AN ANALYSIS OF THE ACTUAL THERMAL PLUMES OF KITCHEN APPLIANCES DURING COOKING MODE

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ABSTRACT

The main purpose 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. In the most accurate design method, the design of a kitchen ventilation system is based on the air flow rate in 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.

INDEX TERMS

Thermal plume, convection flow, kitchen design, displacement ventilation

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 the health, comfort and productivity of workers. In a commercial kitchen, working conditions are especially demanding. There are four main factors affecting 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.

The published studies demonstrate quite clearly the health risk of cooking. Thiebaud (1995) 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 (1993) 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.

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 based on the convection heat gain or to be more specific, based on the thermal plume of a kitchen appliance. The most well-known code which utilizes this approach is German VDI (VDI 1999).

In this paper, the actual plumes of typical kitchen appliances 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 air flow rate is analyzed.

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RESEARCH METHODS

The main idea of the measurements was to analyse the convection flows of the actual kitchen appliances during the cooking mode. The measurements were carried out in a test room, built inside a laboratory facility. Construction consists of a steel frame, with floor dimensions of 10 m x 4 m and a height of 6 m. The room space is thermally insulated with 50 mm thick polystyrene elements from the surroundings. The supply air flow rate is released using displacement ventilation principle from the floor level through six multi-nozzle ductworks which guarantees undisturbed convection flow of a kitchen appliance. The total supply air flow rate of 600 l/s was adjusted to cover the induced air flow rate of convection flow 3 meters above the heated surface. The return air grille was installed at the height of 6 m. The supply air temperature was about 20 ^{o}C.

Convection plumes from an electric range, a chrome range, a gas range, an induction range, a fryer and an induction griddle were studied during the cooking mode. The description of the studied appliances is presented in Table 1. The cooking mode of ranges was arranged by boiling water in two 10 l kettles, Fig 1. In the case of the induction griddle, cooking is exucuded by frying boneless chicken breast, Fig 2. In the fryer, the oil temperature is maintained at 180 ^{o}C.

Table 1. *Description of the kitchen appliances.*

Equipment	Total Power (W)	Boiling Power (W)	Convective Power (W)	Radiation/Rest (W)	Surface temperature (^{o}C)
Iron Range 500x800x 950 (H)	5440	3570 (65.6 %)	1142 (21.0 %)	728 (13.4 %)	~350
Gas Range 400x650x 460 (H)	4625	2270 (49.1 %)	1885 (40.8 %)	470 (10.2 %)	-
Chrome Range 500x800x 950 (H)	6277	3974 (63.3 %)	1372 (21.9 %)	931 (14.8 %)	~400-500
Induction Range 380x700x 145 (H)	3690 (80 % of max. power)	2900 (78.6 %)	220 (6.0 %)	570 (15.4 %)	~ 40-70
Fryer 360x435x 260 (H)	530	-	230 (43.4 %)	300 (56.6 %)	180 (oil)
Induction Griddle 520x440x 175 (H)	872	-	180 (20.6 %)	692 (79.4 %)	210

During the tests, the actual power of the electric appliances was measured with clip-on-ammeter. The power of the gas range was determined from the measured gas consumption. The convection heat power was computed from the measured temperatures and velocities. Based on the amount of vaporized water, the boiling power was also computed. From the balance, the remaining heat power is attributed to be radiation.

The plume measurements were carried out with probes that were attached to a computer-controlled traversing system moving them from point to point and scanning the determined four measurement planes at the heights of 0.8 m, 1.2 m, 1.6 m and 2.0 m above the appliances. The basic measurement grid of 1.1 m x 1.1 m consists altogether 121 measurement points (0.1 m interval) in each plane. Air velocity was measured with Kaijo Denki WA- 390 ultrasonic probes, which have an accuracy of 0.02 m/s. In the case of the induction griddle, the velocity was measured with omnidirectional TSI 1620 hot bulb sensors and a turbulence correction was applied to the velocity results. The air temperatures were measured with Fenwale thermistors having an accuracy of 0.1 K

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***Figure 1**. The cooking arrangement of the ranges.*

***Figure 2**. The cooking arrangement of the induction griddle.*

RESULTS

Measured convection flows were compared with generic plume equation (VDI 1999), Eqs. 1 and 2. In VDI, the virtual origin is set to be at 1.7 D_h below the surface of the appliance. In addition, the effect of the product specific virtual origin was studied. The empirical coefficient of each appliance was adjusted to get reasonable correlation with the measurements.

$$q_{v,p} = 5 \cdot \left(z + a \cdot D_h\right)^{5/3} \cdot \Phi_{conv}{}^{1/3} \qquad (1)$$

where

$q_{v,p}$ is the airflow in convective plume, [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 cooking appliance convective heat output, [W]

a is the product specific factor of the virtual origin

$$D_h = \frac{2L \cdot W}{L + W} \qquad (2)$$

L, W are the length and width of the cooking surface, [m]

The measured and estimated air flow rate of low capacity appliances are presented in Fig. 3. The results of more energy intensive ranges, in turn, are presented in Fig. 4.

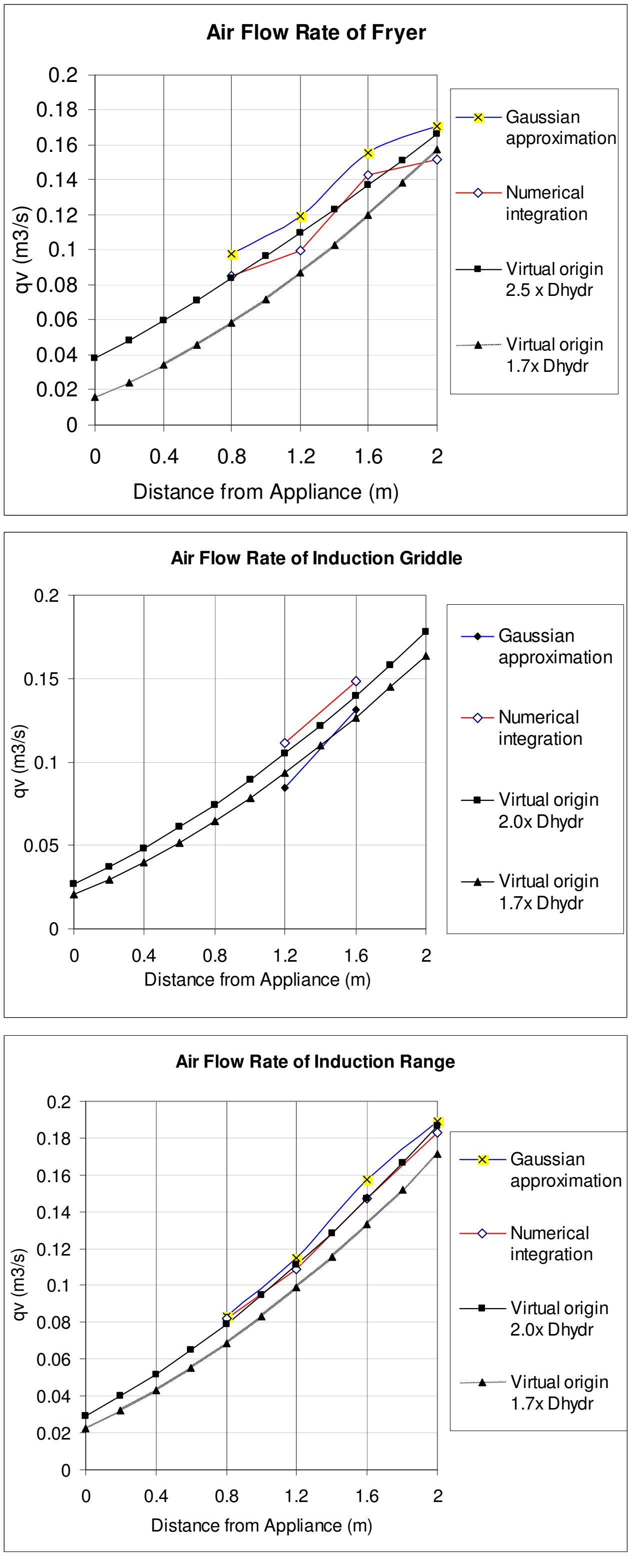

***Figure 3**. Measured and calculated air flow rates of the low heat gain appliances.*

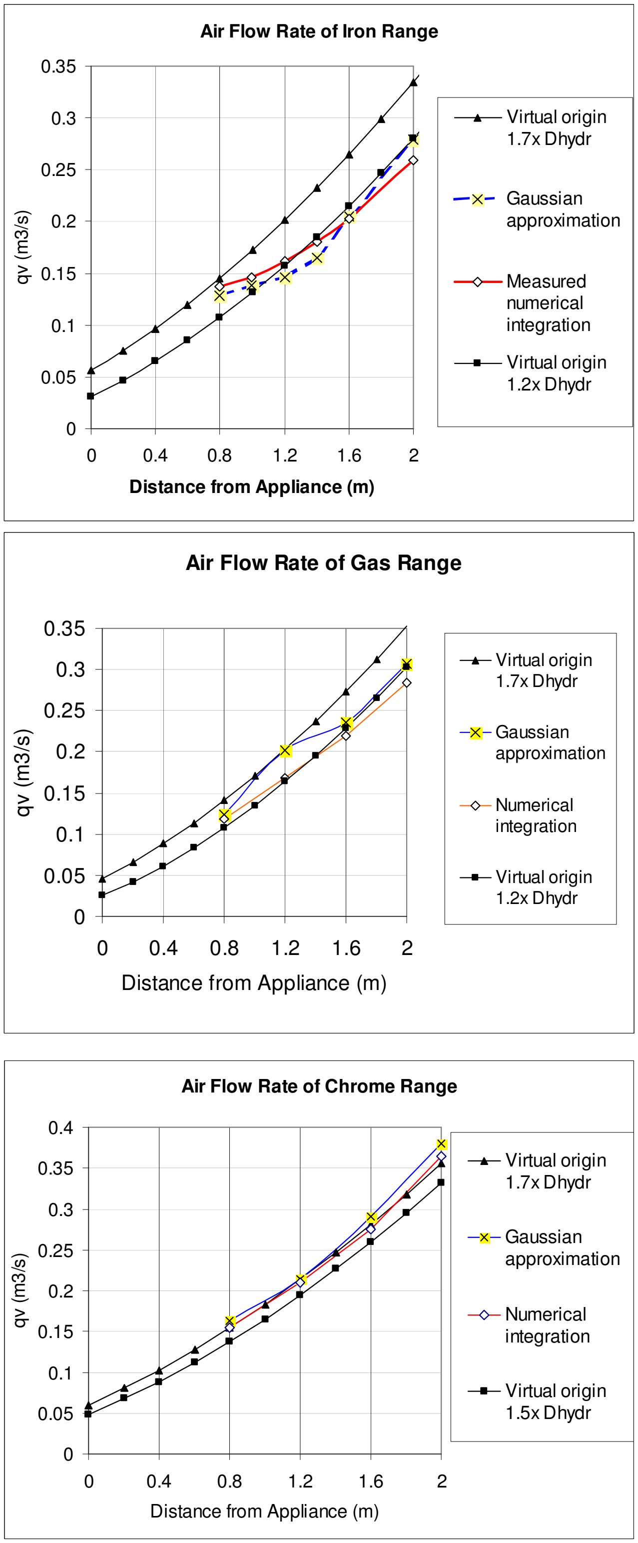

Figure 4*. Measured and calculated air flow rates of the high heat gain appliances.*

The relative difference between Gaussian approximation and numerical integration is more significant with low heat gains. With high gains, the air flow rates of these two methods are quite similar.

With the adjusted virtual origin, it is possible to reach a reasonable accuracy for practical applications. This means that the effect of the released vapour from the boiling and cooking processes does not have significant effect on the convection flow. 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.

DISCUSSION

The conducted measurement show that the power of distance in the generic plume equation can not exactly describe the induced air flow 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 in tandem study of idle mode conditions (Kosonen et al. 2005), it can be stated that the same location of virtual origin can be used during idle and cooking modes. In comparison with the idle mode conditions, the ratio of the convection is not larger in the idle mode. This observation means that if there is no special control features applied in the kitchen appliance, then the idle mode determinates the requested air flow rate.

Typically, the mass flow of water during boiling was only about 1 - 1.5 g/s. Thus, the released vapour flow is small compared with the induced air flow 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 nicely the plume during the cooking process.

When boiling water in two kettles, there are two peaks 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.

CONCLUSION

The generic plume equation gives 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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