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Fine particles and carbon monoxide from wood burning in 17th–19th century Danish kitchens: Measurements at two reconstructed farm houses at the Lejre Historical–Archaeological Experimental Center

Morten Ryhl-Svendsen [a,b,*], Geo Clausen [c], Zohir Chowdhury [d,1], Kirk R. Smith [d]

[a] Department of Conservation, National Museum of Denmark, IC Modewegsvej, DK-2800 Kgs. Lyngby, Denmark
[b] School of Conservation, Royal Danish Academy of Fine Arts, Esplanaden 34, DK-1263 Copenhagen K, Denmark
[c] International Center for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
[d] Environmental Health Sciences, School of Public Health, University of California, Berkeley, CA 94720-7360, USA

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ABSTRACT

Carbon monoxide (CO) and particulate matter ($PM_{2.5}$) were measured in two reconstructed Danish farmhouses (17–19th century) during two weeks of summer. During the first week intensive measurements were performed while test cooking fires were burned, during the second week the houses were monitored while occupied by guest families. A masonry hearth was located in the middle of each house for open cooking fires and with heating stoves. One house had a chimney leading to the outside over the hearth; in the other, a brickwork hood led the smoke into an attic and through holes in the roof. During the first week the concentration of $PM_{2.5}$ averaged daily between 138 and 1650 μg m^{-3} inside the hearths and 21–160 μg m^{-3} in adjacent living rooms. CO averaged daily between 0.21 and 1.9 ppm in living areas, and up to 12 ppm in the hearths. Highest concentrations were measured when two fires were lit at the same time, which would cause high personal exposure for someone working in the kitchens. 15 min averages of up to 25 400 μg m^{-3} ($PM_{2.5}$) and 260 ppm CO were recorded. WHO air quality guidelines were occasionally exceeded for CO and constantly for $PM_{2.5}$. However, air exchange and air distribution measurements revealed a large draw in the chimney, which ensured a fast removal of wood smoke from the hearth area. The guest families were in average exposed to no more than 0.21 ppm CO during 48 h. Based on a hypothetical time-activity pattern, however, a woman living in this type of house during the 17–19th century would be exposed to daily averages of 1.1 ppm CO and 196 μg m^{-3} $PM_{2.5}$, which exceeds WHO guideline for $PM_{2.5}$, and is comparable to what is today observed for women in rural areas of developing countries.

1. Introduction

In the year 2000, more than 1.6 million premature death, and about 3% of the global burden of diseases, mainly for women and young children (e.g., acute lower respiratory infections and pulmonary diseases), were attributed to indoor air pollution from household use of solid fuels (Smith et al., 2004). About half of the world's households depend of some sort of solid fuels (biomass including wood, dung, and coal) for cooking and heating. The majority of these households belong to developing countries, and the use of fuel often take place in open fires placed on the kitchen floor, or in inadequately vented stoves under poor, incomplete combustion conditions that lead to high emissions of small particles, carbon monoxide, and volatile organic compounds (Naeher et al., 2007).

Although reasonable control of wood smoke can be achieved by the use of enclosed metal or ceramic stoves with flue (Smith et al., in press), in the poorest regions their use is not realistic due to the cost. The need to inexpensively reduce indoor exposures from cook fire smoke is not new, however, but existed in all countries using wood through history. In past centuries, for example, Denmark was a low-technology wood-burning society, not able to afford much metal. Winter heating is also needed, and in earlier period's space heating and cooking was provided by a simple open fire on the floor and a smoke exit hole in the roof. The introduction of chimneys in

* Corresponding author at: Department of Conservation, National Museum of Denmark, IC Modewegsvej, DK-2800 Kgs. Lyngby, Denmark. Tel.: +45 33473502; fax: +45 33473327.
E-mail address: morten.ryhl-svendsen@natmus.dk (M. Ryhl-Svendsen).
[1] Present address: Environmental Health, Graduate School of Public Health, San Diego State University, CA 92182-4162, USA.

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Danish farmhouses began around 1600, however, but spread slowly (Michelsen, 1968; Stoklund, 1969). In the next centuries, increasingly advanced fireplace designs were used, with different combinations of hearth, smoke hood, and smoke exit hole(s) in the roof. Metal stoves directly connected to a flue became common only during the 18–19th century.

Although there were regional variations, a hearth system was commonly used during roughly 1600–1850 that involved a waist-height hearth platform with open fire integrated into the lower part of a large open chimney, access to which was open at the bottom to the kitchen or scullery (Fig. 1). Cooking was still conducted on an open fire with a metal tripod to hold the pot, as in previous centuries. Hearth systems like this from the Danish Zealand region were so large that a person would stand completely inside the chimney while operating the stove. A similar kitchen chimney design was used in Eastern and Central Europe, and is known in Germany as *die schwarze küche* (Michelsen, 1968; Stoklund, 1969). Such arrangements require no change in the type of fuel or the way cooking is done over the traditional method and no metal in the construction of the open chimney.

Using houses at a Danish historical research center, we conducted measurements primarily to determine how effective such traditional Danish hearth systems were in removing smoke from the house, and thus, how much exposure might have existed historically. Secondarily, we briefly discuss whether such structures might be considered in developing countries today. Previously, a few experiments have been carried out in reconstructions of prehistoric cottages or houses, where high levels of wood smoke and poor indoor air quality were observed (Eketorp and Herschend, 1982; Skov et al., 2000; Beck et al., 2007), but these houses were much less advanced than Danish historic farmhouses. Enquiries to open air museums gave only anecdotal evidence on the smoke level in such farmhouses, and to our knowledge there exists no previously published investigations.

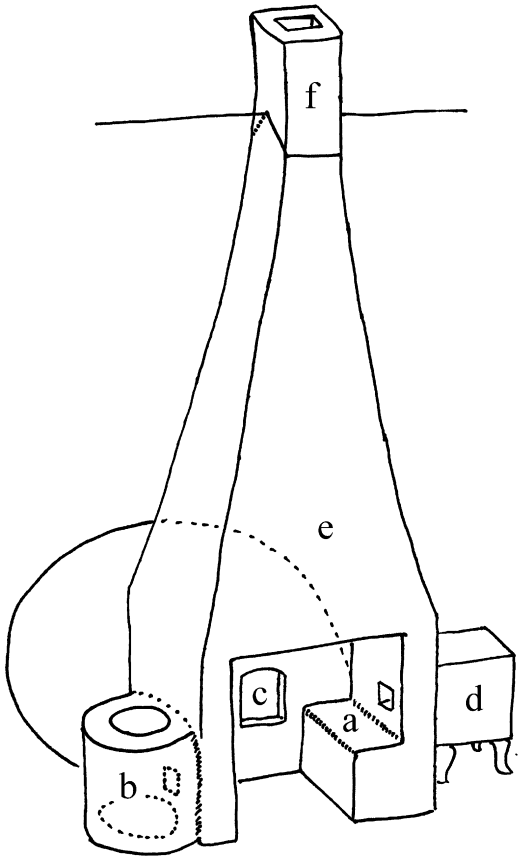

Fig. 1. Principle of complete hearth system: a): waist-height platform for open cooking on metal tripod, b): brick stove holding a copper pot, c): baking oven, d): iron heating stove, e): smoke hood, f): chimney above roof. The hearth would usually be placed in the center of a house, joining walls between a living area and a combined scullery and kitchen area. The iron stove would heat the living room, while the copper pot was placed in the scullery, but all functions were fired from inside the hearth through holes in the wall providing a common means for the smoke to exit the house.

2. Sites and test conditions

2.1. Farmhouses

The investigation was carried out in two reconstructed farmhouses at the Lejre Historical-Archaeological Experimental Center in Denmark (Lejre, 2009). These houses are part of the Lejre Center's attractions, in which families may stay for a week during the holiday season, while living in the style of the 17–19th century. In addition, the houses are used for experimental history and archaeology investigations. The two houses are located about 25 m apart and surrounded by small gardens, fields, and open country. No open roads or other sources of air pollution were noted nearby. The reconstructions were built in 1978 (House 1) and 1965 (House 2) and accurately represent the design, size, and materials of houses in past centuries.

House 1 was a copy of a dwelling house from the village Tystrup, Zealand. The first record of the original house was from 1797, but it was presumably older. Today the original house has been moved to the Danish Open Air Museum north of Copenhagen. The house was a typical countryside smallholding unit supporting a workman's family, and has housed as many as eight people at one time (Michelsen, 1985). It was a half-timbered house with adobe and lime-mortar walls, and a thatched roof. The house was centered around the kitchen hearth, placed inside an open chimney, with a kitchen and scullery area on the left side, and two living rooms to the right. The hearth provided multiple functions; cooking, water heating, bread baking, and space heating in the adjacent living room. The dimensions of the house were 13 × 3.7 m, with a ceiling height in the rooms of 1.9 m, and a chimney height of about 6 m (Fig. 2).

House 2 was not an exact copy of any existing house, but was built in the typical style of farmhouses from around 1700. The design was heavily inspired by a house from Kalvehave, Zealand, that is also today located at the Danish Open Air Museum. In building style and furnishing, House 2 was much similar to House 1, however, representing an older house it has no chimney, but instead the hearth was located inside a brickwork hood that leads the smoke up under the thatched roof where it disperses out through holes. The arrangement of the rooms and the hearth itself was much similar to that of House 1, but smaller (36 m^2 as compared to 49 m^2). On the left side of the hearth were a kitchen and scullery area, and to the right, one living room. Furthest to the right, the building housed a cattle shed and storage room, but this area was not connected to the dwelling by doors or windows. The dimensions of the dwelling were 8.3 m × 4.3 m, with a living room height of 1.8 m (Fig. 2). The kitchen side of the house had no ceiling, but was open to the thatched roof, and with open access to the loft above the living room (height 5.2 m at ridge).

2.2. Test conditions

The investigation was carried out during two weeks of June 2006. During the first week, the houses were not occupied by guest families, but available for intensive tests. During four days of that