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Evaluating the Effect of Two Chimney Configurations on the Overall Airflow and Heat Transfer of A Biomass Cook Stove

Selorm Y. Dorvlo, Ahmad Addo, Francis Kemausuor, Stephen Abenney-Mickson, Jesper Ahrenfeldt, and Ulrik Henriksen

Abstract—Efficient cook stove design is a very vital aspect of effective processing operations. However the chimney configuration of a cook stove affects its overall performance. As such the current study seeks to evaluate the effect of two chimney configurations on the performance of a cook stove that was designed. The Autodesk CFD software was used to evaluate the effect of each chimney configuration on the heat transfer as well as the air flow through the cook stove. The final results show that each chimney has a specific effect on the performance of the cook stove. Whiles one chimney configuration increased the overall draft in the stove, the other chimney maintained a higher overall stove internal temperature.

Index Terms—Airflow, CFD analysis, chimney, cook stove, heat transfer.

I. INTRODUCTION

Improving the design and performance of a cook stove generally involves modifying all the relevant components of the cook stove that affects its performance. However, due to the specific nature of most cook stove design projects, improving cook stove performance is mostly done by modifying each component and then determining the comparative effect it has on the performance of the cook stove. The major steps involved in the execution of a cook stove development project involves design conceptualization, fabrication, testing, evaluation and then modifying the cook stove design based on the tests data collect from the stove evaluation. However the above stated stove design method can be very daunting and cost intensive.

However due to the increasing ability of computers to solve much more complex numerical problems, the use of mathematical models in the design of cook stoves [1]-[6] and the modelling of the combustion of biomass [7]-[9] has proven to be very helpful. Basically, this entails the use of mathematical models to predict the working conditions of a designed cook stove and then the data obtained is used to aid the modification of the design of the cook stove. This method can be very cost effective if the basis on which the

mathematical model is developed takes into consideration the major principles of operation of the cook stove. Due to the benefits of using mathematical modeling in stove design, there is an influx of several cook stove models that can be found in existing literature. Some of such models that have been worked on range from models to aid the understanding of the natural convection occurring in a cook stove to, models that determine the total energy needed for cooking by a household [2], [10]-[12]. The level of complexity, the assumptions on which the model will be based and the acceptable level of accuracy for the results, is basically determined by the specific aim of the stove design project.

In addition to the use of mathematical models in modifying cook stove designs, there is another field of study that has gained grounds due to its versatility; computational fluid dynamics (CFD) analysis. This form of analysis has gained popularity amongst researchers [6], [7], [10], [12]-[15] as well as cook stove designers due to the wealth of knowledge it can provide about the operation of a designed stove whiles eliminating the testing and redesign stages within the cook stove design process. CFD analysis of cook stove performance as well as its use to improve the performance of a cook stove have gained grounds over the past years due to its simplicity. However, the inability of some CFD analysis to produce results close to real working conditions seems to be a major problem for this form of analysis. As such, much research have been geared towards the use of CFD analysis with emphasis on developing equations and modifying models so as to obtain highly sensitive data which will correspond to real working conditions [13], [14], [16].

A study conducted by [17] focused on the air flow within chimneys. The study was geared towards evaluating the ventilation efficiency within a set of chimney configurations so as to propose the best chimney configuration to adopt for their fire place design. This is important because the chimney configuration on a fire place as well as a cook stove affects the air flow through the fire place/cook stove which impacts the overall draft within the cook stove, combustion, thermal efficiency, fuel use and the removal of gases from the stove.

The chimney configuration of a cook stove plays a major role in its performance. A biomass cook stove was developed for local processors, however the effect of the chimney on the stove performance was not analysed. As such this study seeks to evaluate the effect each of two proposed chimney configurations will have on the total heat transfer and air velocity through the designed cook stove.

II. METHODOLOGY

The CFD analysis was used as a tool to understand the

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overall airflow and heat transfer within the designed cook stove. Also the CFD analysis was used to evaluate the different effects the two proposed chimney configurations had on the stove performance (Fig. 1). The chimney design was based on empirical design data, as such the designs had to be evaluated individually. The chimney configuration was evaluated based on the presumption that each chimney configuration will affect the air flow within the cook stove which will consequently alter the heat transfer in the stove as well as the biochar recovery after the use of the cook stove. Fig. 1 shows the chimney configurations that were evaluated (the ZS and SS configurations). The ZS chimney has a 90° angle at its joints while the SS chimney has elbow joints but each has the same diameter, height and length.

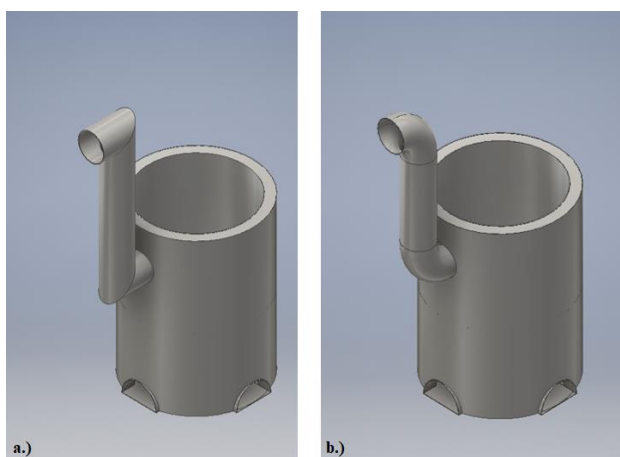


Fig. 1. The chimney configurations evaluated; a.)ZS chimney and b.) SS chimney.

The CFD analysis was done with the Autodesk CFD 2017 software. This version of the software has several improvements and the steps used for the analysis include creating a representative 3D drawing of the system to be modelled and then defining the boundaries as well as making assumptions for the study [18]. The 3D drawing then undergoes processing: geometry refinement, material definition, boundary condition formulation and proper assignment, mesh definition and then defining the solver parameters. The final step is the result interpretation. The current analysis made some important assumptions so as to obtain the best possible 3D drawing for the designed cook stove. Based on the assumptions, a new 3D drawing of the cook stove was performed with the Autodesk Inventor software. The drawing was then uploaded into the CFD software and then the geometry tool was used to create a CFD volume which was modelled as the air through the cook stove.

The next step was the material definitions, the materials defined include the stainless steel for the stove body, setting the volume within the cook stove to be air and then defining the grate to be a resistance material with a free air ratio. This was done based on the porosity of the biomass that will be found in the cook stove. The assumption made here was that the air flow through the biomass was equal to a plate with holes in it.

After material definition, the boundary conditions for the study was defined and assigned to the appropriate sections of the cook stove. Since the study wanted to determine the air flow and heat transfer through the cook stove, the boundary

conditions assigned were volume flow rate, gage pressure, temperature and film coefficient. Aside the gage pressure which is always set to zero for air flow analysis, the other material properties were either calculated or estimated. The temperature was set to 550 °C due to the average temperature obtained for the cook stove during the tests in the laboratory. The volume flow rate and the film coefficients used were both calculated. While the average wind speeds recorded during the stove tests were used to calculate the volume flow rate, the heat transfer coefficient for the materials used for the cook stove was used to calculate the film coefficient value used (Table I).

TABLE I: CFD ANALYSIS PARAMETER VALUES DEFINITION

Flow Boundary Conditions		
Inlet Boundary Conditions	Volume flow rate (Q)	The volume flow rate of the stove inlet is calculated by the velocity of air flow through the inlet of the stove and the area of the stove inlet: $Q = Velocity \times Area \text{ of stove inlet}$ $Q = 10 \text{ m/s} \times 0.0157 \text{ m}^2$ $Q = 0.157 \text{ m}^3/\text{s}$
	Temperature	The average temperature of the stove during the preliminary tests was used as the initial boundary temperature. The value used is 500 °C
Outlet Boundary Condition	Pressure	The outlet boundary condition was selected to be a zero gage pressure. This the default outlet boundary condition for that is recommended for CFD analysis with the AutoDesk CFD software.
Heat transfer Boundary Conditions		
Film coefficient	Stove Housing	The stove housing is made of steel hence the film coefficient was calculated using the following parameters. $Film \text{ coefficient } (h) = \frac{K}{l} K$ $= 43 \text{ W/mK}$ $l, \text{ thickness} = 0.0015 \text{ m}$ $h = \frac{43}{0.0015} = 28666 \text{ W/m}^2\text{K}$
	Water	The film coefficient for water was taken to be 1419.57 W/m ² K (250 BTU/hr.ft ² .F)
Grate		The grate of the stove was modelled with the free air ratio parameter. The free air ration of the grate was calculated based on the holes on the grate and the overall diameter.

The final step before initiating the solver is defining the mesh to be used. However the Autodesk CFD software is such that you can initiate the solver and it will automatically create the mesh. The final meshed model of the cook stove had approximately 13267 nodes and 46929 elements.

After effectively sizing the mesh the CFD solver was used to initiate the analysis. Each of the analysis was set to run 100 iterations and save the results at 5 run intervals. The data

collected include images of the velocity magnitude as well as the temperature profiles through a plane inserted within the stove for easy viewing.

III. RESULTS

The CFD analysis provided information on the operation of the cook stove with enough relevant data on the air flow and heat transfer through the cook stove. The airflow was seen through the velocity magnitude profile graphs obtained while the heat transfer through the cook stove was also examined with the temperature profile graph that was obtained.

A. Air Flow Analysis (Velocity Magnitude Profile)

Air flow through the cook stove was analysed by obtaining the velocity profile graph for each of the stove configurations. The chimney configurations tested were; the ZS and SS configuration. Each analysis consisted of 100 iterations. For easy interpretation, a screenshotted image of the velocity profiles were provided in Fig. 2.

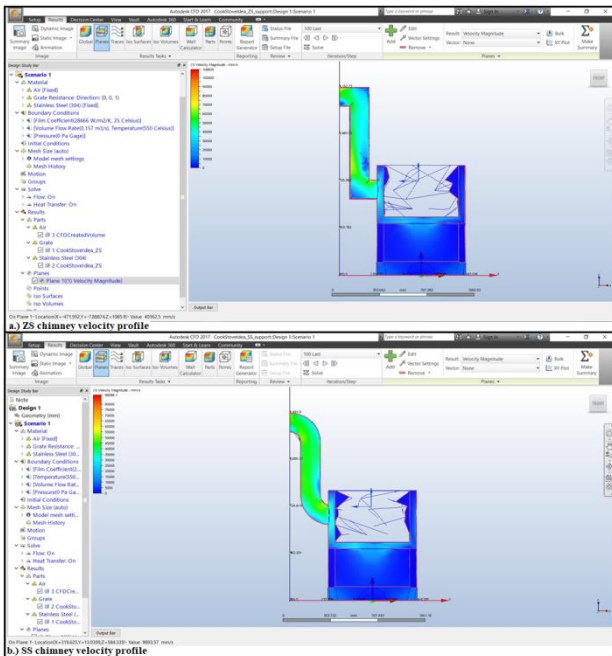


Fig. 2. ZS and SS chimney velocity profiles.

The velocity profiles in Fig. 2 show that there was more draft provided by the SS chimney configuration than the ZS chimney configuration. Taking a look at the graph for the individual iterations (Fig. 3), it shows how the velocity change occurred as the simulation progressed through the iterations. It shows that the velocity within the SS chimney was lower than the ZS chimney for the first 5 iterations before the SS chimney's draft increased. Though both chimney's provided enough draft, the overall observation shows that the SS chimney configuration provided more draft than the ZS chimney configuration.

This observation implies that if the combustion of the biomass is to be delayed so as to obtain more biochar, the ZS chimney configuration will be the best when compared with the SS chimney configuration. However if the objective is to burn the biomass and its char, then the SS chimney configuration will be the best.

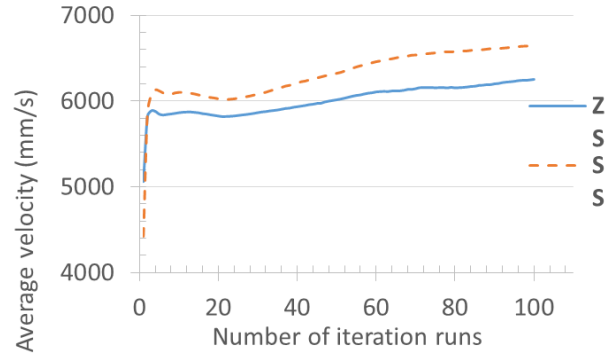


Fig. 3. Graph of average velocity for ZS and SS.

B. Heat Transfer Analysis (Temperature Profile)

Another important feature of a cook stove is its ability to effectively transfer heat to the points within the stove where most of it can be utilised. The overall effect of this helps to increase the total efficiency of the cook stove. As such the CFD analysis evaluated the heat transfer within the cook stove, and the resulting screenshots of the temperature profile for each of the cook stoves are shown in Fig. 4.

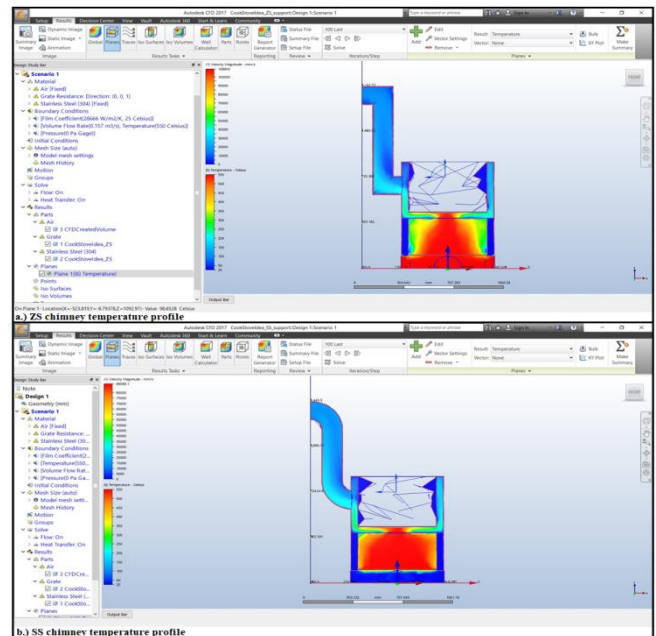


Fig. 4. ZS and SS Temperature profile.

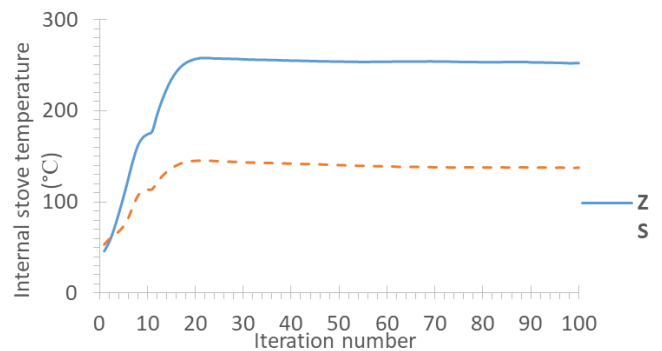


Fig. 5. ZS and SS average temperature graphs.

The temperature profile shows that there was an even distribution of the heat within the cook stove with the SS chimney configuration compared to the ZS chimney configuration. A careful look at the average

temperature plot for the two stoves (Fig. 5), show that the overall temperature was higher within the ZS cook stove than the SS cook stove. This can be attributed to the draft the chimney is capable of producing for the cook stove. Also this suggests that there will be faster heating within the ZS cook stoves than the SS cook stoves.

IV. CONCLUSION

The study set out to evaluate the effect of the proposed chimney designs on the performance of the designed cook stove. The results from the study showed that each of the chimney configurations have specific effects on both the air flow and heat transfer. In effect, none of the chimneys can completely be written off but rather depending on the final outcome expected from the stove a specific type of the configuration can be used. The SS chimney configuration is suitable for a faster heating stove due to the higher overall draft compared to the ZS chimney, but then the ZS chimney maintains a higher overall internal stove temperature. It is therefore recommended that for maintained high temperature during use the ZS chimney is the best.

For further studies, it is recommended that, CFD analysis should be used as a tool for increasing the stove capacity. Also further studies into the development of a generalized model for CFD analysis of stove chimneys should also be explored.

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Selorm Y. Dorvlo has a doctor of philosophy degree in agricultural engineering with specialty in machine systems.

His current study is focused on developing a cook stove which will offer a smoke free work environment and affordable source of heat for the local women (and the children they carry to work) who engage in palm oil production. Hitherto the women have to work in smoke filled tents which predisposes them to respiratory diseases and other health hazards. The clean cook stove he has developed operates on biomass generated at the processing site and the stove also produces bio char which can be used for soil amendment.