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Thermal plumes of kitchen appliances: Cooking mode

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Abstract

The main method in the design practice of kitchen ventilation has been the calculation of the airflow rate, which is sufficient to extract the convective heat and contaminants. Undersized airflow rates could lead into indoor air problems and oversized ventilation system increases unnecessary energy consumption and the life-cycle costs of the system. In the most accurate design method, the design of a kitchen ventilation system is based on the airflow rate of the thermal plume. When the convection flow is calculated, the influence of the cooking process is ignored. In this paper, the actual measured plume characteristics of typical kitchen appliances are presented during cooking mode. The conducted measurements show that the generic plume equation gives a suitable platform for practical applications during the cooking mode as well. The critical factors affecting the accuracy are the estimation of the actual convection load and the proper adjustment of the virtual origin.

Keywords: Heat load based design; Thermal plume; Kitchen ventilation; Displacement 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 workers. 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 [1] indicates 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 [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.

Although cigarette smoking is considered to be the most important cause of lung cancer, smoking behavior cannot fully explains the epidemiological characteristics of lung cancer among Asian women, who rarely smoke but contract lung cancer relatively often. Ng [3] found that over 97% of the women in Singapore do not smoke. Thus, the presumable sources of indoor air pollution for housewives are passive smoking and cooking. This study indicates that greater relative odds of respiratory symptoms were associated with the weekly frequency of gas cooking. Statistical link between chronic cough, phlegm and breathless on exertion was also found.

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 of the extract. The main idea is to adjust the required airflow rate according to the convection heat gain or, to be more specific, 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 [4].

The thermal load design is based on the idle mode. At the moment, there are no publications available about the effects of the actual cooking process on the thermal plume. In this paper,

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Nomenclature

D_h	hydraulic diameter (m)
E	kinetic energy (W)
H	enthalpy flux (W)
L	length of a heat source (m)
M	momentum flux (kg m/s^2)
R_T	profile width where $1/e$ of the maximum temperature is obtained (m)
R_v	profile width where $1/e$ of the maximum velocity is obtained (m)
T	temperature (°C)
W	width of a heat source (m)
a	product specific factor for the virtual origin
m	velocity distribution factor
p	temperature distribution factor
q_v	airflow rate (m^3/s)
v	velocity (m/s)
z	vertical distance (m)

Greek symbols

α	entrainment factor
δ	spreading angle of the plume profile
λ	ratio between temperature and velocity profile widths
Φ_{conv}	convective heat gain (W)

the actual plumes of typical kitchen appliances during the cooking process are presented according to the measurements at the laboratory of Finnish Institute of Occupation Health. Based on the conducted measurements, the effect of cooking on the plume characteristic and airflow rate is analyzed. The measurement results give background information to the design productive working environments where the established airflow rates are sufficient to remove odours and emissions of kitchen appliances. Also, an accurate design method of airflow rates prevents over sizing and enables optimizing the energy consumption of the ventilation system.

2. Research method

This paper is a logical continuation of in tandem study on thermal plumes of the kitchen appliance during the idle mode [5]. This study follows the same research method than the previous study. The principal idea of the measurements is to analyse the convection flows of the actual kitchen appliances during the cooking mode. In practical applications, the measured data can be utilized in improving the accuracy of the existing design practice of the ventilation airflow rates in commercial kitchen. In this study, the temperature and air velocity measurements were conducted to characterize thermal plumes of typical kitchen appliances in a laboratory environment when cooking take places.

The measurements were carried out in a test room with floor dimensions of 10 m × 4 m and a height of 6 m. During the measurements, the temperature difference between the average wall temperature of the test room and ambient air temperature at 1.1 m level was less than 2.0 °C. The temperature gradient in the room space varied depending on the tested appliance between 0.15 and 0.5 °C/m.

The supply airflow rate was released, using the displacement ventilation principle, at the floor level from six multi-nozzle ducts. The total supply airflow rate was 600 l/s and the supply temperature was about 20 °C.

Convection plumes from a iron range of 6 kW (500 mm × 800 mm × 950 mm (*H*)), a chrome range of 6 kW (500 mm × 800 mm × 950 mm (*H*)), a two burners gas range of 5.5 kW (burners of 2 and 3.5 kW, 400 mm × 650 mm × 460 mm (*H*)), an induction range of 10 kW (380 mm × 700 mm × 145 mm (*H*)), a fryer of 6.9 kW (360 mm × 435 mm × 260 mm mm (*H*)) and an induction griddle of 6 kW (520 mm × 440 mm × 175 mm (*H*)) were studied during the cooking mode. The cooking mode of the ranges was arranged by boiling water in two 10 l kettles. In the case of the induction griddle, cooking was executed by frying boneless chicken breast. In the fryer, the oil temperature was maintained at 180 °C.

During the tests, the actual power of the electric appliances was measured with a clip-on-ammeter. The power of the gas range was determined through the consumed quantity of gas. The velocity and temperature measurements were performed using a measurement robot. The convection heat load was determined from temperature and velocity measurements on horizontal planes. The probes were attached to a computer-controlled traversing system moving them from point to point and scanning the determined four measurement planes at the height of 0.8, 1.2, 1.6 and 2.0 m from the appliances. The basic measurement grid of 1.1 m × 1.1 m consists altogether of 121 measurement points (0.1 m interval) on each plane.

In this study, the air velocity was measured with Kaijo Denki WA-390 ultrasonic probes, which have an accuracy of 0.02 m/s. These sensors measure air velocity vector components with three pairs of ultrasonic transducers by registering the flight time of an ultrasonic pulse. Air temperatures were measured with Fenwal thermistors with an accuracy of 0.1 K. Measurements of air velocity and temperatures were time averages over 60 s and the values were recorded with a data logger. The radiation effect of the iron range on the temperature probes was corrected by separate reference measurements.

In the case of the induction griddle, the ultrasonic probes could not be used to the air velocity measurements because of the contaminants released in the frying process. In this case, the more robust omnidirectional TSI 1620 hot sphere velocity probes were used instead. The output of these sensors was later compared with the ultrasonic sensors by a separate plume measurement without the frying and a calibration curve was determined to correct the reading of the omnidirectional sensors. The requirement for this correction comes from different measurement principles of the two sensor types. The time-averaged reading of the omnidirectional sensors is affected by turbulent fluctuations, which must be corrected when calculating the flow rate through the measurement plane. The averaging time was also reduced in the induction griddle measurement to 30 s because of the time constraints of the frying.

3. Results

Velocity and temperature profiles from an electric range, a chrome range, a gas range, an induction range, a fryer and an induction griddle were measured in the cooking mode. Based on the conducted measurements, the actual plume characteristics are analyzed.

3.1. Velocity and temperature profiles of the iron range

In the simulated cooking measurement, the used power of the appliance was 5.44 kW during boiling water in two 10 l kettles. The measured convection and boiling powers were 1.14 kW (21.0%) and 3.57 kW (65.5%). Thus, radiation was 0.73 kW (13.4%). On the corners of the cooking plates, temperatures varied locally between 340 and 350 °C. The measured face surface temperatures range was between 32 and 66 °C.

Velocity profiles of the iron range were measured at four different heights (0.8, 1.2, 1.6 and 2.0 m) from the surface of the appliance (Fig. 1). In all conducted measurements, the average temperature gradient was 0.45 °C/m between the heights of 1 and 3 m.

The velocity profiles and distributions depict that the plume is quite compact and the maximum velocity does not significantly decrease as a function of the distance. The location of the maximum velocity of the convection flow moved both in *y*- and *x*-direction as a function of the distance. Still, the maximum velocity at different levels stays almost constant at 0.9 m/s.

The maximum air temperature was 41.8 °C at 0.8 m level. At level of 1.2 m, the maximum temperature was reduced to 35.3 and 29.9 °C at 1.6 m level. Still at 2.0 m level, the maximum temperature was 27.3 °C. During the measurements, the surrounding air temperature was between 21.0 and 21.2 °C measured at 2.0 m level from the floor.

3.2. Velocity and temperature profiles of the chrome range

In the chrome range the measured power of the appliance was 6.27 kW during boiling water in two 10 l kettles. The measured convection and boiling powers were 1.37 kW (21.9%) and 3.97 kW (63.3%). Thus, radiation was 0.93 kW (14.8%). In the cooking mode, surface temperatures of the cooking area varied temporally between 380 and 440 °C. The measured face surface temperatures varied locally between 28 and 107 °C.

Velocity profiles of the chrome range were measured at four different heights (0.8, 1.2, 1.6 and 2.0 m) (Fig. 2). In all conducted measurements, the average temperature gradient was 0.45 °C/m between the heights of 1 and 3 m. The maximum velocity at different levels was between 0.81 and 0.86 m/s. The centre point of the plume stayed at the same horizontal position when the plume rised. Only, the maximum velocity was moved at the level of 2.0 m.

The maximum temperature was 38.5 °C at 0.8 m level. At level of 1.2 m, the maximum temperature was reduced to 32.7 and 28.9 °C at 1.6 m level. At the height of 2.0 m, the maximum temperature was 27.6 °C. During the measurements, the surrounding air temperature was between 20.7 and 21.0 °C measured at 2.0 m level above the floor.

3.3. Velocity and temperature profiles of the gas range

The thermal plume of the gas range burners was measured during cooking mode. The nominal capacity of the range was 5.5 kW. In the range, there were two distinct burners with capacities are 2 and 3.5 kW. The burning power was 4.63 kW during boiling water in two 10 l kettles. The measured convection and boiling powers were 1.89 kW (40.8%) and 2.27 kW (49.1%). Thus, radiation was 0.47 kW (10.2%). The power was determined from the consumed constant gas flow (0.361 kg/h) and the caloric value of liquid gas (12.8 kWh/kg). In the cooking mode, the measured face surface temperatures were between 24 and 41 °C.

Velocity profiles measured above the gas range are shown in Fig. 3. In all performed measurements, the average temperature gradient was 0.4 °C/m between the heights of 1 and 3 m. The maximum velocity at different levels stayed between 1.0 and 1.2 m/s.

The maximum temperature was 50.6 °C at 0.8 m level. At level of 1.2 m, the maximum temperature was 40.0 and 35.4 °C at 1.6 m level. At the 2.0 m level, the maximum temperature was 31.7 °C.

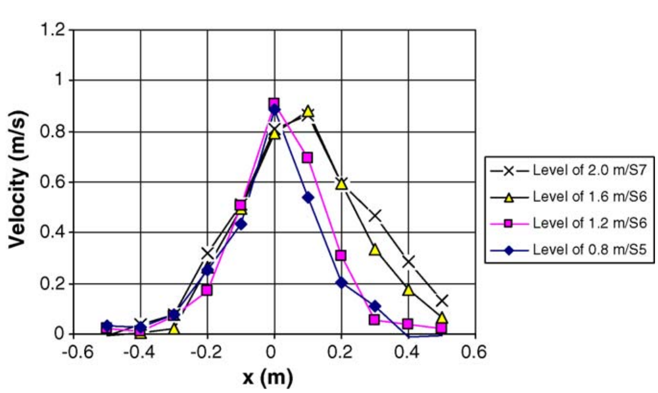

Fig. 1. Maximum velocity profiles above an iron range. *X*-axis is the cross section across the length of the appliance. The ‘‘S’’-cross sections are across the width of the appliance. The ‘‘S6’’-cross section is in the middle of the appliance.

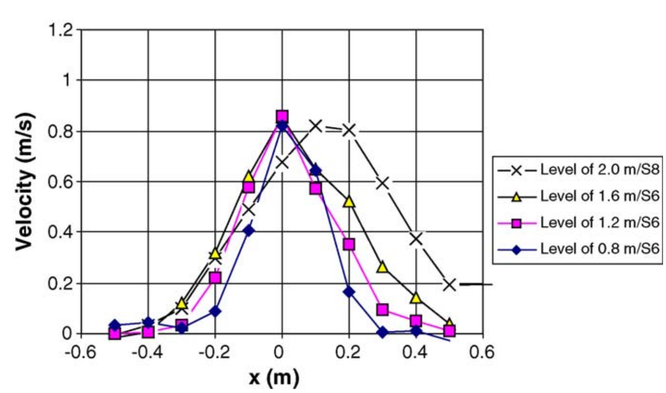

Fig. 2. Maximum velocity profiles above a chrome range. *X*-axis is the cross section across the length of the appliance. The ‘‘S’’-cross sections are across the width of the appliance. The ‘‘S6’’-cross section is in the middle of the appliance.

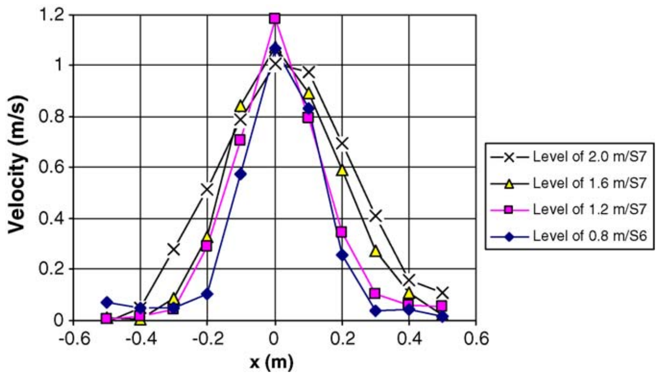

Fig. 3. Maximum velocity profiles above the gas range. *X*-axis is the cross section across the length of the appliance. The "*S*"-cross sections are across the width of the appliance. The "S6"-cross section is in the middle of the appliance.

During the measurements, the surrounding air temperature was 20.9 °C measured at 2.0 m level above the floor.

3.4. Velocity and temperature profiles of the induction range

In the induction range, the electric power of the appliance was 3.69 kW during boiling water in two 10 l kettles. The measured convection and boiling powers were 0.22 kW (6.0%) and 2.90 kW (78.6%). Thus, radiation was 0.57 kW (15.4%). In the cooking mode, surface temperatures of the cooking area stayed at the level of the ambient room air.

Velocity profiles of the chrome range have been measured at four different heights (0.8, 1.2, 1.6 and 2.0) (Fig. 4). In all the measurements, the average temperature gradient was 0.25 °C/m between the heights of 1 and 3 m. The maximum velocity at different levels was between 0.54 and 0.70 m/s. The plume experienced a notable lateral shift during its rise.

The maximum temperature was 28.9 °C at 0.8 m level. At level of 1.2 m, the maximum temperature was already reduced to 24.3 °C. At the level of 1.6 and 2.0 m, the maximum temperatures were 23.5 and 23.2 °C. During the measurements, the surrounding air temperature was between 21.2 and 21.4 °C measured at 2.0 m from the floor.

3.5. Velocity and temperature profiles of the induction griddle

In the induction griddle, the electric power of 3.23 kW was used to fry boneless chicken breast. The measured convection power was 0.20 kW (6.1%). Thus, radiation and frying was together 3.03 kW (93.9%). In the cooking mode, the surface temperatures of the cooking area was approximately 210 °C. The measured face surface temperatures were between 38 and 87 °C. Because of the limited time, the velocity and temperature profiles were measured only at the heights of 1.2 and 1.6 m. The measured velocity profiles are presented in Fig. 5.

In all the measurements, the average temperature gradient was lower than 0.3 °C/m between the heights of 1 and 3 m. The maximum velocity at the two levels examined was between 0.41 and 0.43 m/s.

During the measurements, the surrounding air temperature was 22.6 °C measured at 2.0 m level from the floor. The maximum temperature was 24.6 °C at 1.2 m level and 23.2 °C at 1.6 m level.

3.6. Velocity and temperature profiles of a fryer

In the fryer, the used power of the appliance was 530 W enough to maintain the oil temperature at 180 °C. The measured convection power was 0.23 kW (43.4%). Thus, radiation was 0.30 kW (56.6%). The measured face surface temperatures were between 30 and 69 °C. The measured velocity profiles are presented in Fig. 6.

In all conducted measurements, the average temperature gradient was about 0.14 °C/m between the heights of 1 and 3 m. The maximum velocity at four levels maintained between 0.42 and 0.44 m/s. The location of the maximum air velocity shifted laterally when the plume rised.

During the measurements, the surrounding air temperature was 21.0 °C measured at 2.0 m level from the floor. The maximum temperature was 27.3 °C at 0.8 m level. At the level of 1.2 m, the maximum temperature was 24.6 and 23.8 °C at 1.6 m level. At the height of 2.0 m, the maximum temperature was 22.7 °C.

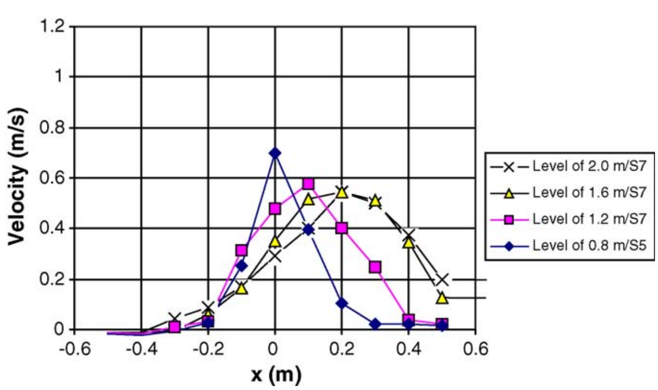

Fig. 4. Maximum velocity profiles above the induction range. *X*-axis is the cross section across the length of the appliance. The "S"-cross sections are across the width of the appliance. The "S6"-cross section is in the middle of the appliance.

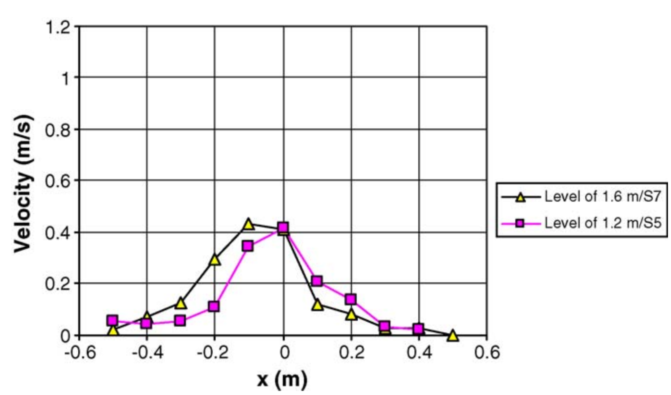

Fig. 5. Maximum velocity profiles above an induction griddle *X*-axis is the cross section across the length of the appliance. The "S"-cross sections are across the width of the appliance. The "S6"-cross section is in the middle of the appliance.

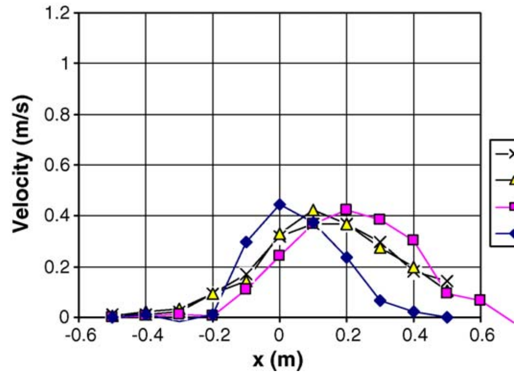

Fig. 6. Maximum velocity profiles above the fryer *X*-axis is the cross section across the length of the appliance. The "S"-cross sections are across the width of the appliance. The "S6"-cross section is in the middle of the appliance.

3.7. Plume characteristic and induced airflow rate

The plume characteristics of the kitchen appliances were computed based on the conducted velocity and temperature measurements. The basic plume parameters are described example. by Popiolek [6] and Kofoed [7]. The results for the cooking mode are presented in Tables 1–6. In the tables, the following parameters are presented:

- R_v and R_T are the width of the velocity and temperature profiles,
- δ_v and δ_T are the spreading angle of velocity and temperature profiles,
- H is the enthalpy flux,
- M is the vertical momentum flux,
- E is the kinetic energy flux,
- p is the temperature distribution factor,
- m is velocity distribution factor,
- λ is the ratio factor of temperature and velocity distribution,
- α is the entrainment factor.

Table 1
Plume characteristics of the iron range

Plume parameter	Distance from the appliance			
	0.8 m	1.2 m	1.6 m	2.0 m
v_c (m/s)	0.88	0.90	0.87	0.86
R_v (m)	0.22	0.23	0.27	0.32
δ_v (°)	8.0	6.7	6.7	6.7
R_T (m)	0.18	0.22	0.28	0.32
δ_T (°)	6.8	6.3	6.8	6.6
ΔT_a (K)	20.8	14.1	8.7	6.7
ρ_a (kg/m^3)	1.12	1.15	1.17	1.17
H (W)	1271	1115	1072	1090
q_v (m^3/s)	0.128	0.146	0.205	0.279
M (kg m/s^2)	0.063	0.075	0.104	0.142
E (W)	0.037	0.045	0.060	0.082
Ar	0.187	0.131	0.107	0.096
λ	0.86	0.95	1.02	1.00
P	32	36	35	49
M	24	32	36	49
α	0.17	0.15	0.14	0.12

Table 2
Plume characteristics of the gas range

Plume parameter	Distance from the appliance			
	0.8 m	1.2 m	1.6 m	2.0 m
v_c (m/s)	1.08	1.20	1.09	1.02
R_v (m)	0.19	0.23	0.26	0.31
δ_v (°)	7.8	7.4	6.8	6.8
R_T (m)	0.17	0.22	0.25	0.31
δ_T (°)	7.0	7.0	6.6	6.8
ΔT_a (K)	29.8	19.0	14.5	10.8
ρ_a (kg/m^3)	1.09	1.13	1.15	1.16
H (W)	1798	2044	1889	1923
q_v (m^3/s)	0.124	0.201	0.235	0.307
M (kg m/s^2)	0.073	0.136	0.146	0.181
E (W)	0.053	0.108	0.106	0.123
Ar	0.154	0.100	0.107	0.108
λ	0.89	0.94	0.96	0.99
P	38	63	49	40
M	30	56	46	39
α	0.15	0.11	0.12	0.13

The convection load is the key factor in the calculation of the airflow rate. During the measurements, the boiling power varied between 2900 and 3974 W. These powers were equivalent of the released water vapour mass flow of 1–1.5 g/s. Using the vapour density of 0.59 kg/m^3, it is possible to compute that the volume flow rate of the water vapour was always below 0.9 l/s.

In this study, both Gaussian approximation and direct numerical integration were used to obtain the airflow rate. In the direct numerical integration, the flow rate is calculated as the sum of the measured velocities multiplied by the respective areas.

Measured convection flows were compared with generic plume equation of VDI [8], Eqs. (1) and (2). In VDI, the virtual origin is set to be at $1.7D_h$ below the surface of the appliance. In addition to this selection, the effect of the product specific virtual origin was also studied. The empirical coefficient for each appliance was selected so as to get a reasonable correlation

Table 3
Plume characteristics of the chrome range

Plume parameter	Distance from the appliance			
	0.8 m	1.2 m	1.6 m	2.0 m
v_c (m/s)	0.83	0.87	0.86	0.83
R_v (m)	0.25	0.28	0.33	0.38
δ_v (°)	8.2	7.5	7.4	7.4
R_T (m)	0.21	0.27	0.33	0.37
δ_T (°)	7.0	7.2	7.4	7.1
ΔT_a (K)	17.8	11.7	8.1	6.6
ρ_a (kg/m^3)	1.13	1.16	1.17	1.17
H (W)	1392	1393	1383	1424
q_v (m^3/s)	0.164	0.214	0.290	0.381
M (kg m/s^2)	0.077	0.108	0.146	0.185
E (W)	0.042	0.062	0.084	0.102
Ar	0.212	0.144	0.121	0.125
λ	0.85	0.96	1.00	0.96
P	26	28	30	37
M	19	25	30	34
α	0.19	0.17	0.15	0.14

Table 4
Plume characteristics of the induction range

Plume parameter	Distance from the appliance			
	0.8 m	1.2 m	1.6 m	2.0 m
v_c (m/s)	0.72	0.60	0.56	0.55
R_v (m)	0.19	0.25	0.30	0.33
δ_v (°)	6.1	6.4	6.6	6.3
R_T (m)	0.19	0.26	0.22	0.22
δ_T (°)	5.9	6.8	4.8	4.1
ΔT_a (K)	7.7	3.2	2.0	1.9
ρ_a (kg/m^3)	1.17	1.19	1.19	1.20
H (W)	365	237	127	131
q_v (m^3/s)	0.084	0.115	0.158	0.189
M (kg m/s^2)	0.035	0.041	0.053	0.063
E (W)	0.017	0.016	0.020	0.023
Ar	0.095	0.076	0.063	0.071
λ	0.97	1.06	0.72	0.65
P	59	52	778	1116
M	56	59	407	477
α	0.11	0.11	0.04	0.04

with the measurements. The same location of the virtual origin of the appliances was used as the idle mode [5]

$$q_v = 5(z + aD_h)^{5/3}\Phi_{conv}^{1/3} \tag{1}$$

where q_v is the airflow in convective plume (m^3/s); z the height above the cooking surface (m); D_h the hydraulic diameter of the appliance (m); Φ_{conv} the convective heat output of the cooking appliance (W); a is the product specific factor of the virtual origin

$$D_h = \frac{2LW}{L + W} \tag{2}$$

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

The measured and estimated airflow rates of the low capacity appliances are presented in Fig. 7. The results of more energy intensive ranges, in turn, are presented in Fig. 8. The relative difference between Gaussian approximation and direct numerical integration is more significant with low heat gains. With high gains, the airflow rates given by these two methods are quite similar.

Table 5
Plume characteristics of the induction griddle

Plume parameter	Distance from the appliance			
	0.8 m	1.2 m	1.6 m	2.0 m
v_c (m/s)	n/a	0.40	0.40	n/a
R_v (m)	n/a	0.26	0.32	n/a
δ_v (°)	n/a	6.9	7.2	n/a
R_T (m)	n/a	0.28	0.34	n/a
δ_T (°)	n/a	7.4	7.6	n/a
ΔT_a (K)	n/a	3.5	1.8	n/a
ρ_a (kg/m^3)	n/a	1.19	1.19	n/a
H (W)	n/a	187	148	n/a
q_v (m^3/s)	n/a	0.084	0.131	n/a
M (kg m/s^2)	n/a	0.020	0.031	n/a
E (W)	n/a	0.005	0.008	n/a
Ar	n/a	0.197	0.123	n/a
λ	n/a	1.08	1.05	n/a
P	n/a	7	22	n/a
M	n/a	9	24	n/a
α	n/a	0.28	0.17	n/a

Measurement data at 0.8 and 2 m not available (n/a).

Table 6
Plume characteristics of the fryer

Plume parameter	Distance from the appliance			
	0.8 m	1.2 m	1.6 m	2.0 m
v_c (m/s)	0.49	0.44	0.44	0.39
R_v (m)	0.25	0.29	0.33	0.37
δ_v (°)	8.1	7.7	7.4	7.1
R_T (m)	0.18	0.25	0.32	0.39
δ_T (°)	5.8	6.5	7.1	7.5
ΔT_a (K)	6.3	4.1	2.3	1.7
ρ_a (kg/m^3)	1.18	1.18	1.19	1.19
H (W)	247	244	207	184
q_v (m^3/s)	0.098	0.120	0.156	0.171
M (kg m/s^2)	0.028	0.031	0.041	0.040
E (W)	0.009	0.009	0.012	0.010
Ar	0.236	0.217	0.141	0.149
λ	0.72	0.85	0.96	1.05
P	59	25	28	15
M	30	18	26	17
α	0.15	0.20	0.16	0.21

4. Discussion

Comparing the results with the idle mode [5] reveals that the relative proportion of the convection load is about 5–25%- units smaller. In the case of the gas range, the proportion of the convection load is 40.8% of the total power during cooking mode. For the iron and chrome ranges, the proportions of the convective loads are 21.0% and 21.9%. The convection part of the induction range and griddle are only about 6% of the total. It should be noted that the convection load of the fryer (total load 530 W) is approximately the same level as that of the induction griddle and range (total loads 3230 and 3690 W).

The location of the virtual origin has the most significant effect on the airflow rate in the plume equation, Eq. (1). The convective heat load must be increased quite a lot to have a notable effect on the airflow rate. In practice, this means that the requested airflow rates in cooking and idle mode do not differ very much. However, the idle mode determines the demand of the airflow rate, e.g. with the iron and gas range. If there is a more sophisticate power control system, the maximum airflow rate demand is set according to the cooking process.

When boiling water in two kettles, there were two maxima of velocity close to the appliances. These two separate plumes merge at a certain distance, after which the Gaussian approximation gives a good correlation with the measurements.

Comparing the parameters p and m during the cooking and idle modes [5] indicates a wider convection plume during the cooking conditions. However, the numerical values of the velocity and temperature profiles are more or less of the same order of magnitude. Also, there is no difference in the spreading angle of the plume between the cooking and idle modes. This

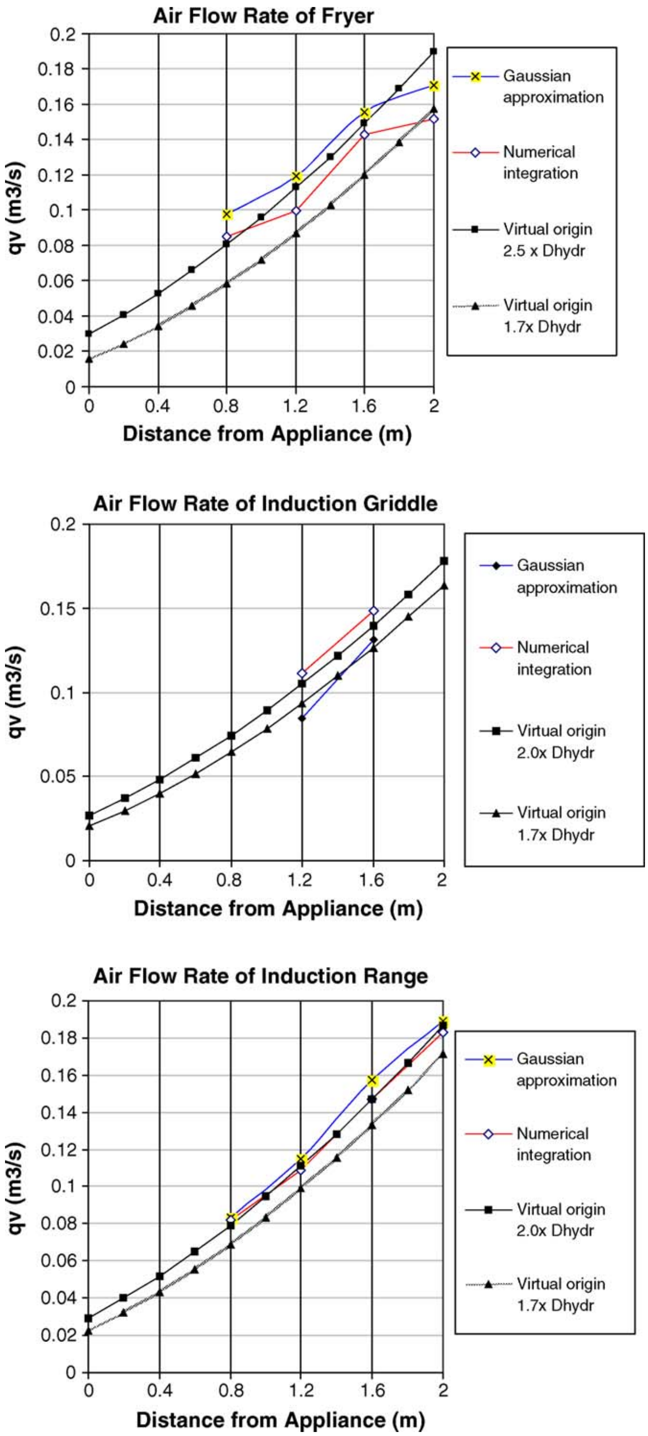

Fig. 7. Measured and calculated airflow rates of the low heat gain appliances.

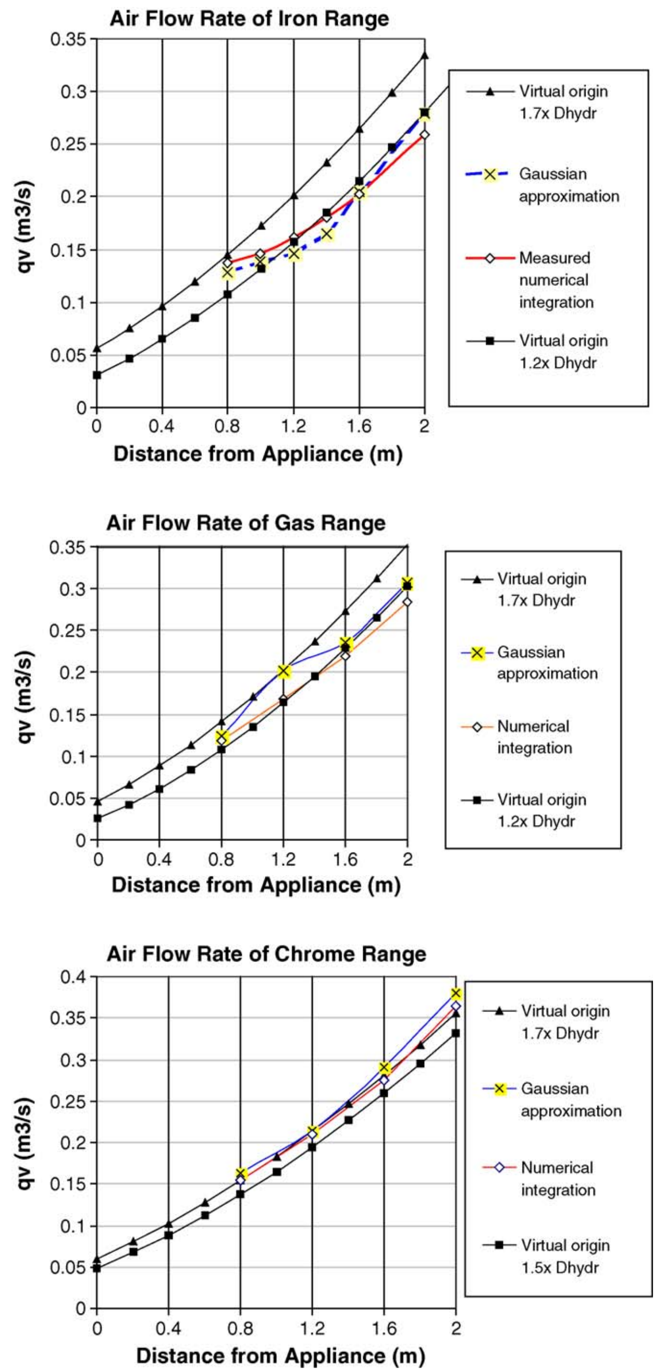

Fig. 8. Measured and calculated airflow rates of the high heat gain appliances.

means that the cooking process does not have any significant effect on the velocity and temperature distribution of the convection flow.

The reason for that is that the mass flow rate of water during boiling was only about 1–1.5 g/s and the volume flow rate of the water vapour is always below 0.9 l/s. Thus, the vapour flow released is small as compared with the induced airflow rate and therefore does not have a significant effect on the convection flow. Thus, the actual convection load and the product specific virtual origin can describe the plume during the cooking process.

The conducted measurement show that the power of distance in the generic plume equation cannot exactly describe the induced airflow rate with high heat gains. However, it gives a reasonable accuracy for practical applications when the convection load is known and the location of the virtual origin is adjusted. Based on the tandem study of the idle mode conditions [5], it can be stated that the same location of virtual origin can be used during both the idle and the cooking modes.

With the adjusted virtual origin, it is possible to reach a reasonable accuracy for practical applications. For the high heat gain appliances, the coefficient of the virtual origin is 1.2–1.5. For the low heat gain appliance, values of 2.0–2.5 gives reasonable correlation with the measurements.

5. Conclusions

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

The generic plume equation gives a reasonable accuracy in the cooking mode, when an appliance-specific, optimized coefficient of the virtual origin is applied. The vapour released from the process does not have a significant influence on the convection flow. The critical factors for accuracy of the equation are the correct estimation of the actual convection load and the optimal selection of the appliance-specific virtual origin.

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