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Developing Empirical Formula of Ventilation Index for Assessing $Pm_{2.5}$ Exposure in Biomass-Fuel Using Households

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Abstract

Equations of 'ventilation index' in industrial and medical sectors are already established, but not yet been worked out for domestic household environments. This study intended to establish an empirical formula for 'ventilation index' for domestic indoor environments. Measurements of 2.5 micron size particulate matter ($PM_{2.5}$) with biomass, air velocity, room index, temperature and relative humidity were used for developing the empirical formula. A total of 54 households from rural Andhra Pradesh and Karnataka states of India were selected. Average air velocity ranges in selected kitchens were categorised into three parts for developing ventilation indices in household kitchen environments. Observations in kitchen environments were found to be very interesting and promising. The formula capturedinverse relation between $PM_{2.5}$ and air velocities, consistently.

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Introduction

More than three billion people in the world use solid fuels collectively in the form of biomass and coal and meet their energy demands for cooking foods or lighting etc.[1,2] The percentage of biomass use is more visible in Africa, South-East Asia and in Central and South America.[3] Biomass burning is more common in the rural area than the urbans and people use traditional cooking stoves of inadequate combustion chamber and poor ventilation. Sometimes, open burning of biomass for heating water and cooking are also observed.[4,5] In India, almost 770 million people living in approximately 160 million households use solid fuels as their primary cooking source.[6] Exposure to household air pollution from cooking results with almost 925000 premature deaths per year which amounts to about 25 million lost disability-adjusted life years (DALYs). About 4 % child death occurs under the age of 5 years due to pneumonia.[7]

The term 'Ventilation Index' is familiar in industries and hospitals. However, establishing the same index

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in domestic indoor settings has not yet formulated. The present study has been a trial to fill this gap. Common perceptions of the people agreethat the well ventilated room reduces air pollution exposure. However,quantitative measure of any representative household air pollutants with respect to ventilation index, especially for biomass-using households, has not yet been explored, globally. This study targets this challenging exercise by capturing indoor air dynamics and $PM_{2.5}$ exposure pattern by using a newly developedempirical formula of ventilation index. Though a number of equations and permissible ranges on 'ventilation index' have been documented in medical and outdoor air environments in some studies across the world,[8,9] yet none of those studies did focus, either qualitatively or quantitatively, on establishing equation relative to air pollutants and air velocity in indoor household environments.

Concept of spot and dilution ventilation has also been a subject of domestic indoor environments and are cited in many literatures. However, the alternate way of assessing air pollutantswith comparatively low-cost scientific measures are still rare. Obviously, the question arises as 'what cost is low cost' – is yet to be defined. Standard monitoring techniques using National Institute of Occupational Safety and Health (NIOSH), USA were adopted for particulate matter in rural indoor household settings of Andhra Pradesh and Karnataka, India. For simplifying sampling complexities, monitoring data of these two states were used to establish an empirical formula for 'Ventilation Index'.

Biomass burning is a common cooking fuel in all developing countries, even today. Biomass includes wood, coal, agricultural residues, animal excrement etc. and burning those as cooking fuel cause indoor air pollution. Exposure assessments for children and women have been assessed in many studies across the world.A few studies concerned with particulate matter ($PM_{2.5}$, health effects of women, children, adults and birthweight in a rural-urban, mother-child cohort.[10,11] Some of these, established the association between respiratory infections and infant mortality in developing countries[12,13] It is also observed that women with domestic exposure to biomass-fuel combustion may develop Chronic Obstructive Pulmonary Disease (COPD) and other respiratory illnesses to the extent comparable to tobacco smokers.[14] Another study has reported on mean 24-h average particulate concentrations in Indian households where significant correlations were observed among particulate matters, fuel type, kitchen type, and fuel quantity. Among solid fuel users, the mean 24-h average exposures were found to be highest for women cooks and were significantly different from men and children.[15] However, studies on the development of ventilation index for assessing household air particulates is still not available.

Air change rate in indoor environment has direct link to the exposure and health. The heating, ventilation, and air conditioning (HVAC) system estimates the filling of air in a room per unit time and assesses air change per hour (ACH). Again, the influence of ventilation index in domestic household is still not clearly quantified.

The 2016 edition of ANSI/ASHRE Standard 62.2 defines the roles and minimum requirements for mechanical and natural ventilation systems and the building envelope intended to provide acceptable indoor air quality in low-rise residential buildings.[16] The households selected in the study were from almost identical geographical region. Though the area belongs to two different states of the country, but similarities were found in residential structures, kitchen configurations and type of wood used for cooking fuels. This study made use of century old ventilation measurement-tool 'Kata-Thermometer' and has proved it's importance in exposure assessment study.

Experimental

The empirical equation was developed with the help of required data produced from someselected villages of Andhra Pradesh and Karnataka, India. Recruitment of households and study participants were conveniently selected using standard monitoring protocols. Ethical considerations were strictly maintained in the recruitment process that resulted out with spontaneous consents of the selected individuals. A total of 54 household kitchens were chosen to conduct $PM_{2.5}$ monitoring using SKC make sampler and kitchen air velocities were measured using Kata Thermometer. Kitchen area concentrations for $PM_{2.5}$ were measured as integrated 24-hour samples, collected using low-volume air sampling pumps (supplied by SKC Inc). Pumps were placed 1.5 m above the ground and were operated at a flow rate of 1.5 L/minute. $PM_{2.5}$ was collected on 37-mm Teflon TM filters (Pall Corporation, Port Washington, NY, USA), backed with cellulose support pads placed in a filter cassette connected to a BGI cyclone (BGI Inc., Waltham, MA, USA). Using a laboratory-calibrated rotameter, flow rates were measured before and after sampling activities in the field. Filters were also weighed before and after sampling, using an electronic microbalance with a sensitivity of 0.001 mg (supplied by Sartorius Inc.) in a temperature- and humidity-controlled room. The Kata cooling power, which is a property of the thermometer, is marked on the glass stem. It gives the heat lost by the air per cm^2 of bulb area, as the alcohol column drops from the 38°C mark on the stem to the 35°C mark. This factor in m.cal/cm^2 divided the time required in seconds for the alcohol column to drop gives the cooling power. This is the dry kata cooling power expressed conventionally in W/m^2. A person doing moderate work generally produces 165 W/m^2.

The Room Index (K) value was determined by this formula:

K= L X W / [L+W] X H

K = Room Index Value
L = Room Length in Meters
W = Room Width in Meters
H = Mounting height from the room floor in Meters

Required meteorological parameters like temperature & relative humidity were measured by LASCAR EL-USB data Logger; room measurements were carried out with a tape and amount of biomass used was measured with a weighing box in pre- & post-cooking periods. The types of biomass fuel were found to be almost identical in both the states and were dry wood from moderate size plants.Data of all variables were fit into the proposed equation to develop the ‘ventilation index’. The developed empirical formula has been found to be encouraging thus far.

Table 1: Distribution of experimental parameters for formulating ‘Ventilation

Average Kitchen Wind Velocity (m/s)	PM 2.5 Conc. (μg/m3)	Room Index	Amount of fuel used (Kg)	24 hr average Temperature (˚C)	24 hr average Relative humidity(%)
< 0.2 (n=18)	432.69.	0.62.	3.12	28.7	71.21
0.2-0.4 (n=15)	160.31	0.62	2.86	29.1	70.18
>0.4 (n=21)	79.21	0.53	3.05	28.5	68.23

Results and discussion

Table-1 contains six environmental parameters chosen primarily to establish ventilation index in indoor kitchens. Wind velocities were categorized and compared with $PM_{2.5}$ concentrations. Other four parameters were considered as probable impact factors, as anticipated, over the primary estimates. Amounts of fuel use, temperatures and relative humidity (Rh) have been observed to be almost equal in all households which helped comparing air velocity and $PM_{2.5}$. Temperature and relative humidity were not incorporated in the equation, but its identical values supported the comparison.

Parameters like room index, fuel type and amount, temperature and relative humidity for exposure assessment in household environments were kept almost identical to compare wind velocity and $PM_{2.5}$ concentration level in indoor environments.

With very weak air movement in the kitchen, mean concentrations of 18 households were observed to be 432.69 μg/m3, whereas, with gradual increase of air movements, the values reduced down to 160.31 μg/m3 with 15 households and 79.21 μg/m3 with 21 households, respectively. All these $PM_{2.5}$ concentrations crossed permissible limits (25 μg/m3) as prescribed by the World Health Organization. However, impact of comparatively higher air velocities lowered the $PM_{2.5}$ load in kitchen environments were captured quantitatively.

Establishment of Empirical Equation Forventilation Index

Considering standard wind velocity (V) in the room as 0.5 meter/second; Room index (RI) as 0.5 (Length: 10 feet, Width: 10 feet and Height: 10 feet); $PM_{2.5}$ concentration (C) as 25 μg/m3 and amount of biomass fuel (W) as 1 kg, the 'ventilation Index' has been calculated by using an empirical formula as:

$$\text{Ventilation Index (VI)} = \frac{C \times W}{V \times RI} \qquad ...(1)$$

[with identical temperature and relative humidity]

Incorporating above cited values of C, W, V and RI, the value of 'VI' has been found to be 100. This means, while attaining $PM_{2.5}$ concentration to the WHO value, the ventilation index will be 100 units. This value has been assumed to be an empirical standard for estimating relative $PM_{2.5}$ concentration as limiting value in household environment. Ventilation Index > 100 unit would be considered higher pollution level, gradually.

Following results were worked out when equation – (1) is applied with distinct parameters of three rows of the table 1:

- When C = 432.69 µg/m3, W = 3.12 kg, V = 0.19 (in the category < 0.2) m/s, and RI = 0.62; Ventilation Index = 11460.01, which is almost 115 times higher than the anticipated safer level of 100.
- When C = 160.31 µg/m3, W = 2.86 kg, V = 0.3 (in the category 0.2 to 0.4) m/s, and RI = 0.68; Ventilation Index = 2247.45, which is almost 22 times higher than the anticipated safer level of 100.
- When C = 79.21 µg/m3, W = 3.05 kg, V = 0.5 (in the category >0.4)m/s and RI = 0.53; Ventilation Index = 911.66 t, which is almost 9 times higher than the anticipated safer level of 100.

Therefore, the ventilation index of the highest $PM_{2.5}$ concentration (432.69 µg/m3) category is almost 5 times higher than the next category with 160.31 µg/m3; On the other hand, ventilation index of the second category is almost $_{2.5}$ times higher than the least observed value of $PM_{2.5}$ concentration (79.21 µg/m3) category.

This indicates better improvement of kitchen environment with air velocity more than 0.4 m/s.

Conclusions

This study is an attempt to standardize an empirical formula that will help assessing the deviation of $PM_{2.5}$ concentrations in indoor settings with respect to WHO standards. This is the first attempt and resultshave been found to be encouraging. Further validation of this equation from more number of households and varying household environments is still needed to conclude statistical quantification of the empirical formula developed thus far. However, the present dataset clearly hinted the success of the empirical equation in addressing inverse relation between air velocity and exposure concentration in indoor environments. Once validated with several bands, $PM_{2.5}$ concentrations can be assessed almost quantitatively without measuring costly and time consuming activities.

The equation would help understanding the estimate of $PM_{2.5}$ concentrations using known amounts of biomass fuel, room wind velocity and room index. This model may also be tested for toxic gas environments in indoors. Simple intervention on kitchen ventilation may mitigate the household pollution, significantly. Once the equation is validated with other air toxicants in household environments, the study may attract policy makers to address the importance of household ventilation and may direct Prime Minister's Housing Schemes for better kitchen configurations to achieve good ventilation for reducing exposure burden at household level. Asthis study showed success even with the limited access of households, itmay also be used as a control banding tool that can strengthen future epidemiological evidence for policy makers.

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Conflict of Interest

There is no conflict of Interest in this manuscript

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