CFD Study of an Improved Biomass Cookstove with Reduced Emission and Improved Heat Transfer Characteristics

Hassan Ali and Terence Tang Jia Wei

***Abstract*—In this paper, in an effort towards reducing indoor air pollution (IAP) exposure for cookstove users, an improved biomass cookstove has been proposed. A computational fluid dynamics (CFD) combustion study has been carried out for the proposed cookstove to analyze the combustion and heat transfer behavior using ANSYS Fluent Simulation. The wood combustion phenomenon inside the stove is modelled as gaseous combustion of volatiles generated by pyrolysis. Temperature gradients, velocity profiles and combustion product concentrations are presented. Based on comparison of CFD predicted results with a popular commercial improved cook stove (ICS), it was concluded that the proposed cook stove yields reduced combustion product concentrations as well as faster cooking resulting in better energy efficiency and a health friendly cook stove.**

***Index Terms*—Biomass, improved cookstoves, indoor air pollution, CFD, $k-\varepsilon$ turbulence, modelling, analysis, combustion efficiency.**

I. Introduction

Indoor air pollution (IAP) is a significant cause of health related ailments for the 2 billion people per year worldwide that rely on traditional biomass fuels (such as wood, charcoal, animal dung and crop residues) for their cooking and heating needs. An estimated 4.3 million premature deaths (involving mainly women and children) per year from various respiratory problems could be associated with exposure to IAP resulting from inefficient cookstoves with incomplete combustion [1].

Over the last three decades, public awareness of the social and environmental costs of using traditional cookstoves and fuels and the need to reduce emissions from cookstoves has increased. Many serious efforts have been made worldwide to switch to cleaner fuels (such as LPG and ethanol) and development and implementation of improved cook stoves (ICS) to burn traditional fuels in an efficient way, avoiding excessive smoke production, together with improved heat transfer (reducing fuel consumption). In 2011, more than 160 ICS programmes were reported across most of the developing nations [2], mainly to reduce fuel use, and emissions to improve health conditions of users. These projects are also aimed at reducing greenhouse gas (GHG) emissions, deforestation, and empowering women and girls who often walk long distances to collect firewood for cooking in many cultures (to free up their time and increase their educational opportunities and household income). However, significant efforts are required towards more efficient cookstoves to gain significant health, environmental, social and economic benefits.

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Starting with the early investigative efforts of Samuel Baldwin [3], Prasad [4], Barnes, Smith [5], [6], and Bryden [7], enormous amount of R&D work has been carried by many researchers on various issues and identification of variables related to the cookstoves such as design, analysis, development, testing, materials, and the in-field performance.

Recently, computational fluid dynamics (CFD) has emerged as a simulation based design tool for biomass cookstoves and many researchers have developed CFD based models for the combustion, design analysis and optimization of biomass cookstoves [8]-[12]. Many biomass cookstove manufacturers have also relied on CFD and heat transfer modelling and analysis studies, along with rigorous efficiency, emissions, durability testing; for geometry and materials optimization in the development of advanced biomass of clean and efficient stoves. In [13], Miller provides a detailed literature review of CFD and heat transfer models applied to natural convection stoves.

In this paper, in an effort towards reducing IAP exposure for stove users an improved biomass fired cookstove has been proposed. Since India is one of the developing countries that is the most problematical concerning deaths due to IAP caused by indoor cooking, a popular ICS available in the Indian market is analyzed to understand its performance and examine the potential for successful improved combustion and heat transfer. Drawing on this study, a new ICS design has been proposed. The proposed ICS combustion chamber is designed to achieve improved combustion of wood thus increasing the combustion efficiency and decreasing the IAP. Using ANSYS Fluent, a CFD wood combustion models integrating the effects of airflow and turbulent characteristics associated with the combustion are developed for the proposed and the selected ICS to yield detailed distributions of temperature, velocity and combustion product concentrations. The CFD analysis results suggest that the improved cookstove results in improved combustion efficiency (reduced emissions) and heat transfer (reduced cooking time).

II. Combustion

Combustion is a sequence of exothermic chemical reactions where fuel is burned in the presence of air to produce heat energy in the form of fire. In case of biomass stoves, wood is used as the most common source of fuel. The hot combustion products, before escaping into the atmosphere, transfer heat to the cooking pot. The efficiency of a combustion process is determined by many factors that can be controlled in the design stage and usage of the cookstove.

Wood is made up of carbon, hydrogen, oxygen, salts, metals, calcium, potassium, Sulphur, etc. In a perfectly clean combustion, the oxygen is sufficiently supplied, and water (H_2O) and carbon dioxide (CO_2) are released as hot gases in the air, when burning wood react with oxygen.

Incomplete combustion takes place either due to the lack of oxygen, not having enough temperature to decompose the biomass fuel, or incomplete mixing. This produces CO, H_2O, CO_2 and other GHG emissions. During incomplete combustion, high amount of GHG gases are released together with carbon in the form of soot particles. The most unsafe constituents of the emission are carbon monoxide (CO), nitrogen dioxide (NO_2), naphthalene ($C_{10}H_8$), benzene (C_6H_6) and formaldehyde (H_2CO).

III. Improved Cookstoves

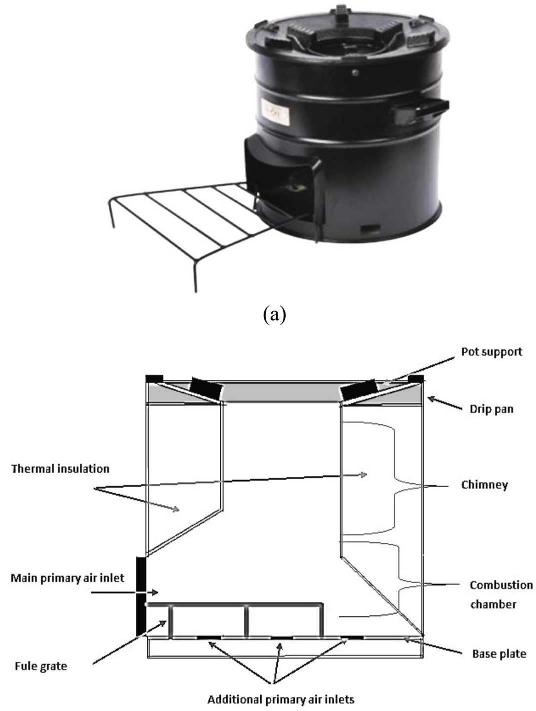
The "Improved Cook Stoves" are designed and built to assist better combustion and heat transfer, for reducing emissions and increasing efficiency performance; while still ensuring lower cost and ease of use. A few common ICS design strategies are placing a metal grate under the burning fuel, provision of a short internal chimney above the fire, provision of specific and low density heat walls for enclosing fire, use of insulation for reducing thermal losses, and designing properly sized channels for forcing heat to the bottom of the cooking pot. Compared to the traditional cookstoves, ICS can help achieve 40–75% emissions reduction and nearly 30% fuel efficiency increase [14], [15]. The two most famous categories of ICS are 'Rocket' stoves and 'Gasifier' stoves [16]; with gasifiers performing the most (in terms of fuel efficiency, emission reductions) in all models that utilize wood or charcoal, at the cost of complex configuration.

IV. Methodology

The newly introduced PCS-1 biomass ICS by Envirofit India is among the most energy efficient high-performance, low-cost biomass cook stove available in the Indian market for low income families. We start our study by analysing this popular commercial biomass stove design. This analysis allows us to design our proposed cookstove. The proposed cookstove performance is compared with the PCS-1 commercial stove.

The latest trends in cook stove modelling involve use of CFD for heat transfer performance and emissions analysis of the cookstove. This method is much more time-saving and cost effective than building and testing out the physical prototype. The literature on these aspects is rather limited, nevertheless, it has been expanding in the past few years [17]. To minimize wastage of funds on building a physical model and based on the test results modifying prototype, we consider using CFD analysis to simulate combustion using computer modelling of the prototype design.

Following the 2D modelling of both the stoves using SolidWorks, ANSYS Fluent function from ANSYS software version 16.2 is used to conduct combustion simulation on the two models. Besides contour plots, important data such as CO_2 and wood volatile emission produced during combustion is tabulated through simulation. This allows us to compare the heat transfer and emission performance of the two models.



(a)

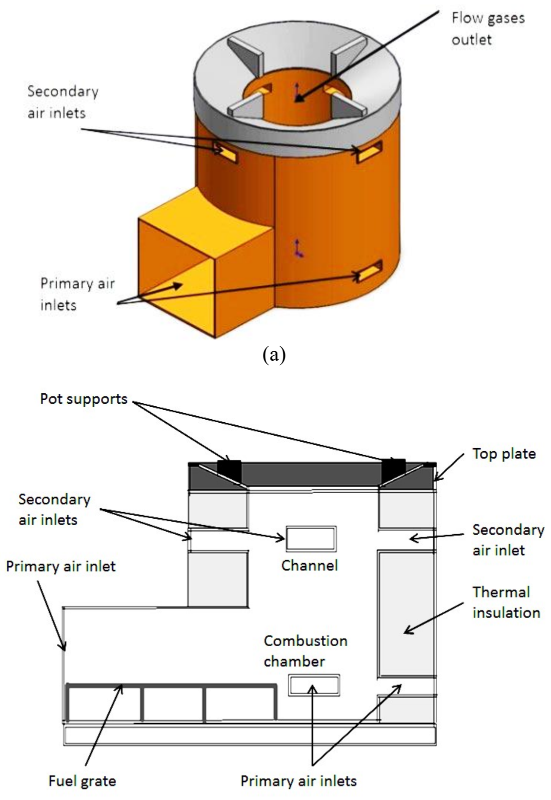
(b)

Fig. 1. PCS-1: a) 3D model and b) internal details.

V. Envirofit's PCS-1 Cookstove

According to Envirofit India [8], the PCS-1 produces cleaner energy at a high performance level as compared to traditional cooking stove. PCS-1 reduces cooking time by up to 50% and toxic emissions by up to 80%. As a result of its emission and fuel efficiency, it reduces the fuel cost by up to 50% due to the reduction of biomass fuel by up to 60%. The PCS-1 has been tested through the Emission and Performance Test Protocol (EPTP) by the Colorado State University in 2013. The results are reported at [18] together with stove's characteristics and a comparison with traditional devices.

PCS-1 3D model and internal details are shown in Fig. 1(a) and 1(b), respectively. The stove has a modified L-shaped (rocket stove) interior, with a main primary air inlet, a combustion chamber at the bottom, followed by an air outlet where heat energy escapes through a chimney to heat up the bottom of the cooking pot. The cookstove has five additional primary air inlets at the bottom of the combustion chamber, allowing additional air streams entering the combustion chamber for to achieve improved combustion. Other important feature of PCS-1 is the internal chimney (channel) above the combustion chamber and widened combustion chamber. The stove has a nozzle between the channel and the combustion chamber which directs the heat to the bottom of the pot. The combustion chamber is shielded with sheet metal and thermal insulation. The stove has a 3 mm-thick cast iron plate at the top with stands to support the pot. Also, the stove is supported with a grate for the fuel wood to rest during combustion.



(a)

(b)

Fig. 2. Proposed cookstove: a) 3D model and b) internal details.

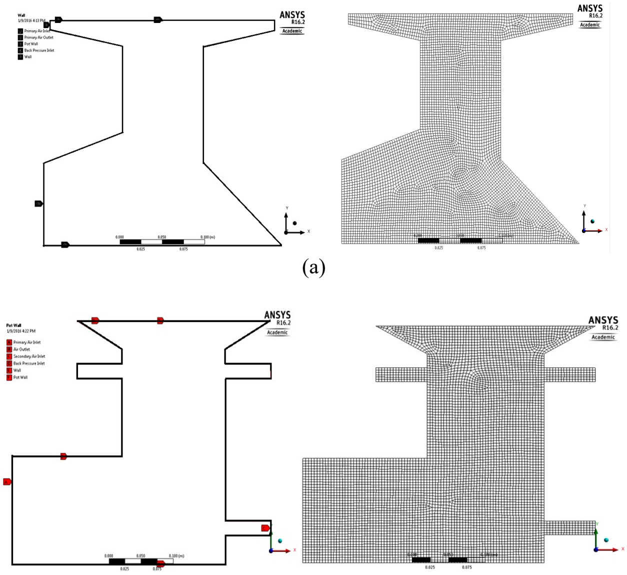
VI. Proposed Cookstove

After a detailed review of the PCS-1 cooking stove design, we decided to adopt the L-shaped rocket stove interior and include secondary air inlets in the prototype design for improved combustion of volatile matter and thus reduced emissions. We also decided to increase the primary air inlet size to allow maximum intake of air for improved combustion. Unlike PCS-1, which carries primary air inlets at the bottom of the stove, the proposed prototype is provided additional primary air inlets around the circumference of the combustion chamber near the bottom region of the combustion chamber. In order to allow maximum heat transfer to the bottom of the pot and conserve heat from hot flue gases, the nozzle was not added. Also combustion chamber size was reduced in the proposed cook stove design to allow improved combustion. The proposed design is illustrated in Fig. 2.

To keep the design simple and reduce the manufacturing cost, the number of secondary air inlets (around the chimney just below the flue gases outlet) was kept to four and in case of primary air inlets around the combustion chamber to three. Like PCS-1, main stove body was kept 300 mm wide and 340 mm in height, making it compact and easy to handle. The top plate serves as a lid to cover the insulation compartment, while serving as the pot support. The stove also carries a grate for fuel wood to rest.

VII. CFD Modelling

The computational domain for the proposed and the PCS-1 cookstove is the interior of the stove. The 2-D computational domain and mesh density for PCS-1 and the proposed stove is presented in Fig. 3. At the top of the stove, the pot should be put during combustion for the water boiling test; the pot holders should allow some free room between chimney's end and pot's bottom. This space along with primary and secondary air inlets and walls of the stove are included in the domain and stove boundaries. All these elements are furthermore represented as proper boundary conditions.



(a)

(b)

Fig. 3. 2-D computational domain and computational mesh: a) PCS-1 and b) Proposed cookstove.

The mesh sizing was set as 'fine' with minimum seed size of 4.3405×10^{-2} mm. The ANSYS Fluent generated mesh quality results are shown in Table I.

The general solver settings are also shown in the Table II. Under 'model' settings, the energy equation was turned on and the viscous model was set as '$k-\varepsilon$', 'Realizable' with 'Enhanced Wall Treatment'.

The wood combustion is represented as 'pyrolized volatiles' burning, hence the working fluid is a mixture of volatiles and air [19]. The 'wood-volatile-air' was thus selected under the species transport settings. Reactions calculations were enabled by turning on 'volumetric' with 'laminar finite-rate' as turbulence-chemistry interaction.

The discrete phase model setting was turned on to introduce fuel injection sources (4 points), to simulate the burning of wood firewood in the combustion chamber for both the stoves. The fuel injection settings for both the stoves are listed in Table III.

TABLE I: Mesh Quality Results

	PCS-1	Proposed
Minimum orthogonal quality	6.36755e-01	5.71842e-01
Maximum ortho skew	3.63245e-01	4.28158e-01
Maximum aspect ratio	3.12763e+00	4.54981e+00

TABLE II: SOLVER SETTINGS

Type	Velocity formulation	Time	Space
Pressure-based	Absolute	Steady	2D, Planar

TABLE III: FUEL INJECTION SETTINGS

Variable	First Point	Last Point
X-Position (mm)	140 (PCS-1) 250 (Prototype)	180 (PCS-1) 290 (Prototype)
Y-Position (mm)	40	40
X-Velocity (m/s)	0	0
Y-Velocity (m/s)	0.069	0.069
Diameter (mm)	40	40
Temperature (K)	523	523
Total Flow Rate (Kg/S)	7.4107x10−5	7.4107x10−5

TABLE IV: BOUNDARY CONDITIONS

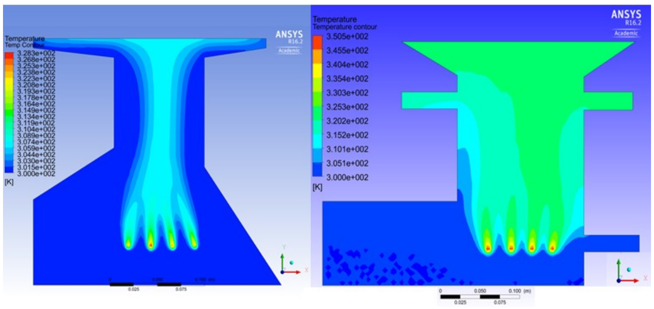
Boundary conditions	Type	Temp. (K)	Velocity (m/s)	Relative Pressure (Pa)
Primary air inlet	Pressure inlet	300	0	0
Secondary air inlet	Pressure inlet	300	0	0
Back pressure inlet	Velocity inlet	300	0.069	0.2
Wall	No-slip	300	/	/
Primary air outlet	Pressure Outlet	300	0	0

The location and naming of boundary conditions were pre-set during meshing. The individual boundary conditions were set during the set up phase. The setting of boundary conditions for both the stoves is shown in Table IV.

Following the setting of boundary conditions, solution methods was set as ‘simple’ with all species discretization targets set as ‘first order upwind’. Under solution initialization, initialization method was set as ‘standard initialization’. Following this, location of interest for calculation was selected under ‘compute from’ as ‘all zones’. The prescribed settings were then initialized and the number of iterations was set to 1200 to improve the accuracy of the results. Almost 300 iterative sweeps of the domain were necessary to obtain convergence.

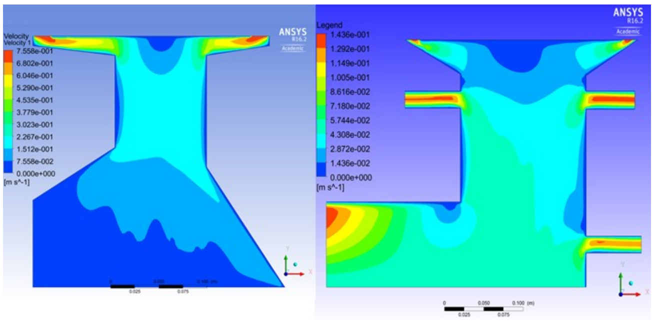
VIII. RESULTS

Fig. 4 shows the temperature contours of both the stoves, during combustion. It can be observed the heat energy exiting the flue gases outlet and transferred to the bottom of the pot is uniformly distributed in case of the proposed cookstove. This allows a more consistent and quicker heat transfer from the stove to the pot, resulting in more efficient use of fuel and shortened cooking time for optimized functioning of the cookstove.



(a) (b)

Fig. 4. Temperature contours: (a) PCS-1 and b) Proposed cookstove.



(a) (b)

Fig. 5. Velocity fields: (b) PCS-1 and (b) Proposed cookstove.

In case of PCS-1, the additional primary air inlets at the bottom of the combustion chamber do not seem to have a significant impact in terms of feeding the extra streams of air/oxygen into the chamber. In contrast, additional primary and secondary air inlets (around the combustion chamber and the chimney) appear to be contributing to the increased combustion and thus increased heat energy generated in case of the proposed stove.

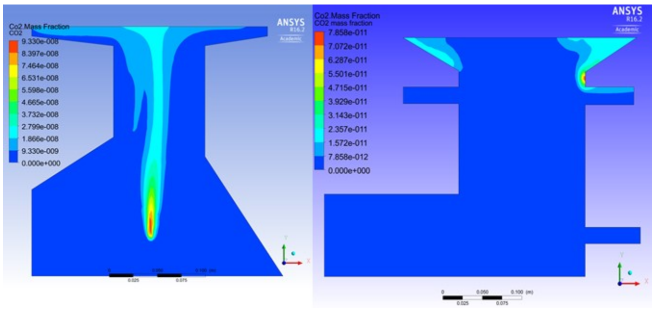
Fig. 5 shows the simulated velocity fields due to combustion in both the stoves. The plots describe how air and pollutants move within the stove domain. As expected, the proposed cookstove carries increased high velocity zones. It is thus anticipated that increased velocity in the proposed cookstove will have eminent impact on emission limits and performance of the proposed cookstove.

Fig. 6 shows the CO_2 contour plots for both the stoves. From the visual inspection of both the models, the highest concentration region of CO_2 can be observed in case of PCS-1.

The exact amount of soot produced due to incomplete combustion can’t be known unless through numerical calculation summary by ANSYS Fluent. However, the vast difference in soot content can be seen for both the stoves in Fig. 7. PCS-1 appears to have higher content of soot getting accumulated in the combustion chamber.

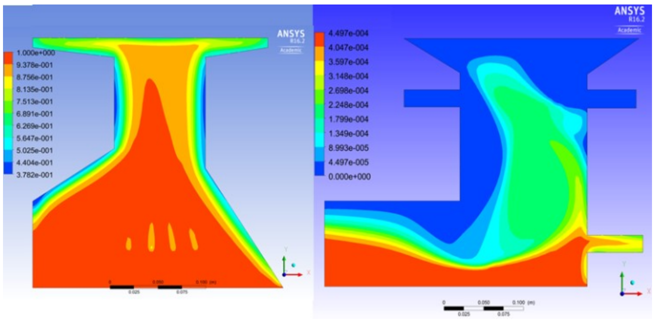
Fig. 8 shows that wood volatile contour plots for both the stoves. As can be seen, much higher level of wood volatiles is produced by PCS-1 in contrast to the proposed cookstove.

Fig. 9 below shows the concentration of oxygen for both the cookstoves. The light blue region shows the area with the lowest oxygen level due to oxidizing species during the combustion process, producing CO_2 and wood volatiles. The yellow region of the chimney shows that there is still some supply of oxygen in the chimney to help with the combustion.



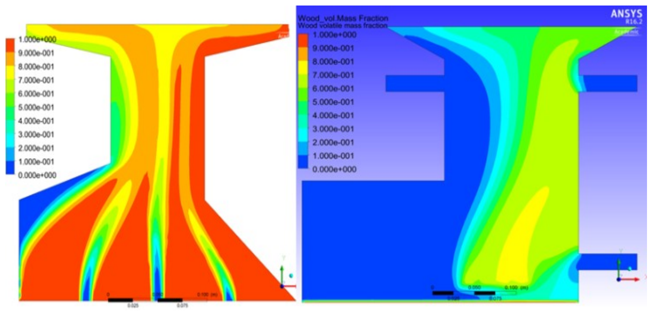
(a) (b)

Fig. 6. CO_2 mass fraction: a) PCS-1 and b) proposed cook stove.



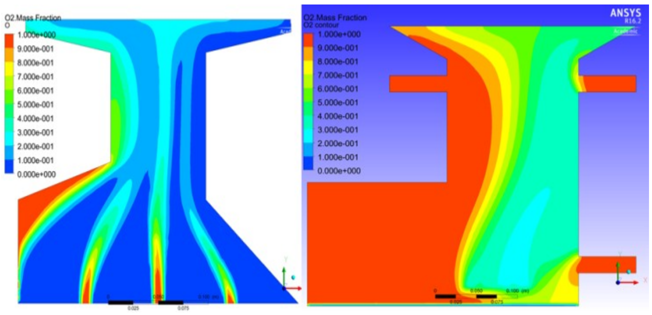
(a) (b)

Fig. 7. Mass fraction of soot: a) PCS-1 and b) proposed cook stove.



(a) (b)

Fig. 8. Wood volatile mass fraction: a) PCS-1 and b) Proposed cookstove.



(a) (b)

Fig. 9. Oxygen mass fraction: a) PCS-1 b) Proposed cookstove.

TABLE V: SUMMARY OF EMISSION AND PERFORMANCE RESULTS

Variables	**Envirofit PCS-1**	**Prototype**
Velocity of air (m/s)	0.745	0.91
Air mass flow Rate (Kg/s)	2.5e-3	3.2e-3
Mass fraction of	9.76e-2	6.84e-2
Mass fraction of Soot	0.32	0.19
Mass fraction of	11.15e-2	11.1e-2
Mass fraction of	8.61e-2	9.41e-2
Mass fraction of wood volatile	2.04e-4	1.56e-4

The highest overall concentration can be clearly observed in case of the proposed stove.

Besides examining the contour plots, the summary of variables (such as the velocity of air flow, the mass flow rate as well as the mass fractions of the different content) ascertaining overall performance of the two stoves is presented in Table V. The results provide us a more precise comparison based on the numerical values and differences. As can be seen, the prototype model has a high velocity of air flow and air mass flow rate as compared to PCS-1 cook stove. This attributes to a much efficient and fast flow of air from air inlets, bringing heat energy from the combustion chamber to the bottom of the pot at a much quicker rate. The prototype model produces much lower content of CO_2, wood volatiles, and soot, as compared to the PCS-1 model. It is thus the prototype model produces reduced harmful emissions, as compared to the Envirofit PCS-1 cook stove.

IX. CONCLUSION

This work describes the design and CFD modelling of a new ICS for indoor cooking in developing countries. The Envirofit PCS-1 cookstove was selected as a model stove for analysis and design of the proposed cookstove. Emission and performance of the PCS-1 model and the proposed cookstove was investigated through CFD modelling of the combustion and heat transfer. Our study shows that the use of secondary air and reduced dimension of the combustion chamber geometry is a very convenient way of reducing emissions and improving the heat transfer. Through the results, the proposed cookstove was found to be better in terms of emission and performance level. Besides being simple, the proposed cookstove holds high potential for clean and efficient cooking in developing countries.

Our future work consists of inclusion of thermo-electric generator (TEG) modules into the proposed stove to power a fan for clean combustion. The emission and performance simulations are also required to be validated by testing/experimentation on the complete physical prototype model of the proposed cookstove.

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