1-min averaged load factor fluctuates greatly, making it difficult to determine the trend. Characteristics of the load factor can be determined when averaging is performed in 5 or 10 minutes. However, as indicated by the dashed circle in Figure 8, when averaging in 5-min, the tendency slightly changes to show two peaks, while only one peak is observed when averaging in 10-min. The load factor should be averaged over a relatively short period of time. Therefore, 5-min is adopted as the averaging time for load factor in this paper.

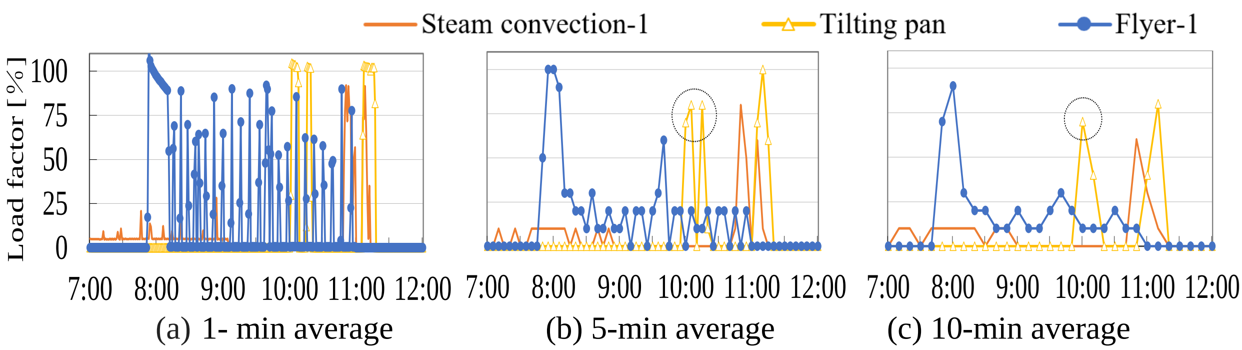
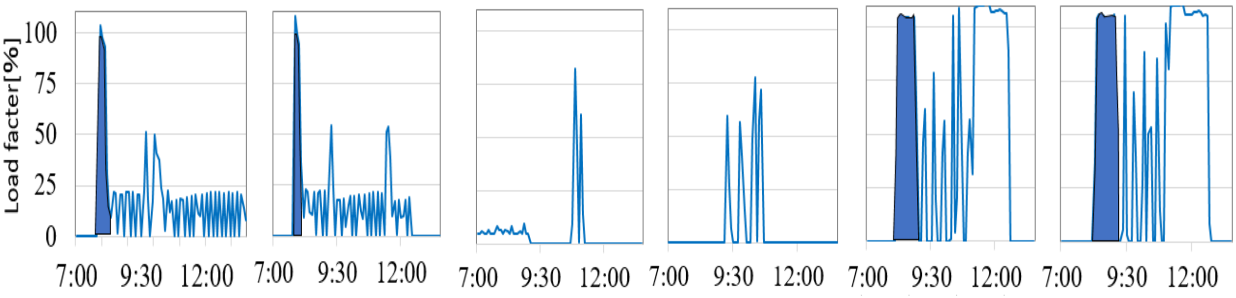


Figure 8: Load factors with three averaging times (Kitchen-B, 12/5)

4.2 Deletion of Unnecessary Data

The design load factor should cover the period when the required ventilation volume and air conditioning load are the maximum. The flyer and the warmer table consume most of the electricity at the beginning of the operation to heat oil and water to the target temperature. Although the load factor is high, the influence on thermal environment in the kitchen is low. Therefore, the time zone of the black portion shown in Figure 9 was deleted.



(a) Flyer (Kitchen-B) (b) Steam convection oven (Kitchen-B) (c) Warmer table (Kitchen-A)

Figure 9: Load factor of cooking appliances (vertical axis: load factor, horizontal axis: time)

4.3 Peak Period of Operating Appliances

Figure 10 shows the result of the peak period during which the load factor of each cooking appliance in 10 kitchens reaches its peak value. There are variations in the peak period of fryers, electrical induction cookers, steam convection oven, and low ranges because the food items differ depending on the daily menu. However, the peak period was between 8 and 11 am, when the cooks prepared to serve lunch. The peak period of the rice cooker was between 9 and 11 am, that of the warmer table was between 11 am and 12 noon, while the dishwasher's was at 12 noon.

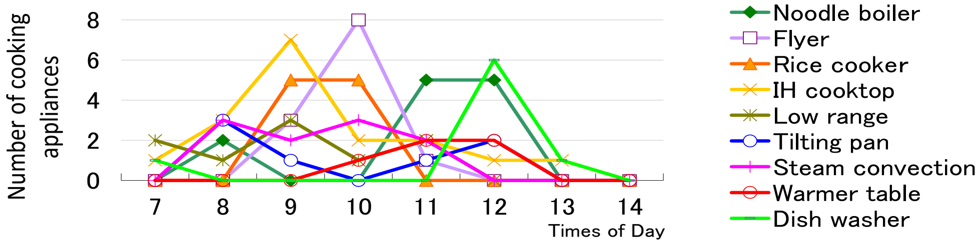


Figure 10: Time variation of number of operating appliances

4.4 Calculation Procedure of Design Load Factor

The proposed design load factor calculation procedure is shown below.

(1) The one-hour average load factor for each cooking appliance was calculated and the peak period of one hour was determined. However, the time zone at the beginning of the operation is excluded for flyers and warmer tables.

(2) The five-minute average load factor was calculated during the peak period.

(3) The percentile value for all the 5-min average load factor data was calculated. The design load factor can be selected from the 90th percentile value, the 95th percentile value, or the 100th percentile value.

The above procedure describes the design load factor of the cooking appliance alone. However, the design load factor for exhaust hood and the entire kitchen can be similarly calculated. In addition, the design load factor was assumed to be used for the calculation of heat load. Therefore, the hourly design load factor is appropriate for presenting in this paper.

4.5 Design Load Factor

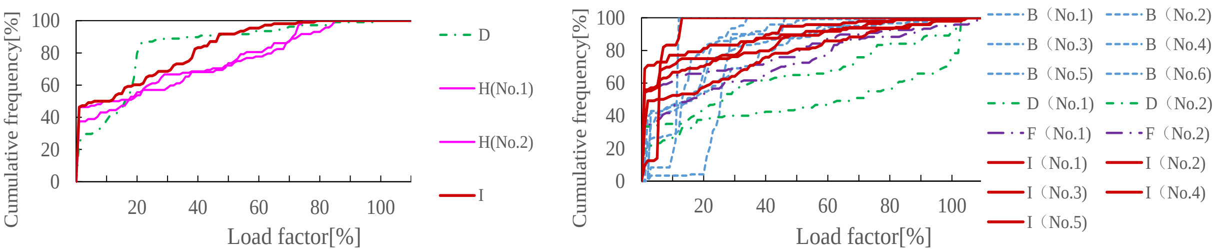
In this section, an example of the calculated results of design load factor is shown by using the data obtained from 10 kitchens.

4.5.1 Design Load Factor for Appliances

The cumulative frequency of the five-minute average load factor of the cooking appliances is shown in Figure 11, while the cumulative value of the five-minute average load factor for each appliance and the design load factor for each cumulative value are shown in Table 3.

The cumulative frequency of the load factor of the flyer shown in Figure 11 (a) varies for each device. As shown in Table 3, the 90^{th} percentile value of each device was 41% to 91%, while the design load factor of the 90^{th} percentile value was calculated to be 66%.

In the case of the electrical induction cooker shown in Figure 11 (b), the cumulative frequency of the load factor varies greatly depending on the equipment. This is because the electrical induction cooker can cook various food items. The design load factor at the 90^{th} percentile value was calculated to be 72%.



(a) Flyer (b) IH cooktop

Figure 11: Cumulative frequency of load factor (5-min average)

Table 3: Load factor for cooking appliances

	Kitchen	A		B		C		D		E		F		G		H		I		J		Design load factor		
	Cumulative value [%]	90	95	90	95	90	95	90	95	90	95	90	95	90	95	90	95	90	95	90	95	90	95	100 ※2
	Noodle boiler	105	106	100	100	76	76	99	99	–	–	99	99	100	101	104	105	83	84	99	99	104	105	108
	Flyer	☆	☆	45	69	–	–	41	68	☆	☆	–	–	81	90	72	73	47	57	–	–	66	75	103
	Rice cooker	94	94					32	47	108	109	49	50	101	103	93	74	32	32			93	94	111
	IH cooktop	–	–	35	41	☆	☆	100	102	☆	☆	85	95	☆	☆	☆	☆	58	72	☆	☆	72	94	112
※1	Low range	65	70			47	51					92	93	99	99	48	48	51	100	60	79	98	100	105
	Tilting pan	89	96	104	104	101	101			73	73	☆	☆	☆	☆	69	70					101	101	104
	Steam eonvection	85	91	65	73	80	80	–	–	38	53	52	75	96	103	92	95	97	97			80	92	106
	Warmer table	111	111					99	101	110	110	–	–									110	111	111
	Dish washer	–	–			53	57	–	–	93	94	91	92	102	103	64	65	72	76			98	100	104

※1：When multiple devices are installed, one example is shown.
※2：While the value should be 100%, it is over 100% because the real power exceeds the rated power.
☆： Not in operation during measurement period.
–：The load factor exceeds 113% because of measurement failure.

4.5.2 Design Load Factor for Hood

Table 4 shows the results of the hood in kitchen D, which include a fryer and two electrical induction cookers. Since the peak period of the two electrical induction cookers are the same from 9 to 10 am, the peak period of the hood was 9 to 10 am. However, since the peak periods of the flyers differ, the load factor of the hood is smaller than the load factor of the electrical induction cooker. The load factor at the 90^{th} percentile value is 58%.

Table 4: Load factor for exhaust hood (Kitchen D)

		Peak period	Cumulative percentile		
			90%	**95%**	**100%**
Cooking equipment	**Flyer (6 kW)**	10–11	41	68	100
	Electrical induction cooker (5 kW)	9–10	100	102	103
	Electrical induction cooker (3 kW)	9–10	103	103	104
Exhaust hood		9–10	58	64	67

4.5.3 Design Load Factor for Kitchen

Table 5 shows the load factor at the peak period, the 100th percentile values in each kitchen, and the design load factor. The peak period varied depending on the kitchen. However, the peak period for many kitchens was from 9 to 10 am. The load factor at 90th percentile values was within the range of 24% to 44%, while the design load factor was 38%. The 95th percentile value was 43% and the 100th percentile value was 60%.

Table 5: Load factor for kitchens

Kitchen		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**Design load factor**
Peak period		9–10	9–10	12–13	10–11	10–11	8–9	9–10	9–10	9–10	10–11	–
Percentile value	**90%**	41	24	26	42	38	34	44	44	25	36	38
	95%	44	27	30	45	41	38	47	47	27	41	43
	99%	46	32	41	50	48	47	58	49	34	54	50
	100%	50	33	42	57	50	50	60	51	35	56	60

5 CALCULATION TOOL FOR VENTILATION RATE USING BIM

5.1 Ventilation calculation tool

A flow chart of the ventilation calculation tool proposed in this paper is shown in Figure 12. The BIM software was developed by Autodesk Revit, while Dynamo was used to create an automatic calculation tool. Figure 13 shows a part of the Dynamo visual program screen.

By importing information on kitchen appliances, the exhaust hood is automatically placed above the necessary cooking appliances. The designer changes the hood type and size to complete the 3-dimensional model, equipment list, and ventilation volume list.

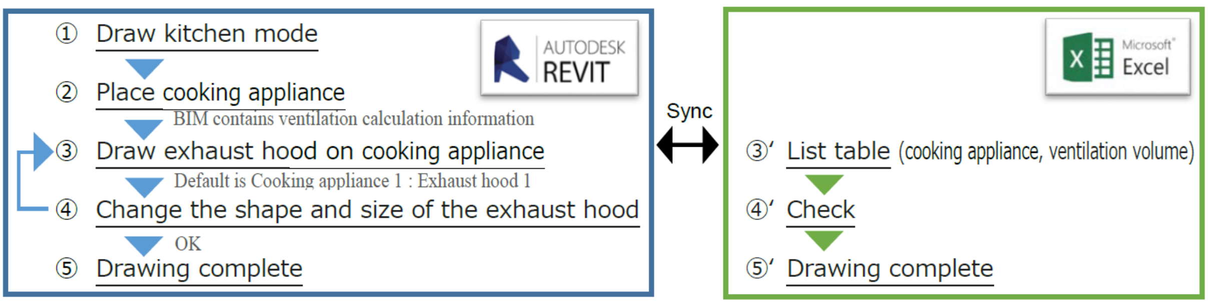


Figure 12: Flow chart of the ventilation calculation tool

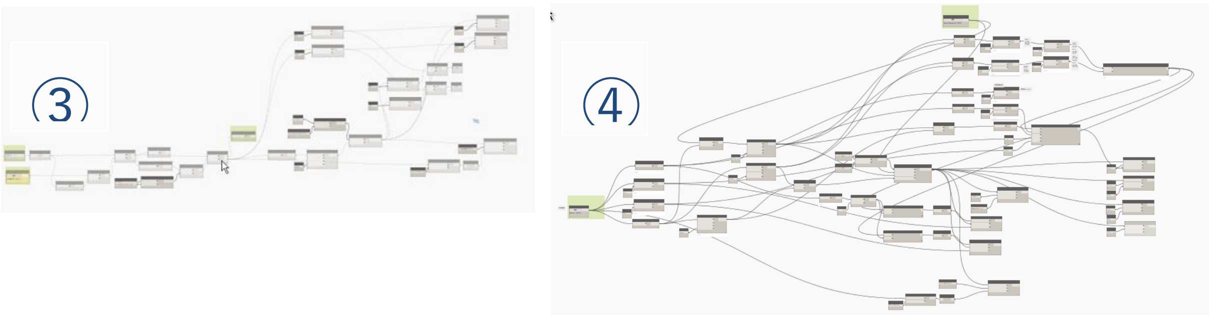


Figure 13: Dynamo's visual program screenshot (③ and ④ are shown in Figure 12)

5.2 Method of calculation

Table 6 presents three methods for calculating ventilation in Japan.

Ⅰ. Ministry of Land, Infrastructure, Transport and Tourism Standards [MLIT, 2015] are commonly used in Japan. Calculations are based on 1) theoretical waste gas volume and electric capacity, 2) the hood face wind velocity, and 3) the air change rate of the kitchen. The maximum value among the three methods should be selected. As a result, it is often determined using 3) the hood face wind velocity.

Ⅱ. Standard of Japan Testing Center for Construction Materials [JTCCM, 2017] shows a calculation method to maintain appropriate air environment in the kitchen. This method focuses on air pollutants from the cooked product and combustion exhaust gas. The calculated ventilation rate maintains the hood capture efficiency at over 90%.

Ⅲ. Standard of Japan Electro-Heat Center [JEHC, 2017] is dedicated to the commercial electric kitchen. Calculation is based on the rated power and the required ventilation rate coefficient, which is listed for the typical hood shape and cooking appliance.

In methods II and III, the temperature of the air supplied should be controlled to maintain good indoor thermal conditions. These methods also strongly encourage the reduction of air disturbance caused by the air supplied to the thermal plume over the cooking equipment.

Table 6: Standards for ventilation rate in Japan

Standard			Keyword for calculation method	
Ⅰ	MLIT	Commonly used	1) Gas usage/ Rated power	Maximum ventilation from 1) to 3)
			2) Surface wind velocity of hood	
			3) Air change rate	
Ⅱ	JSTM	JSTM V 6271:2017	Design load Factor, appropriate air quality, capture efficiency	
Ⅲ	JEHC	JEHC103-2017	Electric kitchen, required ventilation rate coefficient, rated power	

5.3 Calculation example

Figure 14 shows a kitchen where the ventilation amount was estimated. The floor area is 76 m^2 and the ceiling height is 2.5 m. Figure 15 shows a diagram of the operational steps of the ventilation amount calculation tool. Numbers in the figure are the numbers in the flowchart

(Figure 12) and a screenshot of that process is shown. By changing the exhaust hood information, the ventilation volume is calculated in real time. Thus, one can proceed with the design while checking. The ventilation volumes of the three calculation methods are displayed in Table 7. The ventilation rate calculated by method I may be overestimated.

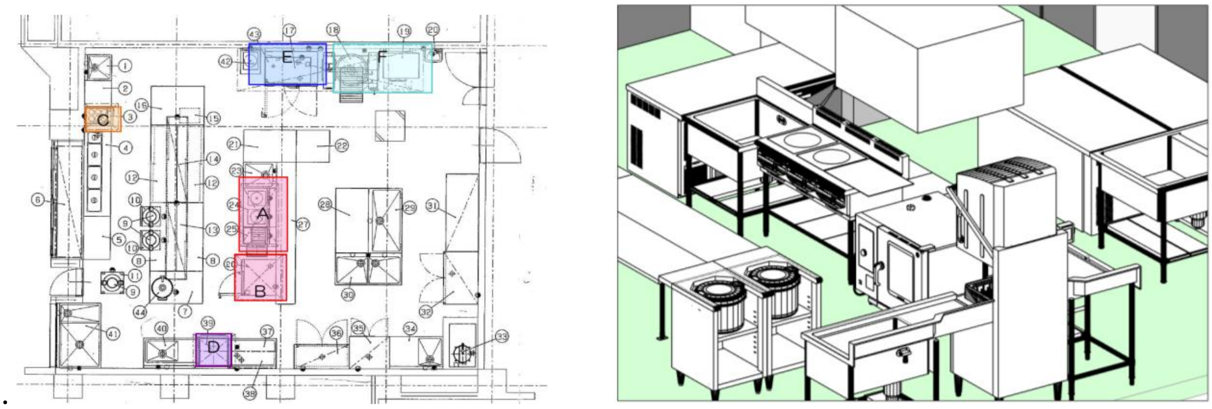


Figure 14：Kitchen used for the calculation example

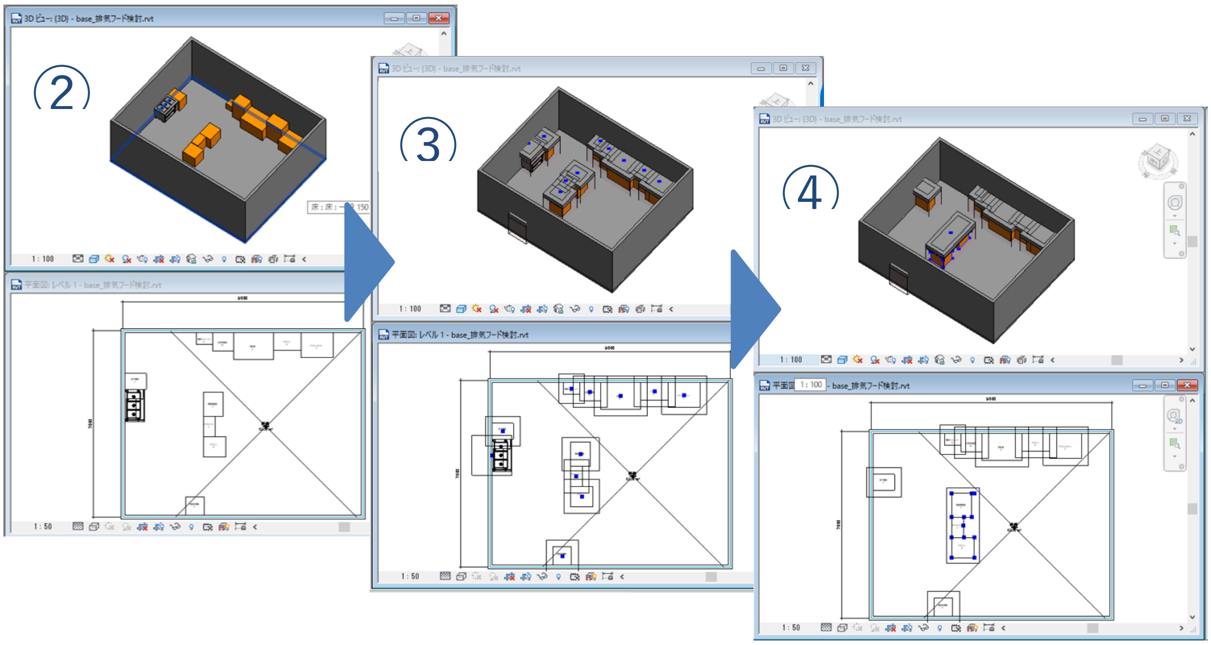


Figure 15: Diagram of the operational steps (③ and ④ are shown in Figure 12)

Table 7: List of ventilation rates

Exhaust hood			Kitchen appliance		Ventilation volume [m3/h]			Notes
Place	Width	Depth	No. 1	No. 2	Ⅰ. MLIT	Ⅱ. JSTM	Ⅲ. JEHC	
A	1.65 m	1.05 m	IH cooktop/8.0 kW	Flyer/6.0 kW	1,871	1,871	1,220	
B	1.10 m	1.10 m	Steam convection/10.1 kW	Noodle boiler/6.1 kw	1,307	871	707	
C	0.80 m	0.85 m	Noodle boiler/6.1 kW		734	734	305	
D	1.00 m	0.80 m	Dish washer/6.1 kW		864	240	320	
E	1.95 m	1.00 m	Low range/5.0 kW	Rice cooker/1.2 kW	2,106	1,696	962	
F	2.40 m	1.10 m	Rotary pot/13.5 kW	Steam Convection/15.3 kW	2,851	1,556	1,036	
Ceiling exhaust						541	351	Ceiling surface
				Total	6,882	5,954	3,865	

5.4 Future Tasks

Unfortunately, methods II and III have been developed recently and do not provide sufficient information for all cooking appliances. If sufficient information becomes available in the future, these methods will become popular in Japan.

Particularly, if a database of hood capture efficiency for various cooking appliances under various conditions based on the standard test method [JTCCM, 2015] is constructed, the appropriate designing of kitchen ventilation can be achieved. The improvement of BIM library and the addition of adequate information on cooking appliances in BIM are also recommended.

6 CONCLUSIONS

The ventilation systems of commercial kitchens in Japan were surveyed through questionnaires and by obtaining drawings. Additionally, based on the measured power consumption of kitchen equipment, the calculation method of the design load factor such as the unit of the cooking appliance or the entire kitchen was examined and a calculation example was shown.

The ventilation calculation tool introduced in this paper is expected to improve the design efficiency and remove human error. This method can not only be applied to kitchens, but to research facilities where many draft chambers are used. In the future, it is possible to further develop the calculation tool of the ventilation rate to cover the entire building.

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