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Original article

# Fuzzy interval propagation of uncertainties in experimental analysis for improved and traditional three – Stone fire cookstoves

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A B S T R A C T

The performance indicators of Improved Cook Stoves (ICSs) for Developing Countries are commonly evaluated and compared using the arithmetic average of replicated tests performed using a standardized laboratory-based test, commonly the Water Boiling Test (WBT).

Possibility theory is here employed to examine energy data retrieved from the WBT-based literature regarding the results of laboratory tests on ICSs and traditional Three-Stone Fire (TSF) stoves; fifty-seven comparisons of stoves are analysed. Chebyshev and uniform possibility distributions are employed to represent energy data affected by epistemic uncertainty. The extension principle of fuzzy set theory is applied to obtain possibility distributions of the *saving of fuel use* parameter for each comparison of cookstoves. The results indicate that at 90%, 95% and 99% degree of confidence, only 22.22%, 15.00% and 15.00% of all the supposed "improved" stoves emerged respectively as real ICSs at most, while the percentage of "improved" stoves obtained by considering the mean values of the WBT is among 3 and 6 times higher than the percentage resulted by taking into account the epistemic uncertainties. The work suggests how neglecting intrinsic uncertainties of tests' results might lead to misinterpret and report non-comprehensive information about ICSs' thermal energy performance, and to reveal some concerns about their effective improvements over traditional devices.



## Introduction

As indicated in the World Energy Outlook 2015 [1], due to the lack of access to clean and efficient cooking facilities, almost 2.7 billion people in Developing Countries (DCs) rely on traditional biomass and three-stone fire (TSF) cookstoves to meet their cooking needs (Fig. 1a). In this context, gases and particulate matter produced by incomplete combustion of solid fuels burnt in low-efficiency traditional cookstoves cause over 4 million deaths per year [2], due to chronic obstructive pulmonary and ischemic heart diseases.

To mitigate the aforementioned problem, an immediate shift from traditional to modern and clean fuels and cooking appliances is not always feasible. Therefore, the introduction of improved biomass-fuelled systems, namely Improved Cook Stoves (ICSs), is supposed to be necessary, since they are considered substantially more efficient than traditional cookstoves (Fig. 1b), reducing pollutant emissions and wood consumption.

Numerous international Institutions, like the Global Alliance for Clean Cookstoves (GACC), research centres and private manufacturers of firewood cookstoves are involved in international programmes of promotion of ICSs all over the world – 28 million devices have been disseminated by the GACC's partners until 2014 [3]. In parallel, laboratory protocols for testing ICSs have been developed by research centres and international organisations in order to provide a homogenous and unique methodology for testing the stoves and reporting the performances. The most widely recognized is the Water Boiling Test (WBT), developed originally between 1982 and 1985 by the Volunteers in Technical Assistance (VITA) [4]. The WBT is currently referenced by GACC for evaluating and comparing stoves' performances and it is used for assessing the Climate Impacts of Cookstove Projects within the Clean Development Mechanism of carbon-market [5]. However, different authors have been raising doubts about the consistency of WBT results, focusing in particular on three issues: (i) L'Orange et al. [6] highlighted the role of thermodynamic uncertainties (*viz.* variable steam production and boiling point determination) on results repeatability; (ii) Zhang et al. [7] raised questions about the rationale of some calculations and about metrics terminology; (iii) finally, Wang et al. [8] criticised the statistical approach recommended by this standardised laboratory-based test to evaluate,

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**Nomenclature**

| | |
|---|---|
| e | energy use [MJ] |
| $E_{II}$ | secondary energy [MJ] |
| $E_I$ | primary energy [MJ] |
| *EF* | emission factor [g/kg] |
| *LHV* | lower heating value [MJ/kg] |
| $m_{wood}$ | mass of wood [kg] |
| $t_b$ | time to boil [min] |
| $\varepsilon$ | savings of fuel use [%] |
| $\eta$ | thermal efficiency [–] |
| $\pi$ | possibility distribution |

*Acronyms – subscripts*

| | |
|---|---|
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| cs | Cold Start |
| DC | Developing Country |
| hs | Hot Start |
| ICS | Improved Cook Stove |
| ISO | International Organization for Standardization |
| GACC | Global Alliance for Clean Cookstoves |
| PCIA | Partnership for Clean Indoor Air |
| PM | Particulate Matter |
| SD | Standard Deviation |
| TEG | Thermoelectric Generator |
| TSF | Three-Stone Fire |
| VITA | Volunteers In Technical Assistance |
| WBT | Water Boiling Test |

**Fig. 1.** Examples of TSF (*a*) and ICS (Rocket model) (*b*).

communicate and compare performances and emissions of tested stoves, *i.e.* using the arithmetic average of three replicate tests.

These doubts related to the WBT structure moved the authors of this work to review the scientific literature regarding laboratory tests on ICSs, and to adopt appropriate statistical methods to critically examine the WBT-based data collected in the review, which concern the performances of cookstoves. Three different approaches have firstly been taken into consideration. The *purely probabilistic* approach is usually employed to represent the uncertainties related to all the parameters of a mathematical model, which describe some real phenomena, by single probability distributions [9]. This approach is commonly adopted to represent precise observations affected by variability [10], and it is the approach indicated in the statistical section of the WBT protocol [11], which suggests representing the uncertainties related to test results through *t-student* probabilistic distributions to draw statistical inferences at 95% confidence level. However, uncertainties cannot be always objectively quantified, especially when they are reported in the form of confidence intervals based on the experience and intuition of who estimates the numerical values of such uncertain parameters (*i.e.* expert judgment), or affected by imprecision due to systematic measurement errors [9]. In this context, the use of probability distribution to express incomplete knowledge and "epistemic uncertainty" is questionable. Baudrit et al. [9] state this concept and the need to consider different approaches with this consideration: «when an expert gives his/her opinion on a parameter by claiming: "I only know that the value of x lies in an interval *A*", the uniform probability with support A is used. This choice introduces information that in fact is not available and may seriously bias the outcome of risk analysis in a non-conservative manner [12]». This is because the adoption of a uniform distribution may mean the expert is totally aware that the value of the underlying parameter is really random in the interval *A*, or simply (s)he lacks in precise information. Therefore, to isolate a single probability distribution in the domain of each parameter may be misleading. More faithful representations of imprecise knowledge of parameters and phenomena exist. The *evidence theory*, introduced by Arthur P. Dempster and developed by Glenn Shafer in 1976 [13], provides mathematical tools to analyse phenomena affected by imprecision (e.g. systematic errors of a measurement apparatus) and variability (e.g. random errors) at the same time. The *numerical possibility theory* described by Zadeh