Original Paper

Indoor+Built Environment

Indoor Built Environ 1996;5:358–363

Evaluation of Ventilation Effectiveness in the Kitchens of Beijing Flats

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Key Words
Ventilation efficiency
Air exchange rate
Tracer gas
Carbon monoxide
Nitric oxide
Nitrogen dioxide

Abstract
The effects of different kinds of room ventilation were evaluated in an experimental chamber and in kitchens of four residences in Beijing. Carbon monoxide was used as a tracer gas in the chamber, and this together with nitric oxide and nitrogen dioxide concentrations from the gas appliances were measured in the chamber and the kitchens. The ventilation styles evaluated were natural ventilation, an exhaust fan and a kitchen range hood. Their ventilation effectiveness was related to design, air flow, the distance between an appliance and air vent, and position of the appliance in the kitchen. A kitchen range hood above the appliance associated with an extra fan installed in a high window was found to be the most effective way to control indoor air quality in the kitchens.

Introduction

Carbon monoxide (CO), nitric oxide (NO) and nitrogen dioxide (NO_2) from gas combustion are the main indoor air pollutants in a Chinese home [1–3]. A typical Chinese kitchen in a city flat is separate from the other rooms and just used for cooking and water heating using gas as fuel. Dinner is usually taken in the entry hall or the living room. Most Beijing kitchens, which represent the typical Chinese style, have a gas appliance for cooking and a water heater installed in an area of about 3–5 m^2, which are in use for about 2–3 h per day. Natural ventilation or forced ventilation, such as an exhaust fan and a kitchen range hood are often used in the kitchen in order to remove contaminants, greasy smokes and odours from gas burning and cooking. As some ventilator designs are poor and may be improperly installed, the ventilation is correspondingly unsatisfactory. CO, NO and NO_2 levels in the kitchen have been found to be higher than in the other rooms of the flat, or in the outside air measured over the period when gas is burnt [1, 4–6].

Several studies have measured pollutant concentrations and emission rates from gas combustion in the Chinese flats [5, 7–9]. Reducing pollutant emission rates and moving pollutants from a room are two common methods to improve indoor air quality. Ventilation is the most convenient way to remove contaminants [10]. This paper describes a study of ventilation effectiveness in the kitchens of flats through measurement of CO, NO and NO_2 concentrations by the tracer gas technique to estimate the air exchange rate and ventilation efficiency [11–15].

Test Setup and Methods

Tests were conducted in an experimental chamber and in four kitchens of residences in Beijing. The ventilation styles evaluated were natural ventilation, an exhaust fan, a kitchen range hood and the hood plus the fan. A common gas fuel in China is liquefied petro-

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1420–326X/96/0056–0358$10.00/0

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Accepted:
July 1, 1996

leum gas, although natural gas and coke-oven gas have been used increasingly over recent years. Liquefied petroleum gas was selected as a test fuel in the chamber experiment and all three gas types were tested in the kitchens.

A special test chamber was built in this study to simulate the domestic kitchen. The dimensions were 2.05 × 2.0 × 2.65 m and the available volume of the chamber was 10.28 m^3, which was of the same scale as the kitchens. A full ventilation system was installed in the chamber to control the test conditions. A gas appliance, an exhaust fan and a kitchen range hood were fitted in the chamber. An automated and manual data sampling and recording system was installed on the outside of the chamber, which enabled monitoring of both tracer gases, the air exchange rate, air distribution patterns and also the continuous monitoring of CO, NO, NO_2, TSP and CO_2 concentrations, as well as air pressure, temperature and humidity, at various locations inside and in the air leaving the chamber. The sample and tracer gas techniques used in the study were pre-tested in the chamber. The results from chamber tests can be used to estimate real-life situations and are useful when controlling indoor air quality (IAQ).

Four flats with a kitchen in the typical Chinese style were used for field tests. The layout of the flats examined in the field investigation and the fuel usage in their kitchens are given in table 1. They were on floor levels 1, 3, 4 and 5 and measurements in bedrooms were made on floors 3 and 4. Most bedrooms in Beijing flats are located to the south of a building to make good use of daylight and warmth from the sun, and consequently a kitchen and a washroom have to be located on the north side. The exhaust opening of the kitchen chimneys, which is about 0.15 × 0.3 m, is not big enough for good natural ventilation and extra ventilation is often needed. A typical Beijing kitchen is equipped with a gas appliance for cooking, a gas water heater for supplying hot water and an exhaust fan or a range hood for kitchen ventilation. Figure 1 shows an example of the plan of a domestic flat (flat No. 1 in table 1).

Air exchange rates were measured by using a tracer-gas decay method, which is a standardized procedure [14, 15]. In the decay method, a small amount of tracer gas is injected into the room space and is allowed to mix with the interior air. After the injection, the mass balance of the tracer gas can be calculated from the formula:

$$A = \frac{1}{T} \ln \frac{C(T) - C_o}{C(0) - C_o} \qquad (1)$$

where A = air exchange rate (h^{-1}), T = elapsed time after injection (h), C(T) = tracer gas concentration at time T (ppm), C(0) = tracer gas concentration at time 0 (ppm), and C_o = outdoor concentration (ppm).

For measuring ventilation efficiency, the tracer gas was injected continuously at a constant rate. The ventilation efficiency is defined as the ratio between the steady-state concentration of contaminant in the exhaust air and the steady-state mean concentration in the room [10]. If the outdoor concentration is not zero, such as CO, both the above concentrations ought to be the difference between the measured concentration and the outdoor concentration. The equation is:

$$E = \frac{C_e - C_o}{C_i - C_o} \qquad (2)$$

where E = ventilation efficiency (dimensionless unit), C_e = steady-state concentration in the exhaust air (ppm), C_o = the outdoor concentration (ppm), and C_i = steady-state mean concentration in the room (ppm).

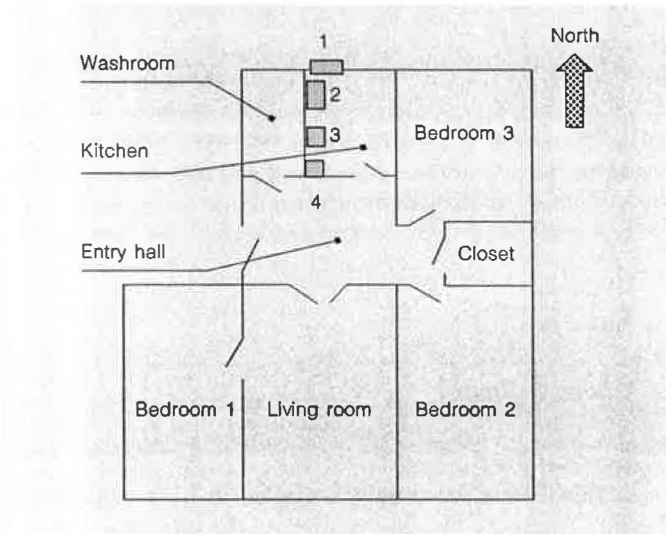


Fig. 1. The scheme of the field flat No. 1 (table 1). In the kitchen, 1 = exhaust fan, 2 = gas appliance, 3 = water heater, 4 = opening of the chimney.

Table 1. The situation of the kitchens in the flats

Flat No.	Floor level	Stories in the building	Bedrooms	Kitchen dimensions, m	Window orientation	Fuel
1	1	5	3	1.9×2.5×2.8	N and O[1]	natural gas
2	5	5	3	1.5×2.2×2.7	N and O	coke-oven gas
3	3	6	1	1.5×2.1×2.75	N and O	LPG[3]
4	4	6	2	1.6×2.2×2.65	N and E[2]	LPG

[1] Window to north and outside.
[2] Window to north and exhaust shaft.
[3] Liquefied petroleum gas.

The ventilation efficiency is also called the contaminant removal efficiency. E is 1.00 when the concentration in the exhaust air equals exactly the mean concentration in the room. A larger value of the efficiency ($C_e > C_i$) means a greater ability to remove contaminants.

CO was selected as a tracer gas in this study because it can be conveniently measured in the field tests and comparisons easily made between both the laboratory test and the field test. CO has the desirable qualities of a tracer gas in detectability, non-reactivity and an otherwise relatively low concentration in ambient air. All the measurements were conducted automatically and CO concentrations were controlled below the level dangerous to health. CO in the domestic kitchens came from the use of gas. CO in the laboratory came from a 98% purity CO cylinder connected with two additional valves, a capillary and a flow meter. Constant injection rates were from 0.002 to 0.009 m^3/min depending on the air exchange rate. CO was used as a tracer gas for both the air change rate and the efficiency but continuous injection and concentration decay could not be synchronized. Steady-state concentrations from continuous injection of CO were measured first for the ventilation efficiency. After the injection, decay concentrations were measured for the air exchange rate. NO_x concentrations measured were compared with CO both for pollutant level and ventilation efficiency.

A gas filter correlation infrared CO ambient analyser (Thermal Electron 48 CO Analyzer, Thermal Electron Corporation, Instruments Division, Franklin, Mass., USA) and a chemiluminescent NO/NO_2/NO_x ambient analyser (Beckman 952 NO/NO_2/NO_x Analyzer, Beckman Instruments Inc., Fullerton, Calif., USA) were used for both laboratory and field experiments.

Table 2. The ventilation efficiency (E, in dimensionless unit) of the exhaust fan and the CO, NO_x mean concentrations (C, in ppm) were measured in the chamber

Source		Location[1]				
		1	2	3	4	5
CO (cylinder)	C	11.6	13.6	14.7	15.8	18.0
	E	1.33	1.10	1.01	0.92	0.79
CO (appliance)	C	12.1				
	E	1.36				
NO_x (appliance)	C	0.64				
	E	1.35				

Air flow rate of the exhaust fan was 4.12 m^3/min. Source strength (S) from the CO cylinder was 58.8 mg/min. S of CO, NO_x from the appliance were 63.3 and 5.25 mg/min. The outdoor concentrations of CO and NO_x were 2.1 and 0.051 ppm.

1 The source was put at the locations shown in figure 2.

Results

Chamber Study

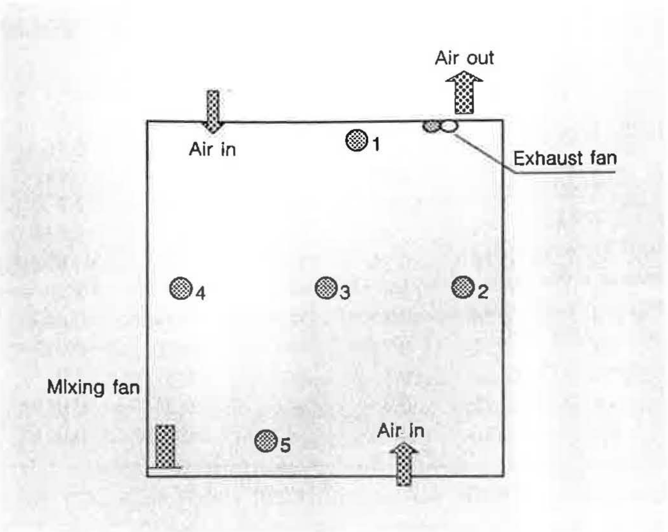
Exhaust Fan

Exhaust fans are usually installed in high windows in Beijing kitchens to expel many of the indoor contaminants to the outdoors. The pollutants from gas burning rise with thermal air flow to be exhausted by the fans. Since the air flow rate through a typical fan is about 3–6 m^3/min and the distance between the fan and the gas appliance is usually more than 1.5 m, exhaust fans are considered to be general ventilation systems. However, the external wind speed and its direction can influence air exchange rates. When the wind direction is opposite to that of the exhaust air flow, the rate of exhaust decreases and some pollutants are returned to the room, so that the ventilation effectiveness is lowered.

To measure the ventilation efficiency in the chamber studies, CO from a cylinder, as the tracer gas to simulate a contaminant source, was continuously released at five locations in the chamber as shown in figure 2. The height of CO injection sources was 0.8 m above the floor, that is, the same height as the gas appliance. A gas appliance was tested at location 1 for comparison with the CO from the cylinder. The results of this test are shown in table 2. When the CO source was at the centre of the chamber (location 3), a mixing fan was only used to ensure that the CO concentration in the exhaust air was the same as the average level in the chamber. The measured ventilation efficiency at location 3 was 1.01, which was not significantly different from 1.00. Otherwise the highest efficiency in this test was 1.33 measured at location 1, nearest the exhaust fan. The lowest efficiency was 0.79 measured at location 5, which was beyond the main air flow from air in to air out and at the farthest distance from the fan to the CO source. The ventilation efficiencies measured from CO and NO_x using the appliance were 2.2 and 1.5% higher than that when using the CO cylinder at the same source strength rate and the same position. The probable explanation was the increase in air flow while the gas fuel was burning.

Kitchen Range Hood

A kitchen range hood fitted above the gas appliance is a local ventilation system, which can exhaust a large amount of pollutants before their diffusion to the kitchen, and consequently can control IAQ effectively. A great number of such hoods, with an air flow rate about 2–8 m^3/min, have been installed in kitchens. The distance from the cooker to the intake of the hood is generally about 60–80 cm, depending upon the individual kitchen. A typical hood opening is about 0.5 × 0.35 m and the size of a cooker hob is about 0.4 × 0.3 m.



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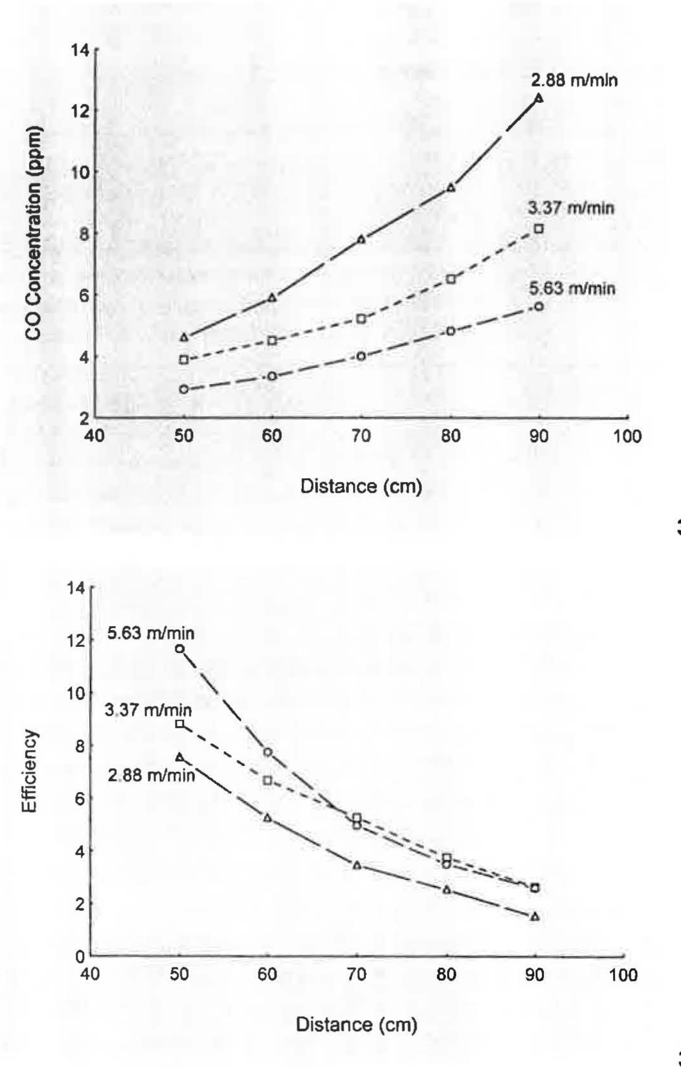

Fig. 2. The location (1–5) of the CO tracer gas source in the chamber. Supply air came into the chamber by two sections simulating the real kitchen situation. The main section was about 70% from the opposite wall of the exhaust fan, which represented air from the other rooms. The minor section was about 30% from the same wall of the fan, which represented infiltration air from outdoors.

Fig. 3. a The CO concentrations in air exhausted by a range hood with increasing distance from a CO source for different air flows. **b** Change in the ventilation efficiency of a range hood with distance for different air flows.

A test of hood efficiency was made at three flow rates for a hood set at different heights above the appliance in the chamber. The results (fig. 3) show that the pollutant levels in the chamber were lower and ventilation efficiencies (E) were much higher than those when an exhaust fan was used, as compared with those in table 2. According to the calculation with the indoor air model, that part of the pollutants that leaked out in the kitchen was about 8–40%, since the hood was not a completely closed ventilation system. When the air flow of the hood increased from 2.88 to 5.63 m^3/min at a distance of 0.90 m, the CO concentration in the chamber decreased from 12.4 to 5.56 ppm. For an exemplary air flow of 3.37 m^3/min, CO concentrations at distances of 0.50 and 0.90 m were 3.89 and 8.16 ppm, respectively. Lower contaminant levels were measured with either the shorter distance or the larger air flow of the hood. Otherwise, when the air flow increased from 2.88 to 5.63 m^3/min at the distance of 0.50 m, ventilation efficiencies of the exhaust fan increased from 7.55 to 11.67. At the air flow of 3.37 m^3/min, ventilation efficiencies at distances of 0.50 and 0.90 m were 8.83 and 2.65, respectively. A greater ventilation efficiency was obtained with the shorter distance than with the larger air flow.

Tests in the Flats

Natural Ventilation

Natural ventilation in the kitchen in many homes was usually by a window open to the outside when water was being heated either on the gas-stove or by a water heater. As the kitchen window is generally open toward the north

Table 3. Concentrations of CO, NO, NO_2 (in ppm) in the flats with natural ventilation and wind direction from the north

Flat No.	A, h	Pollutant	S mg/min	Kitchen	Entry hall	Living room	Bedroom	Outdoor
		CO	38.7	11.5	9.4	4.9	–	1.8
1	15.4	NO_2	12.1	1.84	1.45	0.61	–	0.36
		NO	3.3	0.76	0.60	0.25	–	0.11
		CO	36.2	13.3	11.0	5.7	–	2.1
2	19.7	NO_2	3.1	0.53	0.43	0.20	–	0.038
		NO	1.0	0.26	0.21	0.87	–	0.012
		CO	65.6	20.1	16.4	–	8.1	2.2
3	20.3	NO_2	4.4	0.76	0.57	–	0.19	0.043
		NO	1.2	0.31	0.25	–	0.10	0.015
		CO	45.0	27.2	19.1	–	6.5	2.0
4	10.3	NO_2	3.6	1.22	0.85	–	0.25	0.040
		NO	0.9	0.46	0.32	–	0.096	0.014

A = Air exchange rate; S = source strength.

and it is common in Beijing for winds to blow from the north and the west, the air flow direction in the flat is often from the kitchen to the other rooms. When gas was not being burnt, or even when it was but the winds were from the south, the CO, NO and NO_2 concentrations in all the rooms, except the kitchen, were close to those measured outdoors. However, when the winds were from the north and gas was being burnt, natural ventilation could make pollution levels lower in the kitchen, but higher in the other rooms (table 3). The pollutant concentration decreases in order from the kitchen, entry hall, living or bedroom to the outdoors. For example, flat 1 CO concentrations in the kitchen, entry hall, living room and outdoor were 11.5, 9.4, 4, 9 and 1.9 ppm, respectively. Three kinds of pollutants, CO, NO and NO_2, had the same decay properties in all four flats. Because wind direction is changeable, it is difficult for natural ventilation to control IAQ effectively. In addition there is a further danger of natural ventilation, which is that the wind can interfere with the combustion process resulting in an increase in the emission of pollutants.

Under the conditions of natural ventilation it was difficult to measure the concentration of contaminants in the exhaust air. The ventilation efficiency was given the value of 1.0, because the indoor pressure was the same as the outdoor pressure, the air flow was well distributed, and indoor concentrations at various locations were relatively similar.

Hood and Extra Fan

A kitchen range hood above the appliance was more effective in controlling IAQ although some of the pollutants from gas burning still diffused into the kitchen. A similar hood could not be installed above a water heater, because the higher temperature and radiant heat above the heater would destroy the hood, and also as the normal height of such a heater is about 1.5 m above the floor, the hood would be too high to be operated.

The effectiveness of a hood and an exhaust fan was tested for the water heater in the domestic kitchen (flat No. 1 in table 1). The hood above the appliance was located at location 2, and the heater at location 3 shown in figure 1. The results, given in table 4, show the difference in CO and NO_x concentrations when using the exhaust fan and when using the hood. The ventilation efficiencies of the fan were higher than those of the hood. Compared with results of chamber tests for the gas stove (table 2, fig. 3), quite different results were obtained for the water heater. This results from the hood location far away from the heater and at the same height as the heater. When both the hood and the fan were turned on, E was 1.02 and CO, NO_x concentrations were about half the level found using the hood alone. The best method, therefore, to control IAQ is by installing both a hood and a fan. Considering energy costs, the hood should be used only when cooking and the fan should be used when the heater is on or for general ventilation. Both of them could be used when emission rates of contaminants are large.

Ventilation efficiencies from NO_x were little different from those of CO (tables 2, 4) because of the test conditions. NO_x is a chemically dynamic mixture whose composition changes with time. However, these changes can be neglected for measurement purposes if the total mean age of room air is short because the air exchange rate is

Table 4. The efficiency of a hood and a fan for a water heater, and CO, NO_x concentration in the kitchen

Ventilation style	Air flow m^3/min	CO			NO_x		
		S mg/min	C ppm	E	S mg/min	C ppm	E
Range hood	5.63	36.8	8.2	0.92	9.43	1.40	0.93
Exhaust fan	5.22	36.8	7.5	1.12	9.43	1.24	1.13
Hood and fan	10.85	36.8	4.9	1.02	9.43	0.68	1.01

S = Source strength; C = concentration; E = ventilation efficiency (in dimensionless unit).

The outdoor concentrations of CO, NO_x were 2.1 and 0.05 ppm, respectively.

high and also room humidity is low. In these circumstances NO_x may be used as a tracer gas and repeatable results obtained.

Conclusions

Using natural ventilation the efficiency is about 1 but the concentrations of pollutants in the home can vary, depending on the wind direction. This method of ventilation is the least efficient and ought not to be used.

The greater efficiency from the use of an exhaust fan means that the level of pollutants from fuel burning can be controlled in the kitchen and seldom diffuses to other rooms. Gas cookers and water heaters should be installed near the fan so that higher efficiency can be achieved.

The efficiency of an extractor hood above the appliance depends on the air flow and the distance of the hob from the hood intake. This form of ventilation was generally effective at controlling IAQ in the kitchen.

A kitchen range hood above the appliance associated with an extra fan installed in a high window was the best method to control IAQ. Together they are effective at decreasing pollutant levels and, depending upon the level of pollution, either one or both can be turned on.

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