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Hazards from Products of Combustion and Oxygen Depletion in Occupied Spaces

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A.D. Kent

Poorly ventilated spaces may subject occupants to hazardous air conditions of reduced oxygen content or increased carbon dioxide concentration. If unvented fuel-burning appliances are in operation, there is the further possibility of danger from carbon monoxide poisoning. The effects of these gases will be described and a method outlined for determining ventilation requirements for specific quantities of toxic gas production.

Air Contaminants

Uncontaminated outdoor air consists of about 78 per cent nitrogen (N_2) and 21 per cent oxygen (O_2) by volume, the remainder made up of various inert gases and oxides of carbon. Carbon dioxide (CO_2) normally amounts to 0.03 per cent volume and carbon monoxide (CO) to one or two parts per million (ppm). In cities the concentration of CO and CO_2 may reach undesirably high levels. Man himself contaminates the air. He breathes about 0.5 m^3 (18 cu ft) of air per hour, exhaling about 4 per cent CO_2 and about 14 ppm CO (35 ppm if he smokes cigarettes). This amount of human air pollution, insignificant outdoors, presents a problem indoors unless the space is adequately ventilated. In "tight" houses normal air infiltration gives about one air change every 2 h; less tight buildings permit faster air change. Even in crowded quarters such as tents, cabins or trailers, infiltration usually provides adequate ventilation. With very tight closures, however, the concentration of exhaled CO_2 may exceed the safe limit. Unvented fuel-fired cooking or heating appliances increase the danger of CO_2 poisoning and add the hazard of CO contamination, especially in very cold weather when heaters are operated at high firing rates and ventilation air may be closed off to conserve heat.

Oxygen Depletion

Oxygen deficiency in itself is not as serious a problem in poorly ventilated quarters as high CO_2 concentration, which can cause unconsciousness or death before a corresponding oxygen deficiency would have serious physiological effects. Oxygen concentration may drop from the normal 21 per cent to as low as 15 per cent before it causes even a sense of fatigue.

Carbon Dioxide

Early symptoms of CO_2 poisoning are headache, nausea, sweating and tremor. Increase in CO_2 concentration affects the respiratory process, particularly if accompanied by oxygen depletion. The depth and frequency of breathing increase until at 3 per cent concentration a normal person breathes at double the usual rate and at 5 per cent breathing is extremely labored. At 7 to 9 per cent the individual pants violently and becomes unconscious in about 15 min.

Carbon Monoxide

Symptoms of CO poisoning include impaired vision, headache and nausea. A concentration above 400 ppm produces coma and death. The effects depend on concentration, depth and rate of respiration, duration of exposure, and, to some extent, smoking habits. Cigarette smoking may subject the lungs to a CO concentration of about 475 ppm for 6 min per cigarette; heavy smokers may have significant impairment of night vision. Heavy exertion, especially at high air temperatures or high elevations will increase the effects of CO. Information on the combined effects of two or more gases is scarce, although there appears to be general agreement that effects are additive to some degree.

Ventilation

The occupants of a confined space would soon be uncomfortable if there were no means of dissipating body heat, moisture and odours. Without cooling or ventilation body temperatures would exceed the normal range and death would eventually result. Those unfortunates trapped in the infamous Black Hole of Calcutta died not from lack of oxygen but from heat exhaustion.

Ventilation requirements for confined spaces involve a complex balance of heat, moisture and chemical composition of the air. To dissipate the heat and moisture produced by a group of people in a hot, humid, confined space might require in the order of 0.4 m^3/min (14 cfm) of air for each. Unpleasant odours do not pose a direct health hazard but may require from 0.3 to 0.9 m^3/min (10 to 30 cfm) for proper dispersal.

The problem of toxic gas removal involves the relation between room volume, number of people, gas production rate, gas concentration and ventilation rate. From these factors the ventilation rate required to maintain gas concentration below the safe upper limit or threshold value (0.5 per cent for CO_2; 0.005 per cent for CO) can be calculated. It has been shown, for example, that five people seated in a confined space, each producing 0.019 m^3/h (0.63 cu ft/hr) of CO_2, would require a ventilation rate of about 0.3 m^3/min (10 cfm) to ensure that the threshold value of 0.5 per cent CO_2 is never exceeded[1]. This would allow each individual about 0.06 m^3/min (2 cfm).

The ventilation allowance should be increased by about 50 per cent for anyone standing, when breathing rate and therefore CO_2 production are somewhat higher. A figure of 0.09 m^3/min (3 cfm) per person is the minimum outdoor air requirement for occupants of a confined space. Heavy work or exercise would require up to ten times this amount of ventilation for CO_2 dispersal.

The time to reach a given concentration of gas can be calculated[1] when the initial and final concentrations of the gas are known. If the five persons of the previous example occupied a room of 30 m^3(1000 cu ft) volume, i.e., 6 m^3 (200 cu ft) per person, it would take a little over 3 h to reach a steady balance at the threshold limit value of 0.5 per cent CO_2 with a ventilation rate of about 0.06 m^3/min (2 cfm) per person. If the same space were perfectly sealed. with a ventilation rate of zero, the time to reach the CO_2 threshold limit value would be an hour and a half. These calculations assume that gas concentrations are uniform throughout the space, but unless a circulating fan is used there will be considerable variation in air temperature and CO_2 concentration from floor to ceiling; the heat will rise, while the colder "fresh" air will be concentrated at the floor.

There is a further complication with heating or cooking appliances that emit CO_2 and CO. If figures for the normal fuel burning rate of an appliance are known, it is theoretically possible to calculate the CO and CO_2 production rates, from which a calculation can be made of the ventilation rate necessary for the air of a particular space to stay within the maximum allowable concentrations for the toxic gases. Unfortunately, it is very difficult to tell when such a ventilation rate is achieved in practice, and one can merely make allowances by increasing ventilation when toxicity conditions are suspected to be critical.

Fuel-Fired Appliances

In the combustion of hydrocarbon fuels, heat, water, CO_2 and, usually, small quantities of CO are produced. The complete combustion of 1 g of kerosine, No. 1 stove oil, naphtha, or gasoline produces about 3.1 g of CO_2, but because these fuels differ in density the volume of CO_2 produced per volume of fuel varies from 1.2 to 1.5 m^3/L (181 to 232 cu ft per gal). Methyl alcohol produces 1.375 g CO_2/g (98 $ft^3/gal = 0.6\ m^3/L$) and propane gas 3.0 g CO_2/g (154 $ft^3/gal = 1.0\ m^3/L$).

With knowledge of its fuel consumption rate the CO_2 production of any appliance can be calculated. If combustion is not complete, CO will be produced and perhaps a quantity of unburned fuel in amounts that are more difficult to estimate. The CO produced depends on the design of burner and other factors such as flame temperature. The surfaces of pans or other cooking utensils extending into the inner cone of the flame of a cooking appliance will "cool" the flame and thus produce CO. Oxygen depletion of the atmosphere and a corresponding increase in CO_2 results in increased production of CO by burners, Limits on the CO production of appliances are given in standards of the Canadian Standards Association for catalytic appliances (CSA Designation B140.9.1 -- 1972) and camp stoves (CSA Designation B140.9.2 -- 1975).

Toxicity Studies

A number of portable fuel-fired appliances for heating, illuminating and cooking were studied to determine their combustion characteristics, particularly their CO/CO_2production ratio when operating with both adequate and reduced oxygen supply[1]. The tests were carried out in a special chamber instrumented for continuous measurement of air temperature, relative humidity, CO and CO_2 concentrations, as well as periodic measurement of the appliance's fuel consumption. The air was thoroughly mixed to give it uniform temperature and humidity. Both the fuel intended for use with each appliance and other fuels that might be used in an emergency were employed in supplementary tests.

Most of the appliances performed satisfactorily, but some emitted more CO than others in which the burner mixed, vaporized and ignited the fuel properly and produced a high heat intensity from the combustion process. In general, the amount of carbon dioxide produced was in proportion to the fuel burned.

Catalytic combustion heaters gave off less CO when operated at a low capacity, as for a "slow" start using a limited amount of starting alcohol. If ample alcohol was used for a "quick" start, a considerable amount of CO and unburned fuel was given off at the burner head; so much, indeed, that a lighted match held over the glowing metal gauze would ignite the unburned gases and produce a flame.

Of the kerosine-burning appliances, wick-type stoves gave a reasonably constant CO/CO_2 production ratio regardless of CO_2 concentration; fuel rate fell considerably with high CO_2 concentrations. A pressure burner stove, however, showed a marked increase in CO/CO_2 ratio when the CO_2 concentration exceeded 1.5 per cent. A reflective heater, equipped with a kindler wick and sleeve burner with dome-shaped wire screen partly surrounded by a heat reflector, showed an increase in CO output when operated at less than full capacity. Both this heater and a circular wick stove, when extinguished, gave off objectionably pungent odours until the burner head had cooled. All the kerosine appliances tested, except the reflective heater, were able to operate on No. 1 (stove) oil and even No. 2 (furnace) oil, although carbon formation necessitated considerable maintenance.

Of the two alcohol-burning appliances tested, a wick-type burner gave consistently lower CO output than a vaporizer burner. The vaporizer burner stove, however, produced far less CO when operating with difficult-to-obtain fuels such as ethyl alcohol and pure isopropyl alcohol than with the commoner methyl alcohol, methyl hydrate and commercial isopropyl alcohol.

Of the gasoline- and naphtha-burning appliances, excluding catalytic combustion units, a pressure lantern and a pressure-burner stove showed low CO output when burning either lighting naphtha or aliphatic solvent, regardless of CO_2 concentration. As the warning label implied, they became quickly inoperative when leaded gasoline was used for fuel. Another pressure-burner stove, operating on its intended leaded gasoline fuel, operated with low CO output except at high CO_2 concentrations.

A small picnic stove operating on liquefied petroleum (LP) gas had very low CO output but this increased greatly when CO_2 concentration rose above 1.5 per cent and fuel consumption rate was about half normal. This stove is more suited to summer than to winter operation since the LP gas fuel would have difficulty in evaporating properly at low temperatures; some "bottled-gas" stoves, however, are specially equipped for such operation. Alcohol jelly stoves, intended for short-term cooking and relatively expensive to operate, give a reasonably low CO/CO_2 ratio with an open flame. Charcoal-burning stoves should be confined to outdoor operation or, if used indoors, should be placed in a fireplace so that the products of combustion are vented to the outdoors. Their CO production is so large that even in a well-ventilated room CO concentration could easily reach the danger point. Their use in tents or cabins should be prohibited unless special venting arrangements are made.

In summary, many types of appliance can be used satisfactorily and safely in relatively confined spaces. They consume fuel fairly efficiently, emitting little unburned fuel and generally only small amounts of CO if the oxygen supply is adequate. Reduced oxygen supply greatly increases the production of CO by some models which require special precautions to ensure adequate ventilation. It must be remembered that CO values derived from laboratory tests where the air is effectively mixed may differ from those pertaining to ordinary conditions of occupancy.

In addition to the toxicity hazards inherent in the appliance itself, there is a hazard from CO when cooking operations are carried out with insufficient ventilation. An appliance that normally produces insignificant amounts of CO with an open, free flame can become a menace when the flame is allowed to impinge upon a cooking vessel. Stoves designed for partial immersion of the cooking utensil in the flame should display a warning sign with respect to the use of the appliance within a tightly closed area.

Other dangers in using unvented fuel-fired appliances include hot surfaces, overturning, and fuel spillage in filling. Certain appliances with a valve-operated fuel supply, operating under conditions of reduced oxygen and reduced rate of burning, have a rate of fuel supply exceeding the rate of fuel consumption, creating a serious fire hazard from fuel flooding. Additional problems occur when lighted appliances are subjected to wind currents or drafts; those without wind shielding may flash flames outside the bounds of the appliance, creating a serious fire hazard. On barometric tank heaters the fuel tank must be shielded from wind-blown flame to prevent fuel vaporization in the tank and resulting excess pressure and fuel flooding.

Practical Considerations

Unvented appliances in confined quarters create ventilation problems. Increasing use by campers, hunters and boaters who now extend their activities further into the spring and fall, and even into winter when the toxicity dangers of such appliances are worst, gives fresh significance to the care that must be exercised. Some simple guidelines for such equipment follow:

1. Use appliances that are known to be inherently safe; check for certification by a recognized testing agency.
2. Follow the manufacturer's instructions for use.
3. Use only the fuel intended for the appliance.
4. Ventilate the premises well, especially while cooking and overnight.
5. Locate bunks or other sleeping facilities at a low level. The concentration of toxic gases is usually greater near the ceiling.
6. Know the symptoms of toxic gas inhalation and be on guard at all times.

About the only simple guide to a hazardous CO_2 condition is the flame size of a wick-type appliance: half-normal flame size indicates roughly 1.5 per cent CO_2 and flame extinguishment roughly 3 per cent, which is still not too late to avoid a tragedy.

Carbon monoxide is even more difficult to detect, for the flame can appear to be quite normal while giving off considerable CO. Catalytic heaters operating at high fuel rate sometimes show a pleasant red glow, usually associated with complete combustion, while in fact producing CO at a significant rate. Smouldering wood in fireplaces, like charcoal broilers, is notorious for CO production, and the user should be alert to the possibility of a downdraft from a fireplace that can fill a poorly ventilated space quickly with carbon monoxide.

References

1. Kent, A.D. Hazards from products of combustion and oxygen depletion in occupied spaces, Occupational Health Review, Vol. 21, No. 1-2, 1970, p. 1-18.

This is a staff-written Digest based on a paper[1] by A.D. Kent (now retired).