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The effect of supply air systems on the efficiency of a ventilated ceiling

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Abstract

The ventilated ceiling is a flexible solution for kitchen ventilation where heat loads are relatively low and aesthetics are a concern. The efficiency of the exhaust system should be specially emphasized with the ventilated ceiling systems where the exhaust is located at the ceiling level. The contaminant removal efficiency of the total system must be guaranteed and impurities spreading throughout the kitchen should be prevented. The supply air distribution strategy has a remarkable influence on the pollutant removal effectiveness. The flush-out effect of the supply air reduces the containment removal efficiency by circulating pollutants of the induced convection flow back to the occupied zone. The conducted laboratory measurements of a ventilated ceiling demonstrate that the capture and containment efficiency can be 85–93% using the concept of a low velocity ceiling supply and centralized capture jet and as high as 98% with the displacement system at the floor level. Using the ceiling supply and capture jet concept, the contaminant removal efficiency of 85% is reached by increasing the airflow rate 20% compared with the theoretical plume equation.

Keywords: Ventilation efficiency; Ventilated ceiling; Kitchen ventilation

1. Introduction

Concerns over the indoor environment have increased during recent years as a result of the knowledge about the significance of thermal conditions and air quality on health, comfort and productivity of the workforce. In a commercial kitchen, working conditions are especially demanding. There are four main factors affecting the thermal comfort, these being: air temperature, thermal radiation, air velocity and air humidity. At the same time, high emission rates of contaminants are released from the cooking process. Ventilation plays an important role in providing comfortable and productive working conditions and in securing the contaminant removal.

Existing studies demonstrate quite clearly the health risk of cooking. Thiebaud et al. [1] indicate that the fumes generated by frying pork and beef are mutagenic. Hence, the chefs are exposed to relatively high levels of airborne mutagens and carcinogens. Vainiotalo and Matveinen [2] carried out measurements at eight workplaces. His survey confirmed that cooking fumes contain hazardous components. It also indicated that kitchen workers may be exposed to relatively high concentration of airborne impurities.

The previous studies depict the importance of well-designed ventilation in the kitchen. The removal efficiency of the total system must be guaranteed and impurities spreading throughout the kitchen should be prevented. Based on the sensible heat load, the requested airflow rate is possible to calculate. As for the heat load method, consideration is made for the convective heat output of the cooking appliance, the area of exposure and the distance to the extract. The main idea is to adjust the required airflow rate according to the thermal plume of a kitchen appliance. The most well-known code which utilizes this approach in the commercial kitchen environment is German VDI [3].

It should be noted that the supply air distribution strategy has a remarkable influence on the pollution removal effectiveness. The flush-out effect of the supply air reduces the containment efficiency by circulating pollutants in the induced convection flow back to the occupied zone. That is why the extract airflow rate must be higher than the theoretically calculated convection load indicates.

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Nomenclature

c_o	pollution concentration outdoors/surrounding area (kg/m^3)
c_{occ}	pollution concentration in the occupied zone (kg/m^3)
c_{exh}	pollution concentration in the exhaust air (kg/m^3)
D_h	hydraulic diameter (m)
k	installation factor of the kitchen appliance in plume calculation
L	length of a heat source (m)
$q_{v,\,esc}$	escaped airflow rate (m^3/s)
$q_{v,\,exh}$	exhaust airflow rate (m^3/s)
$q_{v,\,sup}$	supply airflow rate (m^3/s)
S_p	pollution emission (kg/s)
W	width of a heat source (m)
z	vertical distance (m)
Φ_{conv}	convective heat gain (W)
η_{exh}	capture efficiency

VDI [3] proposes for the hood design flush-out factors of 1.05 and 1.10 for the floor level and laminar ceiling supply, respectively. For the tangential ceiling supply, the factor should be 1.25 according to VDI standard [3]. At the moment, there is no published specific standard for design of ventilated ceilings.

In a laboratory study of the kitchen hood efficiency [4], it is demonstrated that the supply air system has a significant effect on the ventilation efficiency. In that study, the thermal displacement ventilation system gives the highest effectiveness. A computational fluid dynamics (CFD) modelling study [5] shows that the selection of the supply air strategy has also an effect on the thermal comfort and thus productivity of the workers.

The ventilated ceiling approach offers a flexible solution for kitchens where the heat loads are relatively low and aesthetics are a concern [6]. With the ventilated ceiling, it is possible to maintain good thermal conditions in the occupied zone with reasonable airflow rate [7,8]. Structurally, the system consists of a stainless-steel element that covers either the entire ceiling or only the active cooking area of a kitchen. This element incorporates the air inlets, exhaust air outlets (including grease filters), and light fittings.

In an earlier study, it is demonstrated that the efficiency of the ceiling exhaust can be improved with a small capture jet installed at the ceiling surface. For a ventilated ceiling, the capture jet could improve the total effectiveness of the ventilation system by reducing the average contaminant level in the occupied zone by 40% [9]. In another study [10], a capture efficiency model is derived and validated with measurements of a simple one-appliance mock-up kitchen [11]. The conducted measurements show that with the capture jet concept a containment removal efficiency of 85–90% is possible.

This paper is a logical continuation of the recent studies by Kosonen and Mustakallio [9,10] on the influence of the supply air systems on pollution removal effectiveness of a ventilated ceiling. The previous studies of a one-appliance mock-up have demonstrated that it is possible to improve the capture and containment efficiency with the capture jet. To obtain a more generic view, the laboratory measurements of an appliance block were conducted with different capture jet concepts. As a reference system, the containment removal efficiency of the thermal displacement system was also studied. Based on the conducted measurements, the flush-out factor of the supply air in the theoretical plume equation is derived.

2. Research method

The principal idea of the measurements is to analyse the effect of different capture jet concepts on the efficiency of a ventilated ceiling. In this study, the containment removal efficiency was evaluated using laboratory measurements in a case-study kitchen. In practical applications, the measured data can be utilized in improving the accuracy of the existing design practice of the ventilation ceiling in commercial kitchens.

2.1. The case-study kitchen

The measurements were performed in laboratory conditions with a mock-up kitchen at Halton's facilities. In the case-study kitchen, the kitchen appliance block consists three electric appliances: (1) a griddle (Fig. 1), (2) an iron range (Fig. 2) and (3) a combi (combination of a hot plate and a griddle) (Fig. 3). The studied appliance block represents the state-of-the art technology of kitchen appliances. During the part-load conditions tests, the actual power of the electric appliances was measured with a clip-on-ammeter. The total heat load of the appliance block was 7.9 kW. The description of the appliances, the temperatures of the cooking area and the electric loads are presented in Table 1.

The studied ventilated ceiling system consists of stainless-steel elements that cover the entire ceiling area. The ceiling comprised exhaust, supply and capture jet units, with lights and ceiling elements between the exhaust and supply units. The capture jet air is supplied horizontally across the ceiling. This jet helps to direct heat and air impurities towards the exhaust.

The measurements were carried out in a case-study kitchen room with the ventilated ceiling dimension of 5.8 m × 5.8 m and a height of 2.6 m. In the case-study kitchen, there are two exhaust (E1 and E2) and two supply

Fig. 1. The used griddle in the study.

Fig. 2. The used iron range in the study.

units (S1 and S2) equipped with the capture jet units (CJ1–CJ3), Fig. 4.

In the test kitchen, also installed is a corner-type floor mounted low velocity unit. Depending on the ventilated strategy employed, the selected supply and exhaust modules were enabled. In most of the conducted tests, the kitchen appliance block was installed close to the wall under the exhaust unit E1. In one test case, an island type of installation was used and the same appliance block was installed underneath the exhaust unit E2.

The effect of the selected ventilation concept on the contaminant removal efficiency was studied with a tracer gas method. In this study, the constant concentration dosing method was employed. The gas analyser together with the sampler and doser unit and a controller computer makes it possible to perform multi-point monitoring and dosing tasks. The tracer gas used in this study was SF6. During the test, SF6 concentrations were sampled at 10-min intervals and the total length of the tests varied between 1.5 and 2.5 h getting representative conditions. For the dosing system, the volume flow rate of the tracer gas supply was adjusted to give reasonable concentrations. The dosing point was installed just over the hot plate of the combi.

The sampling system has six inlet channels and one dosing channel. Four sampling points (P3–P6) are located close to the breathing zone at 1.6 m level from the floor in the occupied zone. In addition, there are sampling points in the exhaust and supply ductwork. The location of the dosing and sampling points are presented in Fig. 5.

Fig. 3. The used combi (combination of hot plate and griddle) in the study.

It should be noted that a minor part of the tracer gas was re-circulated back to the supply air because the exhaust air of the laboratory facilities is released in the same factory

Table 1
Description of the kitchen appliances in the measured appliance block

Appliance	Dimension	Power rating (kW)	Actual capacity (kW)	Surface temperature (°C)
Griddle	800 × 900 × 920 (H)	11.1	4.0	170
Iron range	400 × 900 × 900 (H)	10.2	2.6	300
Combi (hot plate and griddle)	1300 × 800 × 950 (H)	11.2	1.3	260
The whole appliance block	2500 × 800–900 × 900–950 (H)	32.5	7.9	185

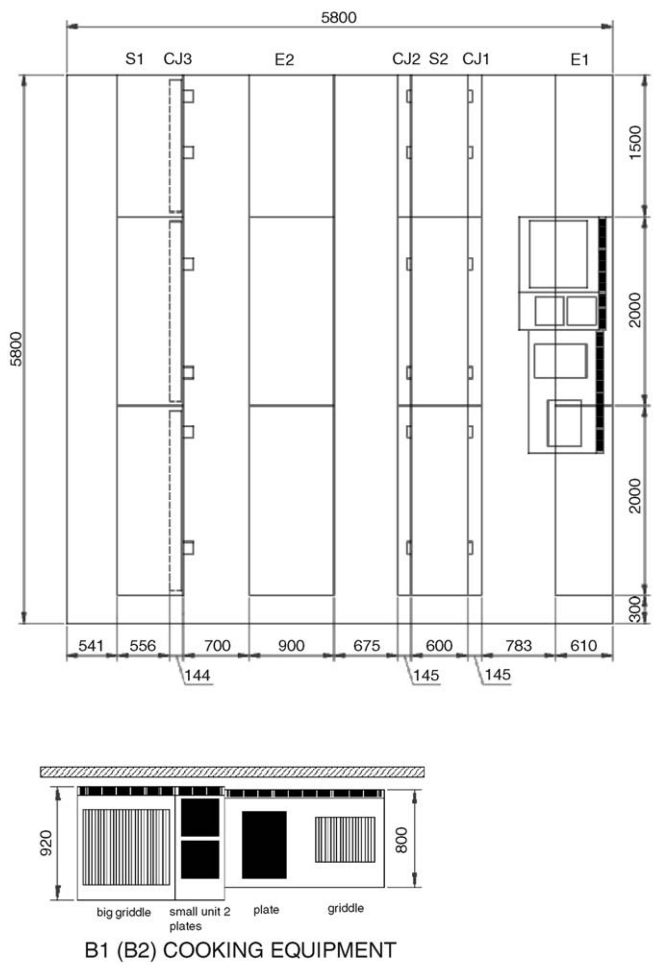

Fig. 4. The layout of the case-study kitchen and the locations of the exhaust (E1 and E2), supply (S1 and S2) and the capture jet units (CJ1–CJ3). The supply and exhaust units are built with two 2.0 m and one 1.5 m modules.

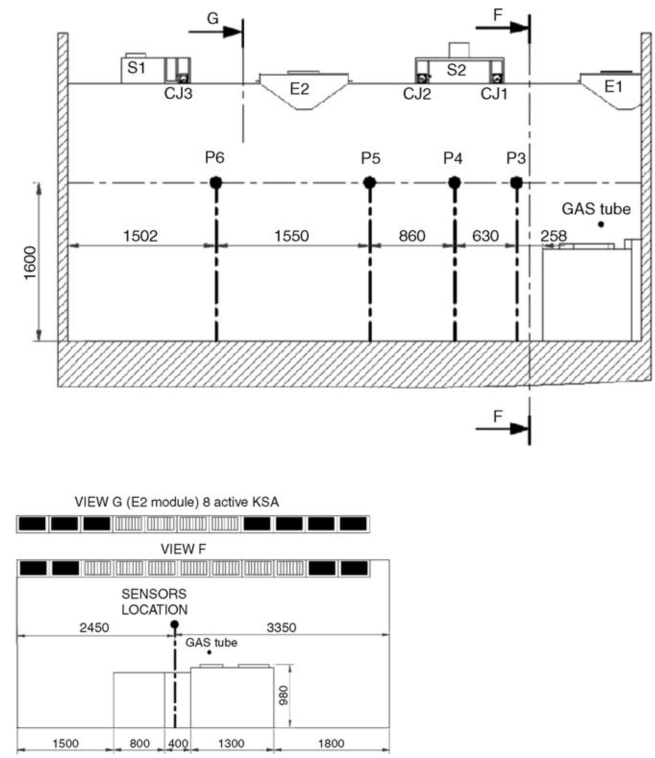

Fig. 5. The locations of the tracer gas dosing and sampling points.

hall where the supply air was taken. The effect of the tracer gas concentration in the supply side was taken into account when the containment removal efficiency was calculated.

2.2. Supply and exhaust concepts

In the study, there were two basic capture jet concepts: (1) full-length and (2) centralized exhaust and capture jet. As a reference system, the thermal displacement is studied without the capture jet. In the tests, the exhaust and supply airflow rates are varied between 580 and 1200 l/s. Infiltration from the surrounding space was controlled by balancing the exhaust and supply airflow rates. In all tests, the capture jet was fixed at 10% of the exhaust airflow rate. Fig. 6 presents the studied capture jet concepts, the airflow rates of the total modules and the active parts of the exhaust and capture jet modules.

In the full-length exhaust and capture jet concepts, the total length of the supply and exhaust modules were utilized. In the centralized concepts, the active parts situated mainly over the appliance block were used. The effect of the location of supply unit was also analysed by introducing the supply air close to the opposite wall using the centralized concept.

The supply and exhaust units were built with two 2.0 m and one 1.5 m modules. In the exhaust modules, there were three (1.5 m) or four (2.0 m) lengths of 500 mm grease filters. In the tests, there were activated 11 (the full-length concept) and seven filters (centralized concept) of the exhaust unit E1 in the wall type of the kitchen appliance installation. In the island type of the kitchen appliance

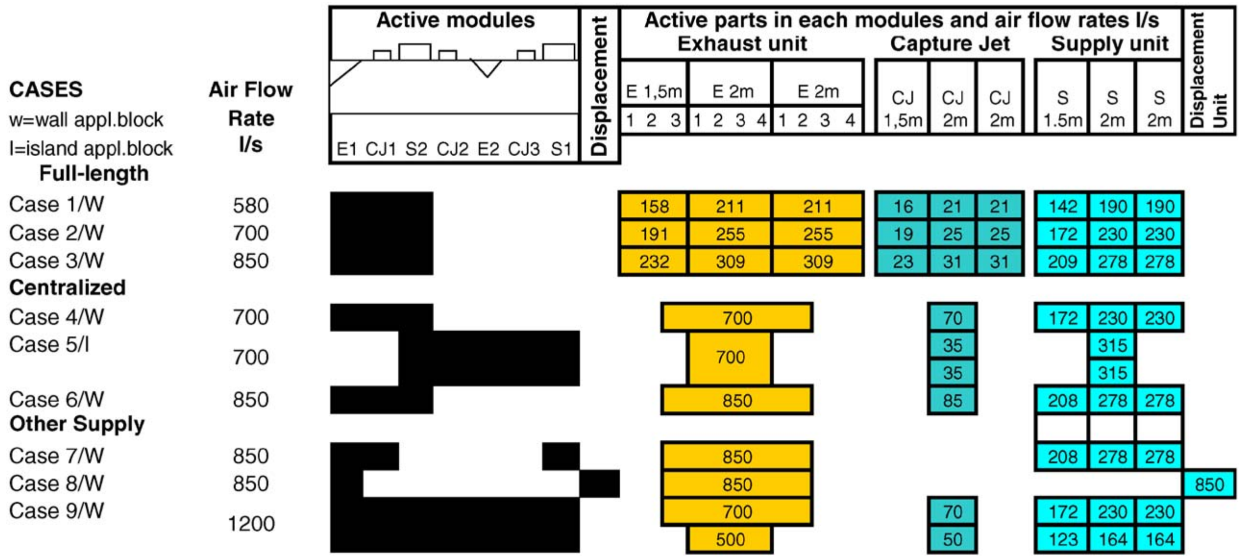

Fig. 6. The description of the supply air cases.

installation, there were four activate filters in both sides of the central exhaust module E2. Altogether, that means eight activated filters of the exhaust unit E2 in the island type of the installation (Fig. 6).

In a separate test, the impact on efficiency of activating two exhaust and supply units at the same time was also studied. In all the previous tests, the kitchen appliance block was locating close the wall. In one test, the appliance block was an island-type installation and both of the supply units (S1 and S2) were employed together with the exhaust unit (E2).

2.3. Concepts of capture efficiency

In any of the kitchen ventilation standards and design guides, there is no mention of any special targets for the capture efficiency of hoods or ventilated ceilings. The main idea in design practice has been to adjust the airflow rate to a value which is sufficient to extract the convective heat and contaminants from the occupied zone.

It is common practice to characterize contaminant removal performance of kitchen hood in terms of capture efficiency. Capture efficiency is defined as a ratio between the flow rate of captured contaminant and the total emission rate of contaminants from the source. Although fairly simple in principle, it is not obvious how to estimate capture efficiency of kitchen extract system.

Consider a local exhaust opening with the airflow rate of $q_{\mathrm{v,exh}}$ (m^3/s) at a source of constant emission rate S_{p} (kg/s). At the steady-state conditions, the capture rate of the exhaust is S_{exh} and the concentration at the exhaust point is c_{exh} (kg/m^3).

Then the total capture efficiency is

$$\eta_{\mathrm{exh}} = \frac{S_{\mathrm{exh}}}{S_{\mathrm{p}}} = \frac{q_{\mathrm{v,exh}} c_{\mathrm{exh}}}{S_{\mathrm{p}}}. \tag{1}$$

It is also possible to derive the capture efficiency using the emission rate escaping (S_{esc}) from the hood:

$$\eta_{\mathrm{exh}} = \frac{S_{\mathrm{exh}}}{S_{\mathrm{p}}} = \frac{S_{\mathrm{p}} - S_{\mathrm{esc}}}{S_{\mathrm{p}}}. \tag{2}$$

There are some practical problems as pointed out by Li and Delsante [12] to use previous Eqs. (1) and (2) in a confined space where there is no general exhaust. If a kitchen space is airtight, the mass balance requires that the contaminant flow rate is equal to the contaminant generated at the source. In other words, the mass flow extracted from the space is the same as that released into the space. The capture efficiency calculated with Eq. (1) gives therefore 100%. In addition, if there is high infiltration (even open space), the escaped contaminant does not cause any significant change in the concentration of the room space.

The concept of direct capture efficiency is proposed by Jansson [13] and Madsen et al. [14]. This approach is also used in the industrial design guidebook [15]. In this approach, the captured contaminants are divided into two parts: (1) the direct captured contaminants by the local exhaust and (2) at first escaped and after that captured contaminants by the local exhaust.

However, there are measurement and numerical calculation problems to distinguish the rate of direct captured contaminants from the total captured contaminants and only an estimation of these factors is possible. Also, to focus only on the direct capture efficiency is not applicable in a ventilated ceiling environment where the pollutants are removed normally from several extract points in the upper zone.

In a kitchen space, it is possible to derive mass conservation of the contaminant to the whole room and on the other hand to the occupied zone (Fig. 7). The room balance is determined assuming that the room air is

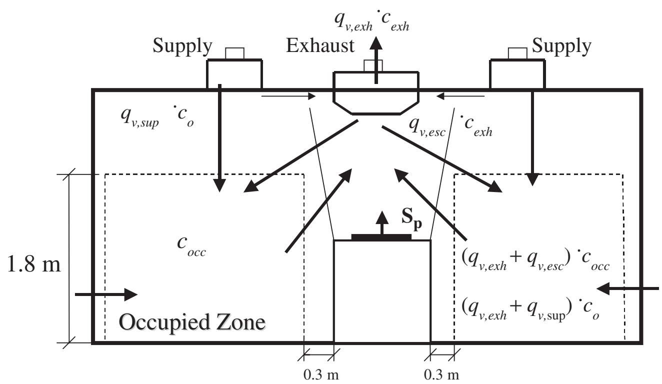

Fig. 7. A two-zone model for a ventilated ceiling.

totally mixed:

$$S_p + (q_{v,exh} - q_{v,sup})c_o + q_{v,sup}c_o = q_{v,exh}c_{exh}, \tag{3}$$

where C_o is the pollution concentration outdoors/surrounding areas (kg/m^3), and $q_{v,sup}$ the supply airflow rate (m^3/s).

The mass balance of the occupied zone is given by

$$(q_{v,exh} - q_{v,sup})c_o + q_{v,sup}c_o + q_{v,esc}c_{exh} = (q_{v,esc} + q_{v,exh})c_{occ}, \tag{4}$$

where c_{occ} is the pollution concentration in the occupied zone (kg/m^3), and $q_{v,esc}$ the escaped airflow rate (m^3/s).

After rearrangement, we have

$$S_p = q_{v,exh}(c_{exh} - c_o), \tag{5}$$

$$q_{v,esc} = q_{v,exh}\frac{(c_{occ} - c_o)}{(c_{exh} - c_{occ})}. \tag{6}$$

Defining the capture efficiency as the ratio of captured contaminants to the total contaminant source (incl. contaminant source and contaminant in the induction air), we have

$$\eta_{exh} = \frac{q_{v,exh}c_{exh}}{S_p + (q_{v,exh} + q_{v,esc})c_{occ}}. \tag{7}$$

Substituting Eqs. (4) and (5) into Eq. (7):

$$\eta_{exh} = \frac{q_{v,exh}}{q_{v,exh} + q_{v,esc}}. \tag{8}$$

Substituting Eq. (6) into Eq. (8) gives

$$\eta_{exh} = \frac{1}{1 + ((c_{occ} - c_o)/(c_{exh} - c_{occ}))}. \tag{9}$$

After rearrangement, we have Eq. (10) that gives a practical platform to analyse the capture efficiency of a ventilated ceiling:

$$\eta_{exh} = 1 - \frac{c_{occ} - c_o}{c_{exh} - c_0}. \tag{10}$$

3. Results

The containment removal efficiency was evaluated using laboratory measurements in a case-study kitchen with different capture jet concepts. The contaminant removal efficiency was calculated by taking into account that part of the tracer gas emission re-circulated back into the room space through the supply airflow rate. As a reference system, the containment removal efficiency of the thermal displacement system was also studied. The effect of supply air system on the efficiency of a ventilated ceiling was analysed. For practical design, the flush-out factor of the supply air on the theoretical plume equation was introduced.

3.1. Full-length capture jet concept

The trace gas concentrations of the full-length capture jet concept are presented in Fig. 8 with three different airflow rates (580, 700 and 850 l/s). In the full-length exhaust and capture jet concepts, the total length of the supply and exhaust modules were utilized.

The airflow rates of 580 and 700 l/s were not sufficient to remove pollutants from the occupied zone. Specifically, the containment level below the supply unit (P4) was high. Also in the point 4, the concentration fluctuated quite a lot. The airflow rate of 850 l/s gave much better performance. Still, the concentration level close to the appliance block (P3 and P4) remained relatively high compared with the points (P5 and P6) further from the appliances.

Table 2 describes the containment removal efficiency. The airflow rates of 580 and 700 l/s gave an average containment removal efficiency of 28% and 67%, respectively. With the airflow rate of 850 l/s, it was possible to reach an average efficiency of 85%. But as the concentrations depict in Fig. 8, the efficiency was much lower close to the appliance block. Close, the efficiency was lower than 80% whilst further away the efficiency was equal to 90%.

3.2. Centralized capture jet concept

The trace gas concentrations of the centralized capture jet concept in the wall and island type of kitchen appliance block installation are presented in Fig. 9. The wall installation was measured with two airflow rates (700 and 850 l/s) and the island type of installation with one airflow rate (700 l/s). In the centralized concepts, the active parts of the exhaust and capture jet units were used just over the appliance block. The rest of the parts were closed in these cases.

In all of the centralized capture jet concepts, the concentration levels in the occupied zone were low and the performance of the exhaust system were quite stable. The centralized capture jet concept functions much better than the full-length capture jet concept by focussing the extract point and the assisting capture jet just over the emission source.

Table 3 describes the containment removal efficiency. In the wall installation, the airflow rate of 700 and 850 l/s attained an average efficiency of 88% and 94%, respectively. This was about 10% higher than with the full-length capture jet concept. In all cases, the difference in contaminant removal efficiency across the room space was not significant. Thus, the centralized capture jet concept created constant conditions in the different parts of the working area.

In the island type of the kitchen appliance installation, the average contaminant removal efficiency was 82% with an airflow rate of 700 l/s. Comparing this to the efficiency of the wall type of kitchen appliance block installation at the airflow rate of 700 l/s, the contaminant removal efficiency was about 6% lower.

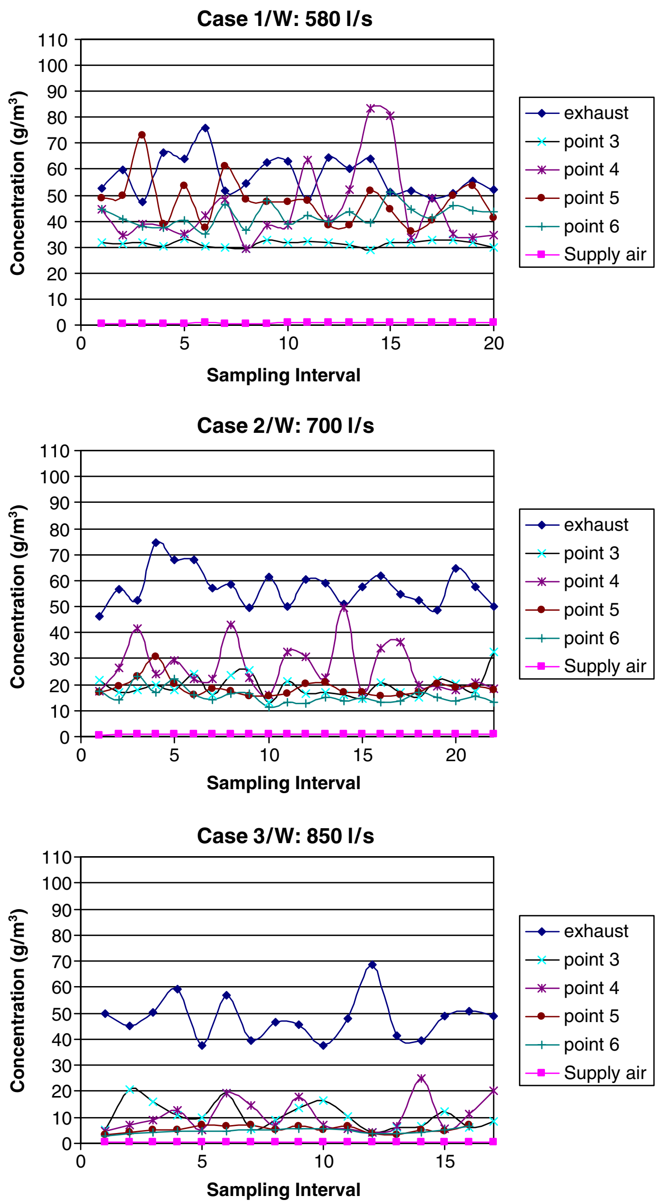

Fig. 8. Concentrations of the full-length capture jet concept in the occupied zone, supply and exhaust air with three different airflow rates.

3.3. Other supply air concept

The contaminant removal efficiency was also studied with the following concepts using the wall type of kitchen appliance installation:

- The capture jet concept when the supply air was introduced close the opposite wall (case 7/W).
- The thermal displacement concept without any capture jet in the ceiling (case 8/W).
- The capture jet concept with two active exhaust and supply units (case 9/W).

The trace gas concentrations are presented in Fig. 10. With the opposite wall supply (850 l/s) and the thermal displacement (850 l/s), the exhaust system worked effectively and the performance of the system was stable. In the concept of all supply and exhaust units being activated (1200 l/s), the concentration levels close the appliance block (P3 and P4) were high. This indicated that the two active supply and capture jet units increased re-circulation of the emission back to the occupied zone.

In Table 4, the containment removal efficiency is shown. With the opposite wall supply concept (850 l/s), the average efficiency was 94%. The efficiency was at the same level as with the concept where the supply was released close to the appliance block. This demonstrates that by locating the supply further from the appliances, there is no improvement in the contaminant removal efficiency. The thermal displacement concept gave the highest efficiency: the efficiency was about 99%. With the same airflow rate (850 l/s), the average efficiency was about 5% higher than the centralized capture jet concept.

Table 2
Average concentrations and pollutant removal efficiency with the full-length exhaust and capture jet concept

Cases	Concentrations		Concentrations and pollutant removal efficiency								Average efficiency	
Exhaust flow rate $q_{v,exh}$ (l/s)	Exhaust P1 (ppm)	Supply P2 (ppm)	P3 (ppm)	Eff. P3 (%)	P4 (ppm)	Eff. P4 (%)	P5 (ppm)	Eff. P5 (%)	P6 (ppm)	Eff. P6 (%)	Average (P3–P6) (ppm)	Average efficiency (%)
Case 1/W: 580	57.1	0.7	31.4	45.7	44.7	22.0	47.4	17.3	42.0	26.7	41.4	27.9
Case 2/W: 700	57.3	0.91	18.0	69.7	25.8	56.0	18.6	68.6	15.4	74.3	19.4	67.1
Case 3/W: 850	47.9	0.5	10.6	78.7	10.7	78.4	5.4	89.7	4.7	91.1	7.8	84.5

The appliance block is installed close the wall.

In the concept where two exhaust (700 and 500 l/s) and supply units are used, the contaminant removal efficiency close to the appliance block was lower (74–80%) than with the centralized capture jet concept with one exhaust unit of 700 l/s (87–88%). However, the difference between the average contaminant removal efficiency was not significant. This depicts that part of the lost efficiency close the appliance can be recovered with the second exhaust further from the appliance block.

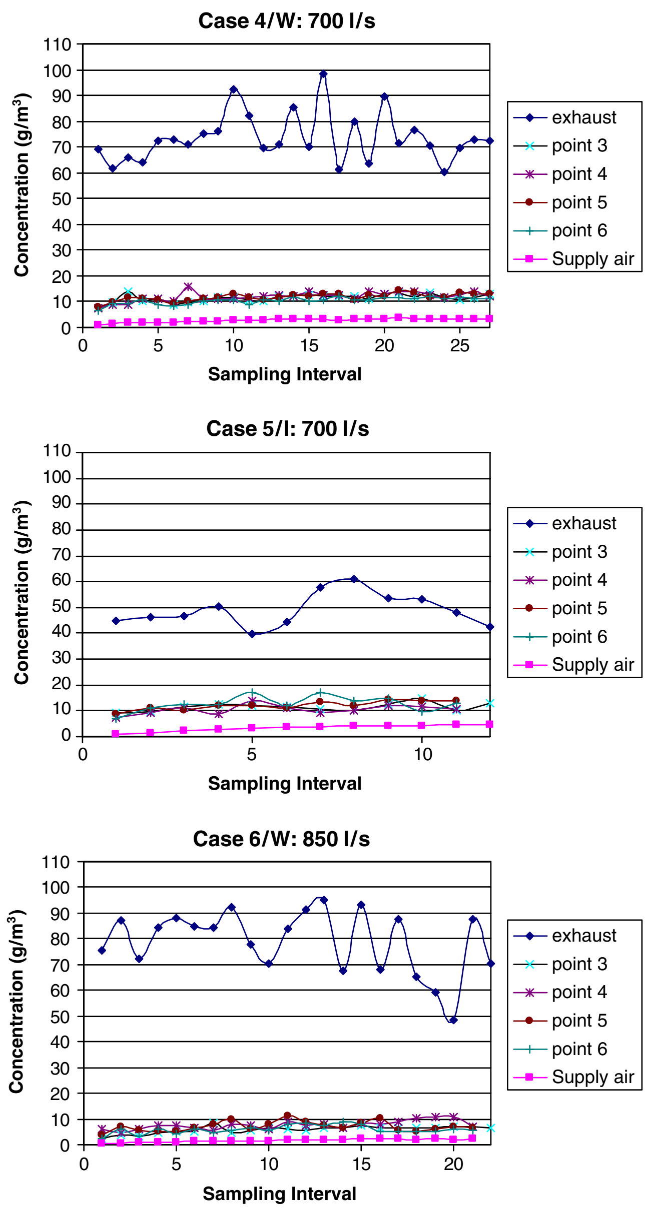

Fig. 9. Concentrations of the centralized capture jet concept in the occupied zone, supply and exhaust air with three different airflow rates.

3.4. Flush-out factor of the supply air

The plume equation gives a platform to calculate the airflow rate that is theoretically required to remove the convective heat output of the appliance block. In this study, the flush-out factor of the supply air on the theoretical plume equation was derived for the centralized capture jet concept.

Measured contaminant removal efficiencies were compared with the generic plume equation of VDI [3], Eqs. (11) and (12). In VDI, the virtual origin is set to be at $1.7D_{\mathrm{h}}$ below the surface of the appliance:

$$q_{\mathrm{v}} = 5(z + D_{\mathrm{h}})^{5/3}\Phi_{\mathrm{conv}}^{1/3}k, \tag{11}$$

where q_{v} is the airflow rate in convective plume ($\mathrm{m^3/s}$), z is the height above the cooking surface (m), D_{h} is the hydraulic diameter of the appliance (m), Φ_{conv} is the convective heat output of the cooking appliance (W), and k is the installation factor of the kitchen appliance block (island $k = 1.0$ and wall $k = 0.63$).

$$D_{\mathrm{h}} = \frac{2LW}{L + W}, \tag{12}$$

where L, W are the length and width of the cooking surface (m).

Fig. 11 describes the results of the computed theoretical convection airflow rate of the studied kitchen appliance block using both the wall- and island-type installation.

Based on the conducted measurements of the centralized capture jet concept, it is possible to derive a correlation between the airflow rate and the contaminant removal efficiency by employing the theoretical plume equation. The ceiling height of 2.7 m in this study leads 491 l/s in the wall and 780 l/s in the island type of installation.

Fig. 12 presents the ratio of the used airflow rate and theoretical convection flow (flush-out factor) as a function of the containment removal efficiency. Obtaining 85% and

Table 3
Average concentrations and pollutant removal efficiency with centralized exhaust and capture jet concept

Cases	Concentrations		Concentrations and pollutant removal efficiency								Average efficiency	
Exhaust flow rate $q_{\mathrm{v,exh}}$ (l/s)	Exhaust P1 (ppm)	Supply P2 (ppm)	P3 (ppm)	Eff. P3 (%)	P4 (ppm)	Eff. P4 (%)	P5 (ppm)	Eff. P5 (%)	P6 (ppm)	Eff. P6 (%)	Average (P3–P6) (ppm)	Average efficiency (%)
Case 4/W: 700	73.5	2.8	11.4	87.8	11.9	87.0	11.7	87.3	10.4	89.2	11.4	87.8
Case 5/I: 700	49.2	3.3	11.5	82.1	10.5	84.3	12.1	80.8	12.8	79.2	11.7	81.6
Case 6/W: 850	78.9	1.6	5.9	94.5	7.6	92.2	7.0	93.0	5.9	94.5	6.6	93.6

The appliance block is wall- or island-type installed.

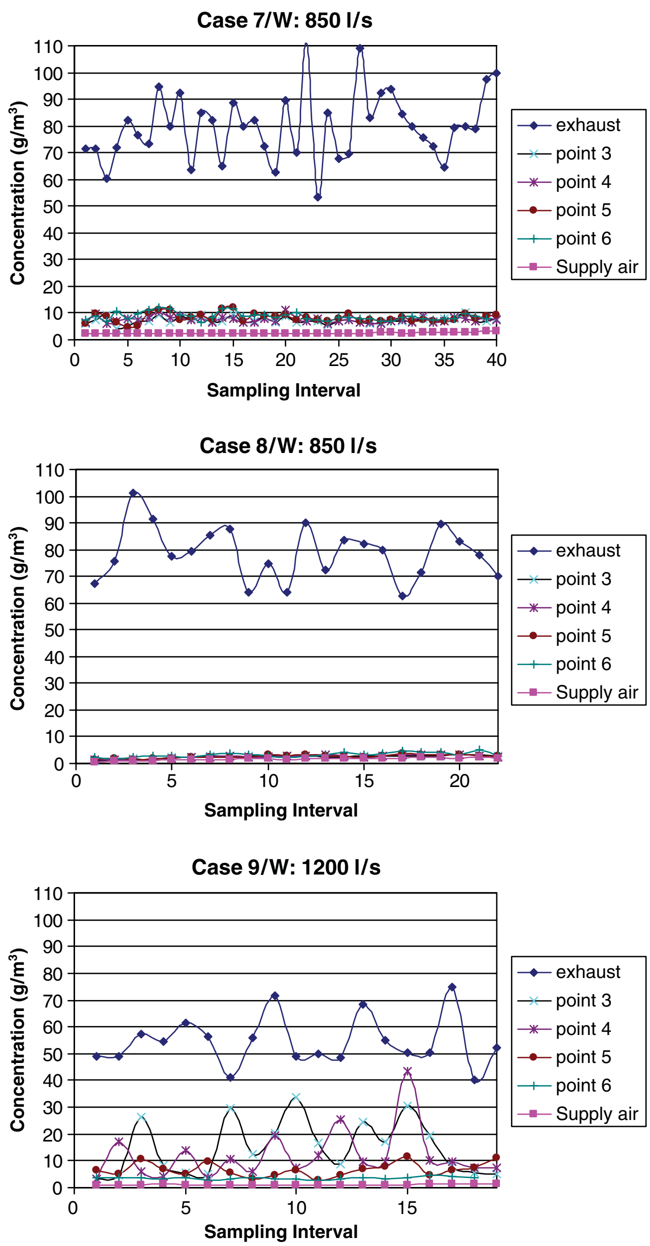

Fig. 10. Concentrations of the reference systems (opposite wall supply, thermal displacement ventilation and two active supply/exhaust units) in the occupied zone, supply and exhaust air.

90% containment removal efficiency leads to a flush-out factor of 1.2 and 1.5.

4. Discussion

The ventilated ceiling is a solution for kitchen ventilation where heat loads are relatively low and aesthetics are a concern. The ventilated ceiling is a good ventilation solution for food service facilities like institutional kitchens and restaurants.

The ventilated ceiling comprises exhaust, supply and capture jet units, lights and structural ceiling elements between the exhaust and the supply units. Capture jet air is projected horizontally across the ceiling. This jet helps to direct heat and air impurities towards the exhaust making use of a push–pull ventilation strategy.

CFD simulations and previous measurements [9,10] have demonstrated that the capture jet could help to improve the total effectiveness of the ventilation system. In an earlier study, the capture jet has shown to improve the total effectiveness of the ventilation system by reducing the average contaminant level in the occupied zone by 40%. At the same time, indoor air quality, thermal comfort and energy efficiency are enhanced.

The supply air distribution strategy has a marked influence on pollution removal effectiveness and thermal conditions. The conducted measurements indicate that it is possible to improve the containment removal efficiency of the previously utilized full-length capture jet concept by centralizing the capture jet and exhaust just over the kitchen appliance block. With the same exhaust airflow rate, the efficiency was about 10% higher than with the full-length concept. Also using the full-length supply, the concentration level close to the appliance block remained at a higher level compared with the points further from the appliances. With the centralized capture jet concept, the concentrations over the working area are almost constant.

In the concept where the supply unit is moved about 4.3 m from the exhaust unit, the containment removal efficiency was not improved. The efficiency was at the same level as that concept where the supply was released about 0.65 m from the appliance block. This demonstrates that the performance of the supply and capture jet unit is quite good even relatively close to the kitchen appliances and the

Table 4
Average concentrations and pollutant removal efficiency with centralized exhaust

Cases	Concentrations		Concentrations and pollutant removal efficiency								Average efficiency	
Exhaust flow rate $q_{v,exh}$ (l/s)	Exhaust P1 (ppm)	Supply P2 (ppm)	P3 (ppm)	Eff. P3 (%)	P4 (ppm)	Eff. P4 (%)	P5 (ppm)	Eff. P5 (%)	P6 (ppm)	Eff. P6 (%)	Average (P3–P6) (ppm)	Average efficiency (%)
Case 7/W: 850	80.0	2.7	7.3	94.1	7.6	93.6	8.2	92.8	8.5	92.4	7.9	93.2
Case 8/W: 850	79.2	1.6	2.5	98.9	2.5	98.8	2.6	98.8	3.2	98.0	2.7	98.7
Case 9/W: 1200	54.8	1.1	15.0	74.2	11.9	79.8	6.7	89.6	3.5	95.6	9.3	84.8

Supply air is introduced from laminar ceiling unit close the opposite wall, two ceiling supply units and thermal displacement units. The appliance block is wall-type installed.

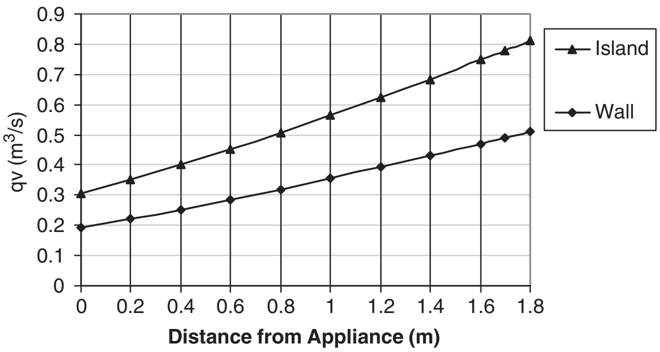

Fig. 11. Requested exhaust airflow rate of the theoretical plume equation as a function of distance from appliance in the wall and island installation.

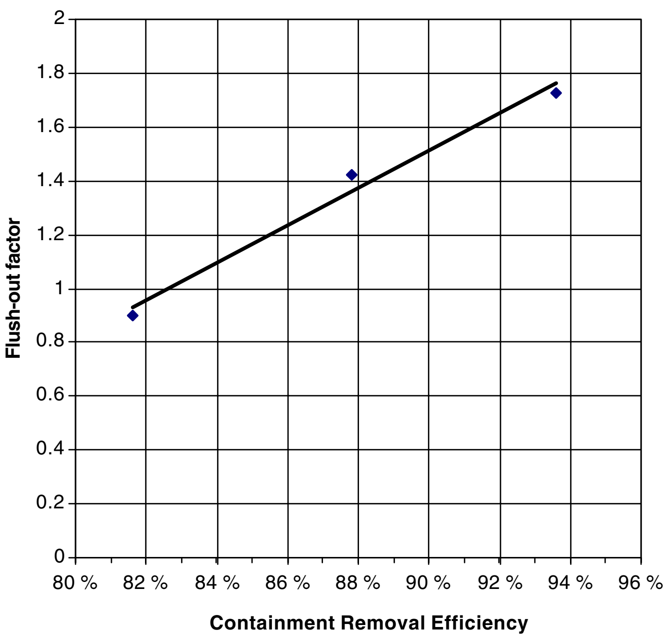

Fig. 12. The flush-out factor of the supply air as a function of the containment removal efficiency.

supply does not disturb the convection flow of the kitchen appliance block.

The concept where two exhaust (700 and 500 l/s) and supply units are employed, the contaminant removal efficiency close to the appliance block was even lower than with the centralized capture jet concept with one exhaust unit of 700 l/s. However, the average contaminant removal efficiency was about the same level. This demonstrates that the efficiency of the exhaust unit over the appliance block decreases if the total airflow rate is increased, but part of the lost efficiency can be recovered with a second exhaust. Still for the control strategy, it makes sense to use only the units over the appliance which are loaded. With the demand-based ventilation strategy, energy economy is enhanced and indoor air quality in the occupied zone is improved.

Thermal displacement ventilation has the best containment removal efficiency. It was possible to obtain a high ventilation efficiency (98%).The average efficiency was about 5% higher than with the centralized capture jet concept. However in practice, the utilization of a thermal displacement ventilation system may be difficult because of the space constrain in the kitchen. However, if the space permits, the thermal displacement ventilation method must be the first option for the supply air solution.

The most accurate design method of kitchen ventilation is based on heat gain of the appliances. In this method, consideration is given to the convective heat output, the area of the appliance and the distance between extract point and appliance. Using theoretical plume equation where the location of the virtual origin is fixed, it is possible to compute the requested airflow rate [3]. For the design method, it is important to specify the factor of the supply air on the requested exhaust airflow rate that is specially valid for the ventilated ceiling system by taking into account the interaction between the convection load and the supply airflow rate.

Based on the conducted measurements of the centralized capture jet concept, it is possible to derive a correlation of the used airflow rate and theoretical convection flow (flush-out factor) as a function of the containment removal efficiency. To obtain 85% and 90% containment removal efficiency, it leads to a flush-out factor of 1.2 and 1.5 with the centralized capture jet concept.

At the moment, there are no standardized target values of capture and containment efficiency even with kitchen hoods in any code of practice. To get some kind of perspective, we can use previous VDI [16] as a basis. In the previous VDI, a room energy balance approach is used. In that code of practice, a default value of room load factor of the hood is set to 0.8 if at least 80% of the kitchen exhaust air is removed via hoods. This assumes that if the convection ratio is a constant 50% and the general exhaust is 20% of the total exhaust airflow rate, the hood efficiency will be 67%.

In this estimation, the radiation load (50%) and general exhaust ration (20%) are coming directly into the space. The missing 10% from the total load of 80% is the spillage from the hood. From the continuity equation, the convection load of the hood is 30% of the total load. The captured convection load is 20%. The hood efficiency calculated convection load share of 20/30 is 67%.

It should be noted that increasing the airflow rate will reduce the absolute values of the contaminants. The main target should be to maintain the contaminant level at an acceptable level and use the capture efficiency as an indicator of the system efficiency. Fortunately, the required airflow rate of the convection load seems to be high enough to ensure acceptable pollutant levels. This is especially the case if the containment removal efficiency is good.

For practical design work, the target for the containment removal efficiency should be 85%. For typical kitchen ventilation requirements this provides good indoor air quality with no unnecessary increase in system airflow rates. This selected target for the efficiency means that 15% of the convection load is released in the room space. That should be taken into account in the cooling load calculation.

5. Conclusions

The main method in the design practice of kitchen ventilation has been the calculation of the airflow rate sufficient to extract the convective heat and contaminants. Undersized airflow rates could lead to indoor air problems and oversized ventilation system increases unnecessary energy consumption and the life-cycle costs of the system.

The supply air distribution strategy has a remarkable influence on the pollution removal effectiveness. The flush-out effect of the supply air reduces the containment removal efficiency by circulating pollutants of the induced convection flow back to the occupied zone. The conducted laboratory measurements of a ventilated ceiling demonstrate that the capture and containment efficiency can be 85–93% using the concept of a low velocity ceiling supply and centralized capture jet and as high as 98% with the floor supply, thermal displacement system. Using the ceiling supply and capture jet concept, the contaminant removal efficiency of 85% is reached by increasing the airflow rate 20% compared with the theoretical plume equation.

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