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Viewpoint

Health effects engineering: Perspectives for environmental health and environmental engineering studies—domestic biomass combustion as an example

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Abstract

Health effects engineering (HEE) is a newly developed research field, which involves collaboration with environmental scientists, engineering researchers, and toxicologists. By employing the methods of HEE, one can not only confirm which attributes of the project are likely to contribute to certain health effects, but can also get rid of the adverse health effects by engineering technologies.

HEE is thought to be particularly important to domestic projects in which there is a lack of environmental assessment. This paper presented the authors' viewpoints of the principles of HEE in the field of the environmental health and engineering studies by using programs of domestic biomass combustion as an example. The authors showed that there are three sub-fields of HEE, which are as follows: engineering behavior, the pollution characteristics, and the health effects. The authors conclude that the principles of HEE compose a helix with the studies in the fields of environmental science, health, and engineering, and give suggestions on how to perform HEE in a practical field.

Keywords: Health effects engineering; Domestic energy use; Biomass combustion

1. Introduction

Health effects engineering (HEE) is a newly developed research field, which involves collaboration among environmental scientists, engineering researchers, and toxicologists. It can be adopted to solve the engineering problems related to environmental pollution and human health in both industrial areas and in domestic use.

More than one-third of the world's population, which is about 2.4 billion people, relies on burning biomasses, such as wood, crop residues, charcoal and/or dung for cooking and heating (Desai et al., 2004). Studies show that more than 50% of the developing countries' energy consumption is composed of burning such biomass. However, burning these biomasses has posed major threats to global public health during recent years, which is indoor air pollution. In addition, the inefficient stoves for burning various biomasses make this threat even worse. It should be noted that only within the last 100 years, wood-burning stoves were adopted by middle- and upper-income families when the access to petroleum-based fuels was a problem, and the recent spate of improved stove programs focusing on energy efficiency began in the 1970s after the large rise in oil prices (Barnes et al., 1994).

People who rely on coal and biomass in the form of wood, dung, and crop residues for domestic energy are almost all living in developing countries. Therefore, the energy efficiency and the adverse effects of indoor air pollution caused by biomass combustion are of particular concern in these areas (Barnes et al., 1994; Bruce et al., 2000; Ezzati and Kammen, 2002; Smith, 2002). Widespread researches have been carried out by experts for assessing these problems in both environmental engineering and environmental health studies.

2. Environmental engineering studies on domestic biomass combustion

As the developed countries were in the forefront of research in environmental engineering studies, the materials that were studied in the environmental engineering of

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biomass combustion were mainly those common in these countries, for instance, woods, barks, sawdust, garden wastes, nut shells, as well as crop residues that are common all over the world. Research on both combustion reactor and field monitoring was conducted and based on these studies, the processes of biomass combustion include hydrolysis, oxidation, dehydrate, pyrolysis, volatilization, char-formation, flam combustion, and smolder (Ferge et al., 2005; Nussbaumer, 2003). The duration of each process, knowing which may help in stove design, is affected by both the characteristics of the fuels, such as granularity, volatile content, ash content and moisture, and the combustion situation, such as combustion temperature, excess air ratio, and fuel load.

Furthermore, in the studies on the pollution caused by biomass combustion, the formation and emission of particulate matters (PM) are the most discussed topic. Many studies have shown that the obtained distribution of the mass concentration of particle size is usually bimodal (Boman et al., 2004; Jiménez and Ballester, 2005). The results of these researches indicate that the number concentration of sub-micron particles increase while fuel load decreases or the excess air ratio increases (Ferge et al., 2005; Johansson et al., 2003; Lillieblad et al., 2004). The inorganic components of sub-micron particles consist predominantly of sulfur, chlorine, and potassium. These components were formed from the gasification of sulfur, chlorine, and potassium in combustion and their condensation with the decreasing of temperature. They were also formed from the melt and sinter of the ash content (Boman et al., 2004; Jiménez and Ballester, 2005; Nussbaumer, 2003; Svane et al., 2005). The formation of these inorganic components in the particles was affected by the ash content of the fuel, combustion temperature, and the oxygen supply. High ash content fuel is likely to form large sinter particles. High temperature combustion is propitious to evaporation and thus results in the formation of small condensation particles. Sufficient supply of oxygen leads to the formation of gaseous potassic oxide that condenses to particles later, and the oxidative atmosphere is propitious to the formation of sulfate dominated particles while the lack of oxygen leads to the formation of chloride dominated particles. Other elements vary largely according to their content in the fuel and the combustion situation; however, generally speaking, Na and Zn form a part in the sub-micron particles, Ca, Mg, Al, Si in the coarse ones, and other elements are rare in the biomass combustion PM (Boman et al., 2004; Jöller et al., 2005; Miller et al., 2002).

Soot and polycyclic aromatic hydrocarbons (PAHs) are concerned on the organic component of biomass combustion PM. Incomplete combustion caused by insufficient air supply leads to the formation of PAHs (Ferge et al., 2005), especially for the highly toxic four to six ring-PAHs (Sáez et al., 2003). Combustion temperature also affects the formation of PAHs. The combustion of phenols and lignin from the pyrolysis of wood produces PAHs (Jordan and Seen, 2005) when the temperature is around 900 °C. In addition, the high temperature is propitious to the pyrolysis of carbonaceous materials, which may directly produce PAHs (Koziński and Saade, 1998), and also cause the PAHs with low molecular weight to convert to those with higher molecular weight and higher thermal stability. Moreover, the free radicals formed in high temperature with small molecular weight are likely to compose PAHs when the temperature decreases (Simoneit, 2002). The formation of soot is caused by incomplete combustion, which is also affected by the similar influencing factors as PAHs.

Although there are still unknown properties of certain fuel and combustion devices under certain environmental conditions, researches such as the ones mentioned earlier have described the phenomenon and mechanisms of how combustion fuels and status would affect the combustion pollutant products, and make the pollution reduction based improvement available. However, questions such as ''What is the priority pollutant to control?'' and ''What is a suitable level for the reduction?'' are not the business of engineers, but of environmental heath researchers.

3. Environmental health studies on domestic biomass combustion

Exposure to the polluted environment that is an outcome of biomass combustion was thought to be related to varieties of illness and health effects, including acute respiratory infections (ARI), chronic obstructive pulmonary disease (COPD), lung cancer, asthma, nasopharyngeal and laryngeal cancer, tuberculosis, cataract, blindness, and low birth weight (Desai et al., 2004). Most current epidemiological studies on this topic have focused on ARI, COPD, and lung cancer. Although detailed epidemiological and toxicological research on the health effects of exposure to indoor smoke from solid fuels has begun only recently, there is increasing consensus on the important role this exposure plays in the burden of disease, especially among the poor and marginalized groups (Ezzati et al., 2004). Estimates of global mortality from exposure to indoor solid fuel smoke are shown in Table 1 (Ezzati et al., 2002; WHO, 2002).

Exposure to the indoor air pollution resulting from biomass combustion was influenced by fuel type, energy conversion technology, housing and ventilation, and behavioral factors, such as fuel preparation and individual time-activity budgets (Warwick and Doig, 2004). Different fuel-device combination leads to different energy efficiency and pollution levels. For instance, wood combustion with open fire produces pollutants several times higher than wood combustion with improved stoves or clear energy such as electricity and LPG (Albalak et al., 2001; Bruce et al., 2004; Naeher et al., 2000). Another example is cooking, which is often done in shorter time intervals and possibly in confined areas. Emissions from open biomass stoves fluctuate over the short time intervals. Emission

Table 1
Mortality and burden of disease as a result of exposure to indoor air pollution from solid fuels in 2000

Regional level of development (defined by the World Health Organization)	Death in children under 5 years of age	Adult deaths	Burden of diseases (thousands of DALYs)[a]
High-mortality developing (38% of global population)	808,000	232,000	30,392
Lower mortality developing (40% of global population)	89,000	468,000	7,595
Demographically and economically developed (22% of global population)	13,000	9,000	550

[a]Burden of disease is a measure of loss of healthy life from premature mortality and morbidity. It is expressed in disability-adjusted life years (DALYs)

peaks when fuel is added or moved, the stove is lit, the cooking pot is placed on or removed from the fire, or food is stirred; thus, the above factors influence the subset of household members consistently close to the source of pollution, usually women and children (Ezzati et al., 2000a, b; Park and Lee, 2003).

The aforementioned studies figured out the profiles of how indoor air pollution affects human health. With these results, engineers get the information of prior controlled pollutants, as well as a suitable level for pollution reduction because that it is impossible to make zero emission. However, further research should be conducted to gather more details on the characteristics of pollution, and to assess the risk of single chemical compounds or the combined effects of some pollution factors. These studies are important for risk-based pollution reduction, which may reduce the cost and improve co-reduction technology of harmful pollutants, rather than total amount-based reduction.

4. Cases for environmental engineering with health concerns: the improved stoves

As mentioned earlier, from the point of view of both environmental engineering and environmental health studies, the choice of fuel-device combination is important to both the energy efficiency and pollutant emission, and it is also easier to change the stoves than to move to a higher energy ladder. Therefore, stove-improving programs are important and these were launched in many parts of the world. In addition to that, related research was performed.

The stove-improving programs and research were performed in China, Guatemala, India, Kenya, Pakistan, South Africa, etc. (Barnes et al., 1994; Warwick and Doig, 2004). However, since there are varieties of fuel-stove combination used by household, and the improved stoves also have different characteristics, it is not suitable to assess these programs as a whole. The effects of some stove-improving programs are listed in Table 2.

As shown in Table 2, not all the improved devices have reduced indoor air pollution, or energy efficiency. In Guatemala, all the experiments showed a significant reduction in indoor air pollution. However, the combined efficiency data for Guatemala showed that the open fire was significantly more efficient than the plancha stoves (Boy et al., 2000), and the time required to boil water was significantly shorter when using the open fire (McCracken and Smith, 1998). In China, two experiments seem to indicate contrary results for both pollution and energy efficiency. According to Edwards et al. (2004), in many cases, greater thermal efficiency was achieved by improving heat transfer efficiency between the combustion source and the pot bottom, but at the expense of a decrease in combustion efficiency, which led to the increase of pollution emission. Moreover, when the flue gas removes much of the health-damaging pollution from the immediate vicinity around the stove, and inside the home, where women and children may be exposed to extremely high concentrations of health-damaging pollutants when unvented, it is likely to reduce peak exposure concentrations. However, emissions in neighborhood, community, and regional environments are increased and may re-penetrate indoor environments, exposing the population to consistently elevated background levels.

According to Barnes et al. (1994), some stove designs are intended to increase heat transfer efficiency by decreasing air flow, which can actually increase smoke emissions. Conversely, efforts to reduce smoke exposure by introducing chimneys can reduce thermal efficiency. Thus, a balance must be sought between engineering design and health demand.

5. The balance: HEE, the principles

HEE was first raised by Fernandez et al. (2005), which involve collaboration between engineering researchers and toxicologists. By employing the methods of HEE, one can determine not only which project attributes are likely to contribute to certain health effects, but also how tendencies of the component related to the health effects that can be engineered out of the project process. From the toxicology study of Fernandez et al. (2005), they found that "bad actor" for the previously reported coal/municipal sewage sludge (MSS) health effects is the combination of zinc plus sulfur, rather than zinc alone. Thus with the HEE method, injection of a kaolinite sorbent downstream of the flame, above the zinc dewpoint, which sequesters the zinc, diminishes the health risk caused by burning fuels containing both zinc and sulfur. This is a successful case study of HEE in the engineering project field, and inaugurates the study of HEE.

Table 2
The effects of improved biomass stove programs

Country/(fuel)	Indoor CO concentration	Indoor PM concentration	Energy efficiency	Reference
China				Sinton et al. (2004)
Traditional type I	26.67 ppm (24-h average)	196 $\mu g/m^3$ (24-h average PM_4)	9% (for all	
Traditional type II	45.7 ppm (24-h average)	293 $\mu g/m^3$ (24-h average PM_4)	traditional)	
Improved	74.5 ppm (24-h average)	223 $\mu g/m^3$ (24-h average PM_4)	14%	
China (wheat residue)				Edwards et al. (2004)
Brick stove	44 g/MJ (EF[a])	3.2 g/MJ (EF of TSP)	0.92 (NCE[b])	
Improved	82 g/MJ (EF[a])	7.5 g/MJ (EF of TSP)	0.78 (NCE[b])	
China (maize residue)				Edwards et al. (2004)
Brick stove	21 g/MJ (EF[a])	0.9 g/MJ (EF of TSP)	0.94 (NCE[b])	
Improved	27 g/MJ (EF[a])	1.3 g/MJ (EF of TSP)	0.88 (NCE[b])	
China (brush wood)				Edwards et al. (2004)
Brick stove	31 g/MJ (EF[a])	1.3 g/MJ (EF of TSP)	0.93 (NCE[b])	
Improved	44 g/MJ (EF[a])	2.1 g/MJ (EF of TSP)	0.89 (NCE[b])	
China (fuel wood)				Edwards et al. (2004)
Brick stove	11 g/MJ (EF[a])	0.7 g/MJ (EF of TSP)	0.97 (NCE[b])	
Improved	15 g/MJ (EF[a])	1.0 g/MJ (EF of TSP)	0.92 (NCE[b])	
Guatemala (fuel wood)				McCracken and Smith (1998)
Open fire	86400 $\mu g/m^3$ (t.t.[c] of WBT[d])	14800 $\mu g/m^3$ (t.t. $PM_{2.5}$)	14.8%	
Improved plancha	2040 $\mu g/m^3$ (t.t.[c] of WBT[d])	1170 $\mu g/m^3$ (t.t. $PM_{2.5}$)	13.7%	
Guatemala (wood)				Naeher et al. (2000)
Open fire	86400 $\mu g/m^3$ (22-h average)	528 $\mu g/m^3$ (22-h average $PM_{2.5}$)	—	
Improved plancha	2040 $\mu g/m^3$ (22-h average)	96 $\mu g/m^3$ (22-h average $PM_{2.5}$)	—	
Guatemala (wood)				Boy et al. (2000)
Open fire	—	—	12.54%	
Improved plancha	—	—	10.35%	
Guatemala (wood)				Albalak et al. (2001)
Open fire	—	1930 $\mu g/m^3$ (24-h average $PM_{3.5}$)	—	
Improved plancha	—		—	
Guatemala (wood and a.r.[e])		330 $\mu g/m^3$ (24-h average $PM_{3.5}$)		Bruce et al. (2004)
Open fire	12.38 ppm (24-h average)	1650 $\mu g/m^3$ (24-h average $PM_{3.5}$)	—	
Improved plancha	4.89 ppm (24-h average)	728 $\mu g/m^3$(24-h average $PM_{3.5}$)	—	

[a]EF = emission factor, geometric mean emissions per MJ delivered.
[b]NCE = nominal combustion efficiency, which indicates the percentage of the fuel carbon converted to carbon dioxide.
[c]t.t. = testing time.
[d]WBT = water boiling test.
[e]a.r. = agriculture residues.

From this first application of HEE, we can draw a brief picture of HEE. As shown in Fig. 1, there are three subjects of HEE, engineering behavior (when domestic biomass combustion is taken for example, that is combustion status), environmental pollution (for instance, the PM and its characteristics), and health effects, and these three subjects compose a helix in the field of environmental science, health, and engineering.

When we focus on an environmental problem, one of the most essential goals is to understand its adverse health effects, and to try to get rid of it. Usually, we get the characteristics of the pollution from monitoring and chemical/physical analysis. Meanwhile, from the toxicology and epidemiological study, we understand the influencing factor of a certain disease among the numbers of parameters of the pollution. That is so in the case of environmental health studies for domestic biomass combustion mentioned earlier. However, scientists did not get any further to finding solutions. That is to say, from the aforementioned research we know how our health is threatened, but we cannot improve the situation. On the other hand, we study the influencing factor of certain pollution characteristics by laboratory simulation and monitoring, and try to find the way to improve the quality of the environment. This is so in the case of environmental engineering studies mentioned earlier. However, we usually work separately and do not relate these two together,

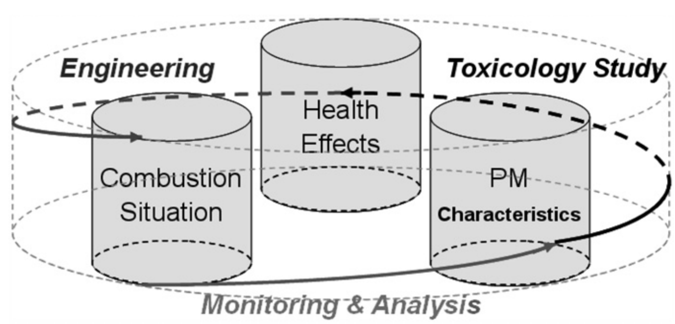

Fig. 1. Principle of HEE: domestic biomass combustion as an example.

which caused some of the stove-improving programs to be unsuccessful, because engineers paid more attention to energy efficiency than how pollution affected human health, or sometimes engineers paid attention to total pollution reduction but not to the most risky factors.

For the engineering project such as what Fernandez et al. has done, environment assessment is required, one that will assess the health effects of the projects, but for the domestic projects, there is a lack of environmental assessment, which is not safe for people's daily life. However, although many people associate public exposures to air pollution primarily with urban outdoor settings, indoor air pollution is one of the largest health-damaging exposures, especially in the developing world. The laws ask the industrial engineering designers to assess the environmental effects before the application of such design, but it is hard for us to arrange an environmental assessment that involves thousands of families and such assessment takes years. Thus, it is more important for the project designer, especially for those domestic works, to keep in mind the effects of HEE, which will help them to design their work in collaboration with experts in the field of environmental sciences and health studies. This will encourage them to produce their design based on the health effects of relative experiments, as well as to pursue an environment and health-friendly work.

6. Suggestions on how to perform HEE

There are some suggested key stages in performing HEE.

(1) Project target: Besides the usual engineering target, the application scope and the health-based pollution-level permission should be especially paid attention to.
(2) Field investigation: Because great differences between regions may exist on the environmental situation, such as fuel types, human activities, and so on, field investigation on these factors, as well as the health status of residents in the target area, can provide the basic data for the design for energy efficiency and environmental pollution control.
(3) Risk assessment: Based on the investigation, a risk assessment should be performed to all the pollution factors and other health-damaging factors, such as dirt, weather, and working behavior. From the risk assessment, engineers may draw the relative risk information that will help set the priorities and neglectable factors in the design for pollution control.
(4) Design and pilot-plant: Based on these previous three steps, a design proposal should also take residents' economics cost into consideration, because the experiment device has no meaning to residents unless it is widely accepted from the point of view of both efficiency and investment. For the pilot-plant research, the environmental situation should be as similar to the target area as possible, because the environmental factors such as atmospheric temperature, relative humidity, oxygen content, will affect the pollution characteristics. It is recommended that the pilot-plant research should be performed in the target area; this is more creditable.
(5) Application and improvement: After the application, researchers should track the performance of the design, and focus on not only the construction quality, but also the pollutant emission and the corresponding health effects. Based on the field monitoring data, it is possible for engineers to improve the devices, which proves the HEE helix to the next thread.

HEE is a new field for exploration, and it asks the cooperation of experts from fields of environmental science, health, and engineering. More studies are needed to clarify the concept of HEE; domestic utilization may be especially important.

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