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Pollutant concentrations and emission rates from natural gas cooking burners without and with range hood exhaust in nine California homes

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ABSTRACT

Combustion pollutant concentrations were measured during the scripted operation of natural gas cooking burners in nine homes. Boiling and simmering activities were conducted on the stovetop and in the oven with and without range hood exhaust ventilation or air mixing via a forced air system. Time-resolved concentrations of carbon dioxide (CO_2), nitric oxide (NO), nitrogen oxides (NO_X), nitrogen dioxide (NO_2), particles with diameters of 6 nm or larger (PN), carbon monoxide (CO), and fine particulate matter ($PM_{2.5}$) were measured in the kitchen and bedroom area of each home. Four of the nine homes had kitchen 1 h NO_2 exceed the national ambient air quality standard (100 ppb). In all homes, the highest 1 h integrated PN exceeded 2×10^5 cm^{-3}-h, and the highest 4 h PN exceeded 3×10^5 cm^{-3}-hr in the kitchen. Range hood performance varied widely, but one with a large capture volume and a measured flow of 108 L/s reduced concentrations 80–95%. Increased awareness of the need to ventilate when cooking, along with building standards for minimum range hood flow rates and volume, could substantially reduce exposures to NO_2 and ultrafine particles in homes.

1. Introduction

The combustion products of natural gas cooking burners (NGCBs) include pollutants that can degrade indoor air quality. While complete combustion directly produces water vapor and carbon dioxide (CO_2), the high flame temperatures also produce nitrogen oxides (NO_X) including nitrogen dioxide (NO_2), a respiratory irritant. Incomplete combustion can produce non-negligible emissions of other air pollutants including carbon monoxide (CO), formaldehyde (CH_2O), and nanometer-sized particles (PN) [25]. Residential NGCBs emit nanoparticles that grow to tens of nm but mostly remain within the <100 nm diameter threshold that defines ultrafine particles (UFP) [20,39].

The U.S. EPA sets national ambient air quality standards to protect both the general population and sensitive sub-populations [35,36]. The EPA limits for CO are 35 ppm averaged over 1 h and 9 ppm averaged over 8 h. The short-term exposure standard for NO_2 is 100 ppb over 1 h. There is a short term standard for fine particulate matter, $PM_{2.5}$, of 35 µg m^{-3} averaged over 24 h; however, the particles emitted from NGCBs don't have sufficient mass to approach this threshold. Currently there are no widely recognized standards or guidelines for UFP exposure. An expert elicitation review of the available literature rated the likelihood of increased short-term UFP exposure causing health effects as medium to high [12]. Another review noted the substantial experimental evidence and plausible mechanisms for respiratory and cardiovascular effects of UFP intake, but deemed the evidence as "not sufficiently strong to conclude that short-term exposures to UFPs have effects that are dramatically different from those of larger particles" [11].

Emission factors of CO and NO_2 from NGCBs have been measured in laboratory and field studies [16,25,26,34]. Several studies have reported emission factors and/or indoor concentrations of ultrafine particles resulting from NGCB use without food preparation [2,20,25,39]. Many studies have reported elevated concentrations of CO and NO_2 in homes with natural gas cooking burners, compared to homes with electric cooking [8,18,23,24,29,30,41,42]. A recent study of 350 California homes reported that NO_2 and NO concentrations increased with increasing self-reported use of NGCBs across homes [18]. A modeling study of

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multifamily housing in Boston found that cooking with gas burners is a major source of NO_2 in homes [4].

While several measurement-based studies have reported time-resolved CO, (e.g. [18]), only a few have reported time-resolved or peak NO_2 concentrations resulting from NGCB use [5,7,17,19,22]. A recent simulation study found that the weekly highest 1 h mean NO_2 concentrations exceed 100 ppb in the majority of a representative sample of Southern California homes in which NGCBs were used without kitchen exhaust ventilation [13].

The primary strategy for mitigating exposure to pollutants from cooking burners is to use a venting range hood or other kitchen exhaust ventilation [33]. Recent assessments of range hoods in the U.S. indicate wide performance variations across devices and also across airflow settings and burner configurations for many devices tested [3,15,21,28]. Several of these studies used capture efficiency, CE, as the performance metric. CE indicates the fraction of pollutants generated at the cooking appliance that are removed or exhausted by the range hood before they can mix into the air of the home. These studies found that for many range hoods, CE is much higher for the back than for the front cooktop burners. The [13] modeling study of Southern California homes found that routine use of a venting kitchen range hood with a 52% CE (reflecting performance of a common hood for front burner cooking) should dramatically reduce the percentage of homes with 1 h mean NO_2 exceeding 100 ppb.

NGCB pollutants that are not exhausted directly by a range hood are removed from the air in the home by air exchange with outdoors and for NO_2 and PN by deposition to interior surfaces. Deposition rates for NO_2 in US homes can be estimated from data reported in several studies. A comparison of decay rates for NO_2 and the conserved tracer SF_6 following gas burner use in 5 homes yielded an estimated deposition rate of 0.8/h [31]. Comparing decay rates of NO_2 to those for NO, CO, and CO_2 – which are not removed by deposition – obtained in 21 homes using unvented gas fireplaces [6,9] yielded a mean deposition rate estimate of 0.7/h. Particle deposition rates vary with particle size and environmental conditions. Measurements in homes provide estimated deposition rates for 15–50 nm particles that range from 0.2/h to 3/h [1,10,14].

The primary objective of the research reported here was to quantify time-resolved concentrations of NO_2 resulting when NGCBs are used under realistic conditions, and specifically to investigate if the threshold of 100 ppb over 1 h is commonly exceeded. We also sought to measure concentrations of NO, NO_X, CO_2, CO, $PM_{2.5}$, and the number of particles with diameters $\geq$6 nm (PN, most of which are UFP) following controlled burner use. Another objective was to conduct a pilot study of the benefits of using venting range hoods to reduce in-home concentrations of pollutants emitted by NGCBs.

2. Methods

2.1. Overview

The study entailed operation of NGCBs and measurements of the resulting pollutant concentrations in nine homes in the San Francisco Bay area of California. Experiments were conducted, by permission, when residents were away from the home. Researchers controlled the operation of cooking appliances, ventilation, and forced-air heating systems. The NGCB operation sequences were designed to represent common cooking patterns. To avoid generating pollutants from food preparation, pots containing tap water were used as heat sinks. Air pollutants including NO_X, NO, number concentrations of particles $\geq$6 nm (PN), CO, CO_2, and estimated $PM_{2.5}$ were measured in the kitchen and a hallway or bedroom that was far from the kitchen. CO_2 was also measured in a common room between the other two locations but generally closer to the kitchen. NO_2 was inferred as the difference between NO_X and NO, even though that value likely includes non-negligible amounts of nitrous acid (HONO) [32].

The base set of experiments included operation of each type of cooking burner (cooktop, oven bottom burner, and broiler top burner, as available) with windows closed, no forced air unit (FAU) operation, and no mechanical exhaust. Additional experiments were conducted with the FAU operated in fan-only mode when this setting was available, and with a venting range hood when available.

2.2. Study homes

The nine homes varied in size and layout, as described in Table 1. They included seven detached houses, one flat (first floor of two-flat duplex), and a small apartment. There were three homes with open floor plans and no walls enclosing the kitchen. Four of the homes had kitchens that were distinct rooms, connected to other rooms in the home via standard interior doorways. Two homes had semi-open kitchens. One of these (labeled H6) had a small galley kitchen with both a floor-to-ceiling passage and a large pass-through connecting the kitchen to the adjacent dining room. The other (H9) had two wide, open passages between the kitchen and adjacent rooms.

Cooking appliances varied across homes. Table 2 summarizes the natural gas cooking appliances in each study home. The burner firing rates were obtained from the nameplate tag found on the appliance or by searching online product literature for the make and model. Five homes had a gas range with cooktop, oven bottom burner and broiler top burner; two homes had a gas range with only a cooktop and oven burner; and two homes had a gas countertop cooktop separate from an electric oven. A venting range hood was present in six homes. Six homes had FAUs that could be operated in fan-only mode.

Study home access was arranged with owners or renters who were paid $200 for each day and $200 for each overnight period that a home was unoccupied and made available for experiments, up to a total allowable payment per home of $600. A single day of experiments required 11 h of access to the home without occupants.

Table 3 describes the kitchen exhaust fans in the study homes. Six of the homes had exhaust devices above the cooktop. Two of the venting hoods were “microwave over range” (MOR) appliances that combine the functions of a microwave and externally venting exhaust fan. Home H3 and H4 had no range hoods of any kind. H7 had a non-venting (recirculating) range hood that was operated during two experiments.

2.3. Burner operation and simulated cooking

A procedure was developed to simulate common usage scenarios for cooktop, oven, and broiler burners. The procedures, used in homes H2 to H9, are described in Table 4. The “Boil” and “Sautee” activities were done simultaneously in the “Cooktop” procedure. The procedures were not finalized until after experiments were completed in H1; H1 experiments featured variations of the procedures, as discussed in the Supplemental materials. The same clean pans and pots were used in all homes, but cooking appliances generally were operated as found. In a couple of cases the appliances were wiped with wet paper towels to remove large debris.

Upon arriving to each home, we reviewed the planned experimental procedures with the host (homeowner or renter) and obtained her/his signature for the agreed usage periods. With the host, we conducted a walk-through to identify potential hazards