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A STUDY ON VENTILATION OF THE KITCHEN WITH A RANGE HOOD FAN

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ABSTRACT

Experimental measurements and numerical simulations are conducted to investigate effective ventilation of a kitchen equipped with a range hood fan. A realistic full-size model kitchen is constructed with which a tracer gas technique is employed to study effects of the location of a single air inlet and the flow rate of the supplied air on the ventilation efficiency of the kitchen fan. Furthermore, flow visualization experiments using a 1/4-scale model kitchen and numerical simulations are performed to capture flow features in the kitchen. It is found that when the mechanically supplied air interferes with the buoyant exhaust upflow, the ventilation efficiency is affected significantly.

KEYWORDS: Ventilation Efficiency, Collection Efficiency, Ventilation in a Kitchen, Mechanical Air Supply, Tracer Gas Technique

INTRODUCTION

It is required by the Japanese Building Standard Law that a forced ventilation system must be installed in a kitchen equipped with a gas range in order to maintain clean indoor air quality. The apparatus should remove satisfactorily combustion products and cooking vapor from the room while the range is used to heat the food. The airtightness of buildings increases owing to the needs for lessening the air-conditioning load to save energy. It has been recognized that such airtight structure results in an excessively low indoor pressure when a kitchen ventilator fan is activated. This situation can cause difficulties with opening doors and be attributable to thermal discomfort in the kitchen and adjacent rooms due to infiltration. To overcome these problems, implementing a mechanical kitchen air supplying system to the kitchen space has been suggested.

An ideal condition can be visualized as having a localized ventilation system, which can balance the supply air and the exhaust gases. The supply air route should directly connect the inlet and the range hood fan, with minimum mixing with existing air in the kitchen. In contrast, in the worst case combustion gases and supplied air would mix completely in the kitchen area. This is least desirable from the standpoint of pollutant removal. Actual situations realized when a range fan is in operation lie somewhere in-between these extremes. This mixing can affect the collection efficiently of the gases near a range hood fan. The inlet location and the flow rate of the mechanically supplied air can have significant effects on the mixing among the fresh incoming air, existing air in the kitchen and the burnt gases. An appropriate flow rate to be supplied mechanically depends on the maximum allowance of the pressure difference between the indoor and the outdoor and on the airtightness of a building.

The present study is conducted to investigate effective ventilation of a kitchen having a range hood fan. Its primary objective is to obtain useful data for design of a ventilation system which (1) does not affect the performance of a range hood fan and (2) can effectively remove escaped exhausts. A full-scale kitchen module is used to investigate the effects of the location of an inlet air opening and the ratio of the mechanically supplied air to the total ventilation on the collection efficiency of the range hood fan and air exchange inside the kitchen. Flow visualization experiments and numerical computations are also carried out to study flow characteristics of the kitchen.

EXPERIMENTAL APPARATUS AND MEASUREMENT METHOD

The full-scale model kitchen utilized for measurements by a tracer gas technique is shown schematically in Figure 1. The kitchen unit is equipped with a cupboard, a kitchen sink, a three-burner range and a range food. Three different locations, designated as Openings A, B and C in the figure, are considered for an air supply opening. The equivalent opening area of the present model kitchen is found to be 6.2 cm^2/m^2 with doors closed. Figure 2 displays a schematic

diagram of the measurement system. Ultrasonic flow meters are connected to both inlet and exhaust ducts to regulate the flow rates. A tracer gas (100% carbon dioxide gas) is injected into the water vapor which is generated by heating the water in an aluminum pan of 22 cm outer diameter. The ventilation efficiency is calculated from the CO concentrations in the exhaust duct and in the kitchen measured using infrared CO gas meters. The carbon dioxide concentrations at the same locations are monitored for checking a steady state. The collection efficiency and the residence time of cooking exhausts are considered as indicators for the ventilation efficiency to evaluate effects of the air supply conditions. The collection efficiency η_c is computed from the CO tracer gas concentration:

$$\eta_c = Q_e [(C_e - C_{e0}) - (C_r - C_{r0})] / Q_{CO} \quad (1)$$

where Q_e is the flow rate of the exhaust. C_e and C_r are the CO concentrations in the exhaust duct and the kitchen, respectively, and Q_{CO} is the flow rate of carbon monoxide gas. The subscript 0 denotes initial values. Two situations are considered for the pressure difference between the kitchen and an adjacent room: In the first case, a kitchen door F is open to have no pressure difference. While in the other case, the doors are closed to generate a pressure drop in the kitchen area when the ventilator is in operation.

Note that the collection efficiency defined previously does not provide any information concerning a ventilation efficiency for the exhausts which escape from the range hood. The average residence time of CO (i.e., the cooked gas) in the kitchen, τ, (Sandberg and Sjöberg 1983) is considered to be a more appropriate indi-

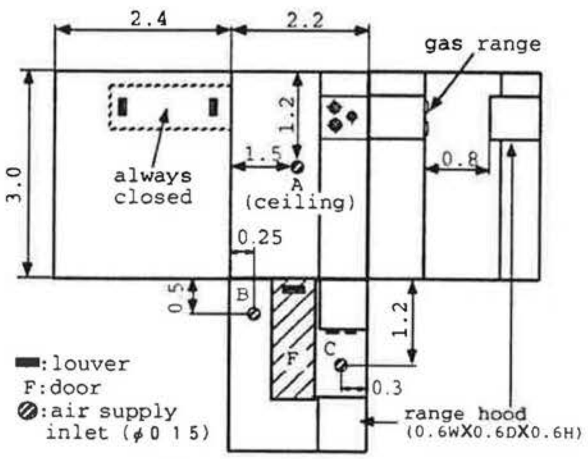


Figure 1 Model kitchen

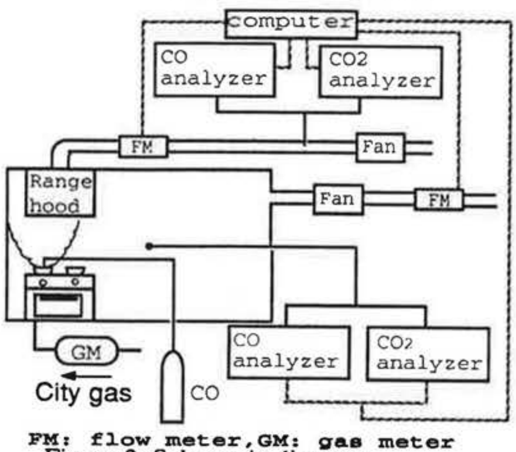


Figure 2 Schematic diagram of the measurement system

cator for ventilation efficiency for this purpose.

$$\tau = (Q_e / Q_{CO}) \int_0^{\infty} [C_e(t) - C_{e0}]\, dt \quad (2)$$

where Ce(t) is the CO concentration in the exhaust duct t sec after the tracer gas supply is terminated. For the present analysis, the nominal time constant of ventilation η_t (≡ τn/τ, τn being the inverse of the air exchange rate, Sandberg and Sjöberg 1983)) is used. If the cooking exhaust is removed from the kitchen at a faster rate than would occur in complete mixing, η_t takes a value larger than 1.

In the measurements, the tracer gas is shut abruptly sometime after the flow in the exhaust duct reaches a steady state. The average residence time is computed by measuring the tracer decay in the exhaust duct.

RESULTS AND DISCUSSION OF THE FULL SCALE MODEL EXPERIMENTS

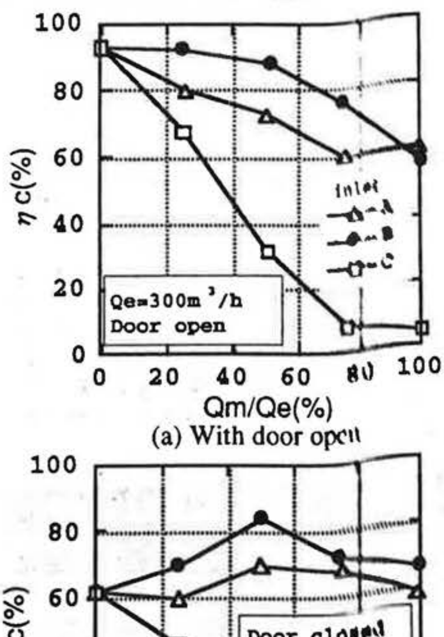
Effects of the Opening Locations on the Collection Efficiency

Figures 3 (a) and (b) represent relationship between the collection efficiency η_c and the ratio of the mechanically supplied air to the total ventilation flow rate for various inlet opening locations. The curves in Figure 3 (a) are the data obtained for the opened kitchen door, while Figure 3 (b) shows the results for the closed door. The symbols Q_e and Q_m, both in m³/h, stand for the total flow rate of the exhausts and the flow rate of the mechanically supplied air, respectively. In both figures it can be seen that for Opening C as the ratio Q_m/Q_e increases, η_C decreases rapidly. In the range Q_m/Q_e > 80 %, the collection efficiency is less than 10%. For Opening B, which is positioned at a lower portion of the wall remote from the range hood, η_C does not exhibit significant reduction up to Q_m/Q_e about 50% when the door is open. It gradually decreases for larger Q_m. For Opening A on the ceiling, η_C gradually decreases. When the door is closed, η_C attains maximum values at around Q_m/Q_e=50% for OpeningsAand B. The collection efficiency is overall lower for infiltration only.

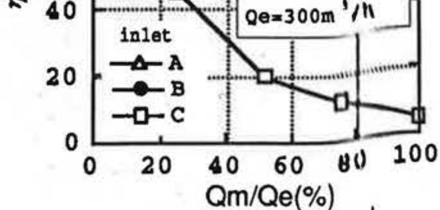
For Opening B, Qe is varied from 200 to 300 m³/h to examined effects of the flow rate of the exhaust and the collection efficiency. The results show similar trends for all the cases to those presented in Figure 3 for 300 m³/h.

Effects of the Opening Locations on the Nominal Time Constant of Ventilation

Figures4 (a) and (b) represent the relationship between η_t for the exhausts and Q_m/Q_e for different inlet openings. When the doors are closed, the effect of the opening locations on η_t is similar to that on η_C previously examined. When the doors are open, ηt decreases in a sequence of Openings B, A and C, irrespective of Q_m/Q_e values. For Opening B, η_t reaches a peak value at. Q_m/Q_e = 50%. For Openings A and C, η_t is seen to decrease as Q_m increases. When the doors are closed, the curves for Openings A and B almost overlap, having



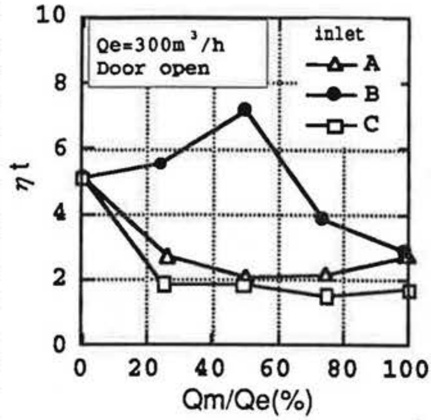
(a) With door open



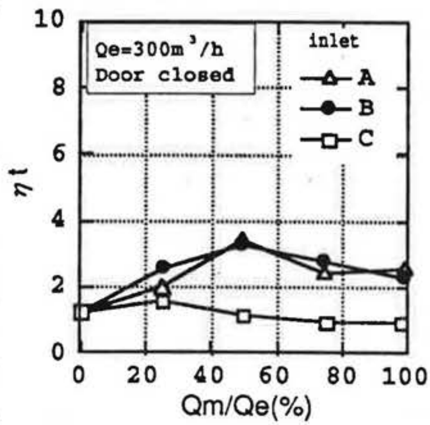
(b) With door closed

Figure 3 Effects ofthe opening locations on η_c

maxima at Q_m/Q_e = 50%. For Opening C, η_t is overall lower and attains a peak at. Q_m/Q_e = 25%. It, however, gradually decreases as Q_m increases. Over Q_m/Q_e = 75%, η_t is less than 0.95. It should be noted that, when the door is open, the room air including the cooked exhausts can flow out through the door opening. Hence, it is difficult to accurately evaluate the average residence time. This is true particularly in cases of high mechanical ventilation rates. Notice that η_t is larger than unity except for limited cases for Opening C. This suggests local distribution of the cooked exhaust gases which are not completely mixed with the kitchen air. In the full-scale model kitchen experiments with the closed doors, the collection efficiency is overall lower for the case of infiltration ventilation than that of the mechanical ventilation. A possible cause for this trend may be that the air velocity across cracks increases to affect the flow near the range hood.



a) With door open

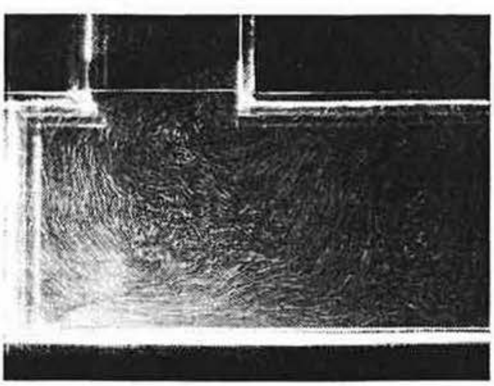


(b) With door closed

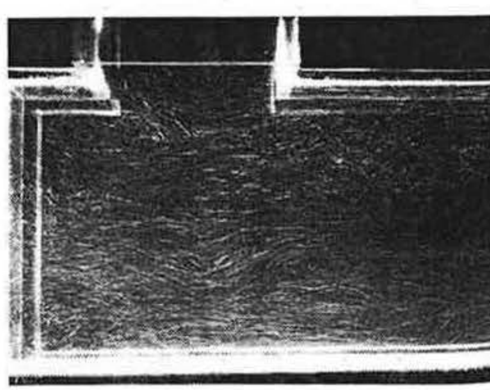
Figure 4 Effects of the opening locations on η_t

FLOW VISUALIZATION RESULTS

In order to gain better pictures of flow features in the kitchen in more detail, flow visualization experiments and computer simulations are conducted. A 1/4-scale model kitchen is fabricated from acrylic plates to allow visual access to the flow field inside the space. Fine particles with the diameter of approximately 80 μm are injected with the supply air from the inlet opening and their movements are made visible using a laser light sheet (Murakami and Kato 1989). In scaling the physical phenomena, the Reynolds number at the inlet is matched between the full and 1/4 scale models. Furthermore, numerical computations are performed for selected cases considered for the full-scale measurements. The governing equations for flow and heat transfer are solved by a finite difference technique using a general fluid flow solution package Harwell FLOW3D.

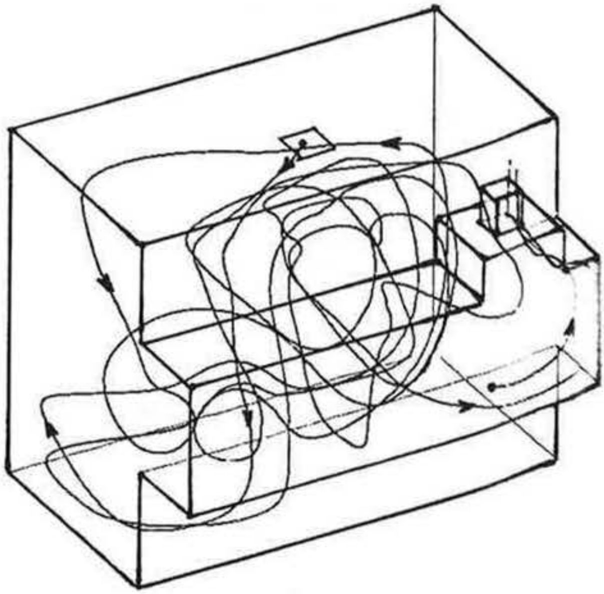


(a) Opening B



(b) Opening C

Figure 5 Flow visualization photographs
(The flow rate is equivalent to 300 m^3/h in the full-scale experiments)



(a) Opening A

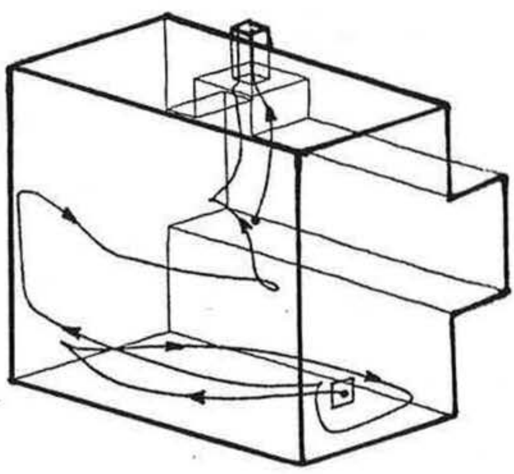
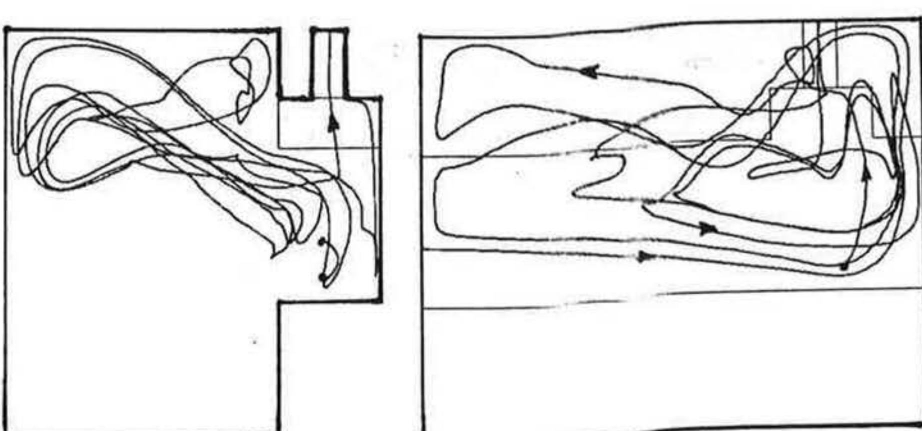


Figure 6 Particle tracks inside the kitchen ($Q_e = 300\ m^3/h$)

(b) Opening B

(c) Opening C



Figures 5 (a) and (b) depict flow patterns near the range hood for Opening B and C. For Opening B, rising flow to the range hood is evident. However, in Opening C, flow in the transverse direction predominates and flow is drawnonly near the narrow region at the bottom of the range hood. Figure 6 (a), (b) and (c) display particle path traces of the air streams initiated from the inlet opening and the range burner for Opening A, B and C, respectively. For Openings A and B, the exhaust gases are directly drawn from the range hood; however, in the case of Opening C, the exhaust streams circulate inside the kitchen space with the fresh incoming air before they exit through the range hood.

These results demonstrate that η_c and η_t are reduced by the mechanically supplied air which flows directly over the range and interfere with the buoyant exhaust stream.

CONCLUSIONS

The effects of the inlet air conditions on the ventilation efficiency of the kitchen having an air supply system are investigated by measuring the collection efficiency and the average residence time of the exhausts by employing tracer gas techniques Furthermore, flow visualization experiments using a 1/4-scale model and numerical simulations are made to detect flow patterns in the kitchen. The following conclusions may be drawn from the obtained results:

1. The collection efficiency is reduced when the fresh air stream from the supply inlet opening flows directly over the range since the incoming air interferes with the buoyant flow over the range.
2. In the absence of the pressure difference between the kitchen and an adjacent room, the collection efficiency is almost constant over the range of $0 < Q_m/Q_e < 50$ % when the air inlet is mounted on the ceiling or the lower part of the wall locating far away from the range hood. The collection efficiency decreases if the mechanical air supply is further increased.
3. When the kitchen is isolated from other rooms and only crack ventilation is present, the ventilation efficiency is affected by infiltration caused by a pressure drop since it increases the air velocity of the infiltration.
4. Average residence time of the exhaust may be employed as a ventilation efficiency for the entire kitchen space. It provides information concerning the behavior of escaped gases from the range hood and the exhaust concentration in the room.

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