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Architectural Design Solution for Reducing Smoke Build-Up inside Rural Kitchens in Kenya, Africa

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Abstract

Families living in rural Africa must rely on burning biomass as their fuel source for cooking. Examples of biomass sources include including wood, dried dung and crop residue, all of which produce high levels of smoke. Repeated long-term exposure to the smoke can cause pneumonia, emphysema and lung cancer. The World Health Organization (WHO) estimates that over 2 million persons die prematurely each year as a result of such exposure. The persons most affected are women and their young children. Scientists, engineers and public health professionals have attempted to address this problem in the past but have focused primarily on the use of more efficient stoves. New stoves are often difficult to maintain and cost more than families can afford. The introduction of innovative architectural ventilation design solutions has not been reported in literature. To determine whether new architectural design approaches could be used cost-effectively in reducing indoor air pollution, scale-model based laboratory simulations were carried out to study the thermodynamic and airflow characteristics inside traditional kitchens. The tests revealed that use of window and roof openings to increase ventilation negatively impacts smoke removal by lowering convection (buoyancy) of the smoke generated by a fire. Based on this insight, a new architectural design approach was developed which allows the smoke to exit the kitchen freely in spite of limited convection. The scale-model simulations yielded an 85% reduction of indoor smoke-build up. Testing of a full-scale prototype kitchen in Kenya, Africa showed a reduction of indoor kitchen smoke build-up in excess of 95%. Implementation of this design in the form of a retro-fit option for existing rural kitchens is proposed. Improvements in the health and wellbeing of women and children in rural communities is hoped for.

Keywords: Rural kitchens, smoke exposure, health, architectural design

1. Background

Families living in rural areas of developing countries often rely on indoor open fires for cooking. The most common fuel sources include scavenged wood, dried animal dung and crop residue. These biofuels are easily accessible and free but create hazardous health conditions caused by the high levels of smoke inside confined settings (Bruce 2000, 2002, Ezzati 2004). Repeated exposure to this indoor air pollution can lead to serious chronic respiratory health problems such as pneumonia, emphysema, asthma and even lung cancer. Those most affected are also the most vulnerable: Women with the traditional responsibility of cooking, and their young children, who remain under the care of their mothers and spend extended periods of time in the kitchens. The World Health Organization (WHO) estimates that over two million women die prematurely each year as a result of indoor air pollution exposure (Smith 2004, Subramanian 2014). The WHO also calculates that pneumonia caused by indoor pollutants is the reason for 45% of the deaths of children under five (Moeti 2018).

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Lack of electricity in rural communities prevents families from using mechanical means to ventilate their kitchens. The relatively high cost of stoves that use more efficient fuels such as Kerosene, Propane or Butane has limited their widespread implementation (Torres-Duque 2008). The inability of the rural poor to access these options led to our search for an alternative approach to improved indoor air quality. The answer seemed to lie in ventilation. Implementation of innovative passive ventilation methods based on new design solutions have not been reported in literature. To determine whether new architectural design approaches could be used cost-effectively in reducing indoor air pollution, scale-model simulations were carried out to study the thermodynamic characteristics of airflow and identify alternative approaches to removing smoke generated by indoor stove fires.

2. Construction methods

Historically, rural kitchens in Kenya were circular in design that included thatched roofs. More recent designs are rectangular in shape and utilize corrugated sheet metal for roofing. Construction materials still include clay and mud packed onto vertical wood scaffolding that form the walls. Kitchens are usually separated from other structures used for living and sleeping. In general, there are no ventilation features in these kitchens that allow smoke produced by an open fire to exit freely. This creates a "smoke-house" environment where the concentrations of smoke reach dangerously high levels. Figure 1 illustrates the exterior and interior views of a traditional kitchen without windows. Figure 2 illustrates current construction methods in rural Kenya.

Figure 1. Exterior and interior views of a traditional kitchen in Kenya

Figure 2. View of current construction techniques used in rural Kenya to build kitchens

3. Methods

A series of laboratory simulations were carried out to study the temperature parameters believed to influence smoke movement inside the rural kitchens. The tests were designed to document changes in the vertical temperature profiles and subsequent smoke distribution patterns associated with indoor stove fires. A 1/12 scale model of a kitchen was built to assess the impact of window and roof openings on smoke dispersion patterns. The goal was to identify architectural design options to achieve effective ventilation without the use of electrical fans.

3.1 Indoor air temperature

A temperature "tower" was used in measuring air temperature changes and changes in convection inside a confined space. Four thermocouples temperature probes were placed inside the tower to record changes in the adiabatic lapse rate as a result of selected roof and window openings. The tower was 154 cm in height and 18 cm in width on each side. The thermocouple temperature probes were placed at heights of 31 cm, 69 cm, 104 cm, and 140 cm. Two 10 cm x 5 cm openings (windows) including shutters were located opposite to each other at a tower height of 23 cm. An incandescent 80 watt light bulb was positioned in the center of the tower base producing constant and controlled heat output (thermal convection). Tower adiabatic lapse rate changes were recorded for both open and closed window configurations as well as for roof openings ranging from 0% to 100%. The design of the temperature tower is illustrated in Figure 3.

3.2 Indoor smoke patterns

Indoor smoke movement was observed using the 1/12 scale model of a traditional rectangular kitchen. Smoke tracers were used to visualize the smoke. Additionally, a Paraffin fuel-cell candle was used to generate convective heat movement as well as measurable CO_2 emissions. The scale model is illustrated in Figure 4.

Figure 3. Temperature tower used for assessing changes in the adiabatic lapse rate resulting from roof and window openings

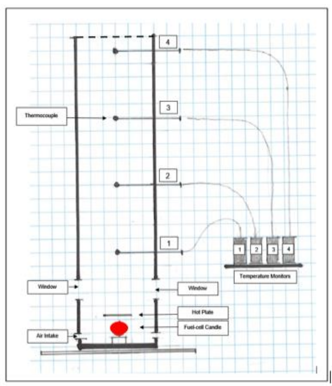
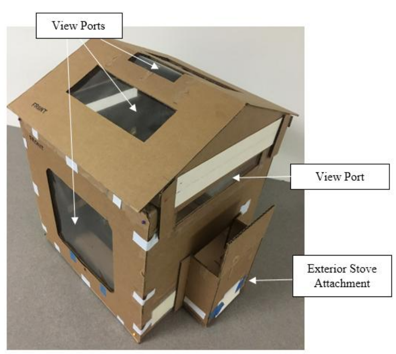


Figure 4. Scale model used for assessing indoor smoke movement influenced by window openings and an exterior stove attachement



4. Results

4.1 Tower tests: Roof openings

Air temperature was measured at points #1, #2, #3 and #4for roof openings of 0% (completely closed) 5%, 25%, 50%, 75% and 100% (completely open). The temperature difference between the lowest level (#1) and the highest level (#4) was computed as summarized in Table I. It can be seen that the temperature difference was highest for the fully closed configuration (0% open), at 12.2^{0}C, while the smallest difference was seen for the fully open configuration (100%) at 2.1^{0}C. The temperatures for all of the roof opening configurations was highest at the lowest level (#1) and always lowest at the top (#4). Table 1 summarizes these observations.

Table I. Summary of tower air temperature difference between levels #1 and#4 for roof opening configurations0% to 100%.

Roof Opening Configuration (%)	Floor-Roof Temp. Difference (^0C)
0	12.2
5	10.7
25	3.1
50	2.4
75	2.2
100	2.1

4.2 Tower tests: Window openings

Tower temperatures were recorded at points #1, #2, #3 and #4 for the closed and the open window configurations. Table 2 summarizes the corresponding air temperature values.

Table 2. Summary of tower air temperatures observed for open and closed window configurations

Tower Height	Windows Closed (^0C)	Windows Open (^0C)
1	38.0	32.1
2	31.2	28.9
3	27.9	26.7
4	26.4	25.4

4.3 Model tests: Ventilation

A liquid fuel cell candle was used to produce heat and measurable combustion bi-products. CO_2 concentrations were used as a proxy for room ventilation, i.e., high CO_2 values indicated a low kitchen ventilation rate while low CO_2 values represented a high ventilation rate. Table 3 summarizes the CO_2 concentrations measured at 1-minute intervals during a 10 minute monitoring period. The ambient laboratory air CO_2 concentration was 700ppm. When the fuel cell was placed at the center of the model, the CO_2 concentrations reached 2,369 ppm. When the fuel cell was placed into the exterior stove attachment, the CO_2 concentration remained similar to the ambient level. Table 3 summarizes the CO_2 concentrations observed for the two placement locations.

Table 3. Summary of CO_2 concentrations observed with an interior and exterior placement of the fuel-cell candle

Time (Minutes)	Interior Fire CO_2 Conc. (ppm)	Exterior Fire CO_2 Conc. (ppm)
	700	700
1	1650	778
2	2143	789
3	2270	792
4	2324	801
5	2355	796
6	2264	783
7	2318	776
8	2322	770
9	2325	766
10	2369	763

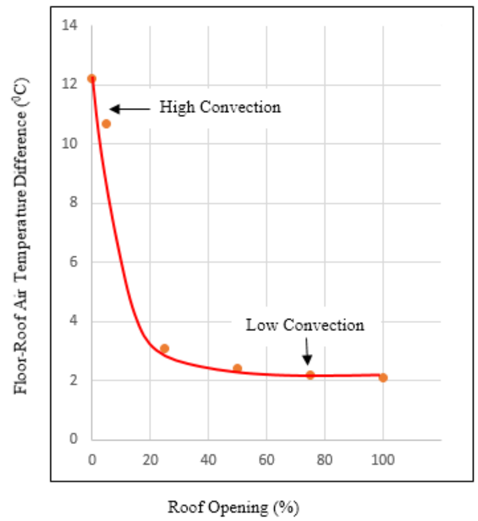
5. Analysis

5.1 Roof openings

The temperature tower tests revealed that the extent of a roof opening influences the vertical temperature profile for a confined space.

The fully closed (0%) roof configuration yielded the largest temperature differential while the fully open configuration (100%) yielded the lowest differential. The temperature differences between the lower and higher levels determine the potential for convection, or "buoyancy", for the smoke generated by a stove fire. Therefore, a closed roof configuration provided more convection (buoyancy) than an open roof. The data help explain why traditional rural kitchen designs in Kenya did not include roof openings. Figure 5 illustrates the temperature differentials associated with the various degrees of roof opening configurations.

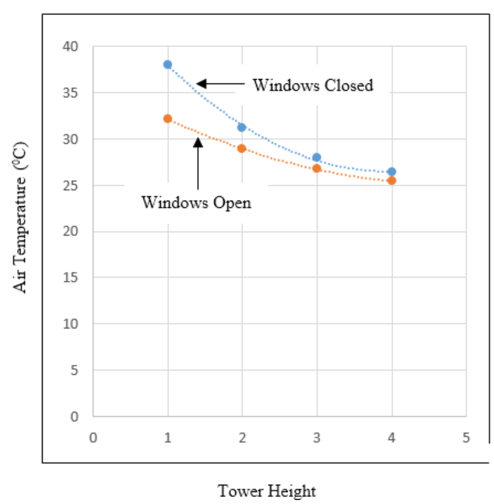
Figure 5. Air temperature differentials associated with 0% through 100% roof opening configurations



5.2 Window openings

The influence of window openings is illustrated in Figure 6. It can be seen that the temperature difference between the lower level of the tower and the upper level of the tower is reduced significantly when windows are open. This reduction in temperature differential reduces the buoyancy of the smoke generated by an indoor fire. The data show that closed windows promote smoke convection. This, again, helps explain why traditional rural kitchens in Kenya did not use window openings to ventilate their kitchens.

Figure 6. Vertical temperature reductions due to window openings.

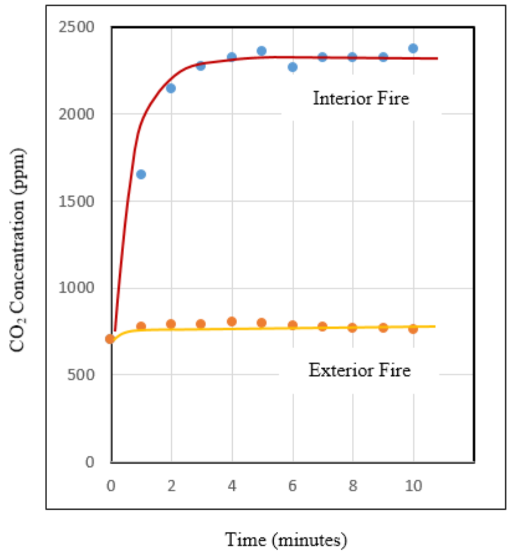


5.3 Interior smoke

Figure 7 illustrates the accumulation of CO_2 inside the model as a result of emissions produced by the fuel-cell candle when placed in the middle of the model and when placed into the exterior stove unit.

The reduction in CO_2accumulation offered by the use of the exterior stove unit suggests that this design feature can offer a significant reduction in indoor air pollution.

Figure 7. Indoor CO_2 accumulation when fuel-cells placed in the middle of the scale model and when placed into the exterior stove unit.



6. Prototype kitchen

A full-scale operational kitchen, including an external stove attachment unit, was constructed in rural Kenya and field tested to determine the interior CO_2 accumulation during regular cook stove use by a family. Measurements indicated that the external stove attachment allowed all of the smoke generated by a stove fire to exit without impacting the interior of the kitchen. No increase in the CO_2 values could be determined. While there was no significant outdoor wind turbulence at the time of the measurements, it is likely that some smoke will enter the kitchen as a result of outdoor wind bursts. Figure 8 illustrates the interior and an exterior of the prototype kitchen.

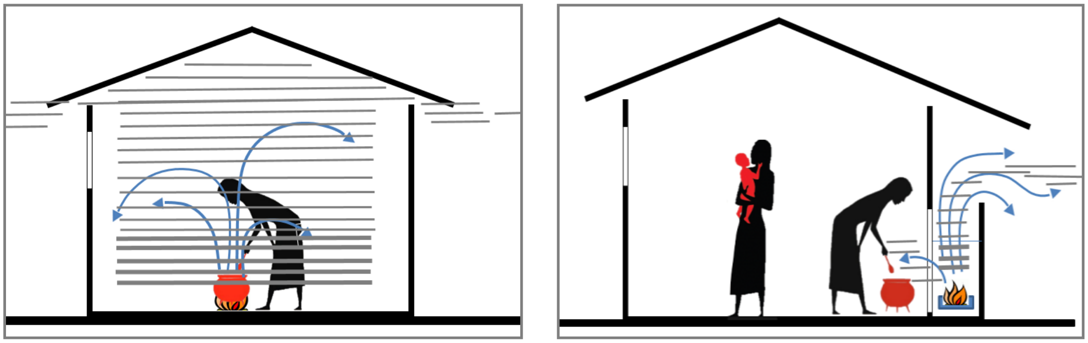
Figure 8. Exterior and interior views of prototype kitchen constructed in Kenya, Africa

7. Conclusions

The laboratory investigations offered important insights into the thermodynamics of airflow within an enclosed space. The data showed how roof and window openings create negative effects on indoor thermal convection and a subsequent decrease in smoke buoyancy. Our findings confirm the appropriateness of traditional approaches that limit roof and window openings to control indoor smoke dispersion. Development of the exterior stove attachment design was the result of integrating these principles. The effectiveness of this new design solution was confirmed by actual field observations. Figure 9 illustrates artistically the differences in smoke movement between the traditional stove location and the new stove attachment.

We believe that by retrofitting existing kitchens with the new design feature can improve the indoor air quality for many families in the future without the burden of additional financial hardship.

Figure 9. Graphic illustration of the smoke movement observed for the traditional indoor stove placement and the exerior stove attachment



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