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Influences of Numbers of Stove Air inlets on Wood Burning Cookstove Performance

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Abstract

The traditional three-stone fire place is used in many households in rural areas of developing countries. These open fires are very inefficient at converting energy into heat from biomass fuel needed each year for basic cooking. Currently different types of improved biomass cookstoves are being introduced and distributed in Ethiopia. The key to maintaining an improved stove is careful control of the air supply. This study was conducted on stoves with different numbers of air inlets to evaluate and compare their burning efficiencies. In this study, five types of wood burning stoves with different numbers of air inlets were designed, constructed and their performances were tested. Equal weights of oven-dried wood samples were used for cooking rice of equal weights in each of the pots. All the pots were placed at the same distance from fire. The tests were repeated five times. Comparisons were made by taking food, stove body and stove smoke outlet temperatures. Three parameters were selected for comparison. These were time to reach initial cooking temperature of $75^{o}C$*, maximum temperature reached during cooking and effective cooking times. Parameter tests were made by one-way ANOVA followed by pair comparisons whenever significant differences were obtained. Stove body and smoke outlet temperatures were first plotted and areas under the curves were calculated using Matlab R2018a software. The treatments showed significant differences on time to initiate cooking at* $p = 0.05$ *level. Pair comparisons showed stoves with 3 and 4 air inlets different (around 10.5 minutes) from the one air inlet (15 minutes). No such significant differences were observed for the maximum temperature and effective times of cooking. The stove with one air inlet exhibited the highest relative heat energy loss through the body while the three air inlet showed the least (18% less).The stove with four inlets had the highest relative heat loss through the smoke outlet and again the one with three air inlets showed the lowest loss (17% less). Over all the results of S4 (stoves with three air inlets) slightly showed better performances than the other stoves.*

Keywords: Cooking temperature, cooking time, Stove air inlets, Stove efficiency, Wood burning stoves,

1. Introduction

In order to improve energy security in developing countries it is especially important to promote more efficient and sustainable use of traditional biomass. Currently different types of improved biomass cookstoves are being introduced and distributed by governmental and nongovernmental organizations to people living in rural and urban areas of Ethiopia (Yohannes, 2011). The most efficient stoves require proper design of the combustion chamber, provision of insulation around the combustion chamber to reduce conduction heat loss across the walls of the chamber and adequate air supply. The size of air inlet is also important to ensure the availability of sufficient air for the complete combustion of the fuel wood (Gaya and Tewar, 2015).

The traditional three stones fire place (Fig. 1.1) used mostly by the rural community are inefficient in several ways. It has limitation in terms of not confining the heat energy and therefore part of the heat produced escapes into the surrounding air. The other is heat loss through the base of the stove. If the base is soil there is heat energy transferred to the soil by conduction. The spaces between the stones are not only used as air inlet, but they are also passageways for the smoke produced. As a result it disperses smoke all over the place and consumes more fuel wood. From this traditional cook space the smoke that comes out form in-between the three stones creates inconvenience and health risk to the cook. Besides, the area around the fire is not neat. On the other hand, the use of three stones in traditional cooking can be considered as three air inlets and it does not seem to have limitation as far as letting in sufficient amount of air is concerned.

Figure 1.1: Traditional three stone cooking place

The use of small portable stove circumvents most of the problems encountered by the three stone fire place. First, it is easy to move it around with its content when the cooking environment is not conducive or when there is limitation of air at the cooking area. It is confined and does not use much coking space. Since the fuel and the ash produced are contained within the stove and thus the surrounding area is neat. The fire itself is confined within the stove, which means, the possibility of combustible materials coming in contact with the fire is less. That reduces the risk to the cook as well. With provision of smoke outlet extension such stove can move most of the smoke from indoor to outdoor, thereby reducing suffocation around the cooking area. With more research, such a stove can be improved to create healthy cooking environment and reduction in the use of fuel wood.

The key to maintaining a good fire is careful control of the air supply. Keeping the air flowing correctly through wood burning stoves is essential for safe and efficient operation of the stove. Limiting the amount of air available to react with the fuel can lead to incomplete combustion. One of the areas where research is required is in knowing the optimum size/number of air inlets. In areas where wind direction changes frequently, the use of multiple air inlets increases the chance of facing the prevailing wind. The use of multiple air inlets is therefore to maximize air entry without losing much energy to the surrounding. The latter can be achieved if the area of air inlet is small.

The air inlet allows air into the combustion chamber from the bottom of the wood rack (Biratu, 2016). Under ideal conditions the air that has entered the combustion compartment should not escape from the compartment. This can be achieved by constructing stoves without cracks even around the air inlet or the smoke outlet. In some cases the gases have to travel through two sharp turns to reach the outlet (Thakur *et al*., 2016).

Air is fed into the firebox through an air inlet and then sucked through the fuel by the buoyancy (reduced density) created by the smoke outlet. Since air is the key ingredient of the combustion process its supply should not be limited. The fuel must have oxygen to burn. When the air enters below the fire rack the relatively low pressure created inside the smoke outlet forces the air to move upward to the fire. Such a strong draft causes a hot fire. The draft is obtained in the stove with the help of connection between the smoke outlet, the flue chamber and the combustion unit (Joshi and Srivastava, 2013). Air intake above the firewood reduces fire temperature and firewood efficiency (Nienhuys *et al.*, 2005). Attention should be given to the control of the upward flow of the combustion gases to increase the transfer of heat to the cooking pot (Foley *and Moss*, 1983).

Fresh air needs to enter the wood compartment to provide oxygen for the fuel as the fire burns. The stoves designed with different numbers of air inlets allow the user to adjust the air flow to optimize conditions. Depending on the outside ambient conditions and depending on the state inside the firebox, the amount of fuel, the fire intensity differs with amount of air. The multiple air inlets are assumed to give the user better control over the fire. In line with this, the general objective of this study was to assess wood burning stoves with different number of air inlets.

2. Materials and Methods

2.1. Materials

The materials used in this study were: metal sheet, metal tubes for the air outlet, iron bars to construct the grates and the stove handles, welding machine, welding rods, a digital kitchen thermometer (AMB.TEMP, No: 10L03250) made in Japan (Fig. 3.1), laboratory oven (SONYO OMT Pf120, 200) made in the United Kingdom, beam balance, mercury thermometers, meter stick, mobile clock, identical pots of diameter 20 cm and height 20 cm, wood samples (*Eucalyptus*) of the same moisture content, axe, a lighter, rice grains and water.

Figure 2.1: Kitchen thermometer

2.2. Design and construction of the stoves

The five stoves were designed to have different number of the air inlets. All air inlets have identical sizes (4 cm x 5 cm). The first stove (S1) was without air inlet (hole). The second stove (S2) was designed to have one air inlet. The third stove (S3) has two air inlets at right angles to each other. The fourth stove (S4) has three air inlets with the center of the holes separated by 120 degrees (more or less similar to the three stone traditional stoves). The fifth stove (S5) was also designed and constructed with four air inlets (obviously with the opposite air inlets on the same line). The dimensions of the angles and total area of the air inlets are as given in Table 2.1 and the constructed stoves are shown in Fig. 2.1.

Table 2.1: Specifications of the constructed wood burning stoves

Treatments /stoves	Diameter of stove (cm)	No. of air inlets	Total area of air inlet (cm^2)	Angle b/n air inlets (in degrees)

S1	21	0	-	-
S2	21	1	20	-
S3	21	2	40	90°
S4	21	3	60	120°
S5	21	4	80	90°

Figure 2.1: View of the five stoves constructed stove with different numbers of air inlets

All stoves were designed and constructed with the same dimensions.

2.3. Experimental procedures

For this experiment, fire wood samples were prepared to sizes of about 15 cm length and 2 cm thickness. An axe was used to cut and split the woods into small pieces and also digital balances and meter sticks were used to make sure that the woods have the same weights and same sizes, respectively. The woods were oven-dried for 24 hours at 105^{o}C to bring them to the same moisture level.

Sufficient quantity was dried for all the treatments and the five replications. In this study the five types of wood burning stoves with different numbers of air inlets were used as treatments. The woods were arranged in each stove such that the bottom of the pot would be at a distance of 6 cm from the bottom of the fire. Five identical pots made from the same material were used to cook rice. Small holes were made on the lids of the pots to allow insertion of kitchen thermometer (thermocouple), which was used to measure the temperature of rice cooked in the five stoves. A cup of rice (242 g) and a liter of water were added in each pot. Equal weights of woods (350 gram) were taken and carefully arranged horizontally on the grates constructed within the wood stove. The wood samples in each stove were lit by fire at the same time. A very small quantity of kerosene was used to make sure the fires start simultaneously in each stove. Just before placing the pots on the fire, the temperature of water rice–water mix in the pot was measured and recorded using kitchen thermometer as initial temperature of the food to be prepared. At the same time, atmospheric (ambient) temperature was also recorded at slightly far distance from the location of the stoves not to have the influences of the stoves. After the fires have properly started in each stove, the pots were placed on their respective stoves and the timer was started. Six identical mercury thermometers were inserted in their respective slots of each stove body and five smoke outlets (conventional stove was without smoke outlet) prepared for this purpose to measure stove body and the temperatures, respectively. Thereafter, measurements of the three temperatures (food, stove body and smoke outlet) were recorded every 7 minutes for each stove for roughly 85 to 90 minutes. The weights of the leftover wood (wherever present) were also recorded. At the end of each experiment, ambient temperature was recorded again. Arrangement of the stoves with the pots is as shown in Fig. 2.2.

Figure 2.2: View of the five stoves with pots during data collection

2.5. Data analysis

The method of data analysis in this test involved ten steps.

1. Since temperature measurements for each treatment on each day were taken at the same time, to standardize the time, averages of replications were made for each treatment.
2. The next step was time synchronization. In the experiment simultaneous food temperature measurement was not possible because there was only one kitchen thermometer available. Hence measurements were taken at different times for each stove. Plots of T_f (food or rice temperature) versus t (cooking time) were made for each treatment using Matlab (R2018a) and robust equations (equations with best R^2 values) were obtained for each treatment.
3. The equations obtained in 2 were used to recalculate temperatures for common times for all the treatments. This was done not only for T_f but also for T_b (stove body temperatures) and T_s (stove smoke outlet temperatures).
4. Plots of T_f, T_b and T_s where done separately, for all the treatments together using Microsoft Office Excel. All the plots were curve-fitted with robust equations.
5. From the plots of 4, t_i (initial time to pass the 75°C mark), T_{mx} (the maximum temperature observed during the cooking process) and t_f (the final time at which the food temperature drops below 75°C) were determined and tabulated for all the treatments. These were averaged values.
6. Separate curve fittings were done for each replication of each treatment and for all the treatments. From the fitted curves t_i, T_{mx} and t_f values were estimated.
7. The values obtained in 6 were tabulated, rearranged and used for comparison of significant differences among treatments using one-way ANOVA followed by pair comparison. These were done for t_i, T_{mx} and Δt ($= t_f - t_i$), independently.
8. Next plots of T_b versus t (cooking time) and T_s versus t were made separately for all the treatments. The plots were curve-fitted for each treatment with robust equations. Temperature of 75°C was selected and the treatment which exhibited maximum t_f was identified as the treatment of large integration range. This was done for both T_b and T_s.

9. Each equation (of each treatment) was used with the limits of integration (0 – t_f obtained in 8) to find the relative area under each plot. For this Matlab was used. The areas obtained are indicators of how much relative heat energy was lost through stove body and stove smoke outlet of each stove.
10. The relative areas were compared in terms of differences and percent reductions for both T_b and T_s.

3. Results and Discussion

3.1. Food temperature and cooking time

In cooking there are three parameters of interest. The first is the *onset of effective cooking* (the time at which the food temperature reached 75°C). In this experiment it is represented as t_i and it is indicative of how fast (early) the stove starts to cook. The smaller the t_i is the better. The second is the *maximum food temperature* (T_{mx}) reached. The maximum temperature recorded is indicative of the intensity of cooking. This temperature must be greater than the critical temperature (75°C) for effective cooking. The third is *effective duration of cooking* (represented as Δt), which is the time interval between onset of cooking and the time at which the food temperature drops back to 75°C (348K) mark, on its way to cooling. It is the difference between t_i and the last time the stove drops below the75°C mark (t_f). This time indicates the time during which the food is actually cooking. The longer this time is the better. The three (onset of cooking time, maximum temperature and effective cooking time) each were compared for all the treatments using graphical and statistical methods.

3.1.1. Graphical method of estimating the three parameters

The plot of temperature versus time shown in Fig. 3.1 depicts the heating and cooling trends of the six different types of stoves (the sixth, conventional charcoal stove).

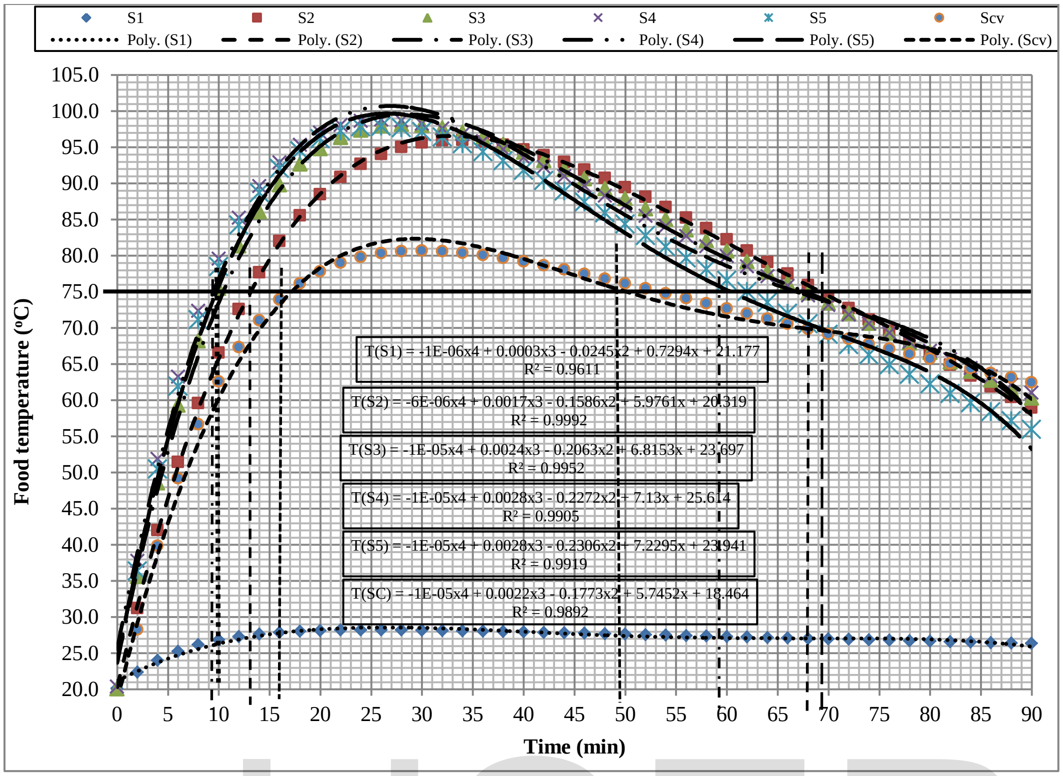

Figure 3.1.: Food temperature versus cooking time shown for all the treatments together

The plots shown in Fig.3.1 are the averaged values of all replications in each treatment. The three parameters are estimated for each treatment from the plots for comparison. This is one of the methods (though not statistical) used to compare the three parameters. The result obtained here is later to be assessed with the statistical results.

As observed in the figure, the temperature of the stove with no air inlet barely rose above the ambient temperature. This is understandable since combustion requires adequate or at least bare minimum amount of air (oxygen). The inclusion of this stove was also deliberate to show how significant air inlet is to the process of cooking. Except the conventional stove which deviates from the rest both in terms of late t_i and early t_f, the other stoves are roughly identical in their shapes. Table 3.1 indicates the t_i, T_{mx} and Δt values of each stove estimated from Fig. 3.1.

Table 3.1: Influences of number of air-inlets on temperature and cooking times

Treatment	**t_f**	**t_i**	**Δt (min)**	**T_{mx}**	**No. of air inlets**	**% in cooking initiation time**	**% increment/reduction in cooking time**
S1	0	0	0	28	0	NA	NA
S2	71	13	58	96	1	100	1
S3	71	10	61	97	2	123	5
S4	69	10	59	101	3	108	2
S5	62	10	52	100	4	54	-10
Cs	53	17	36	82	Conventional	-69	-38

t_f = final time at which the food temperature falls below 75°C; t_i= initial time at which the food temperature rises above 75°C; Δt = time difference between the two; NA = not applicable

Based on the results in Table 3.1, S3, S4 and S5 seem to have better and the same onset of effective cooking time (10 min.). All of the maximum temperatures were above effective cooking temperature of 75^{o}C. But in terms of effective cooking times S2, S3 and S4 are close to each other (58 - 61 min.), while S5 is relatively lower (52 minutes or 10% reduction from S2). The conventional stove was a poor performer in terms of t_i and Δt with a reduction of 69 and 38% compared to the single air inlet stove (S2). Using this graphical method, both S3 (two air inlet) and S4 (three air inlet) seem to be winners.

3.1.2. Statistical method for comparisons of t_i

Statistical test is necessary and better than the graphical method to reach a more scientific conclusion. For this purpose one–way ANOVA test was made (at p = 0.05) among the four treatments disregarding the first treatment (stove with no air inlet and hence did not reach cooking temperature at all) and the conventional stove. The test result of t_i is shown in Tables 3.2.

Table 3.2: One-way ANOVA to compare t_i values of the four stoves (S2 –S5)

Source	df	SS	MS	F	F_c	Significance
Treatment	3	65	22	4.3	3.24	*
Error	16	80.8	5.05			
Total	19	145				

The ANOVA table shows significant differences of t_i among treatments at p = 0.05 level. Whenever such significant differences are observed it is necessary to follow it up with pair comparisons and such pair comparisons for onset of cooking time (t_i) is shown in Table 3.3.

Table 3.3: Results of pair comparisons of ti values between each pair of the four stoves (S2 –S5)

B/n	SE(d)	t	CD= t*SE(d)	PD*	[PD - CD]**	D/ND
S2 & S3	1.4	2.8	3.9	3.7	-0.2	ND
S2 & S4	**1.4**	**2.8**	**3.9**	**4.5**	**0.6**	**D**
S2 &S5	**1.4**	**2.8**	**3.9**	**4.1**	**0.2**	**D**
S3 & S4	1.4	2.8	3.9	0.8	-3.1	ND
S3 & S5	1.4	2.8	3.9	0.4	-3.5	ND
S4 &S5	1.4	2.8	3.9	0.4	-3.5	ND

The result of Table 3.3 shows significant differences between S2 and S4 and S2 and S5, but no difference between S4 and S5. Therefore as far as early onset of cooking time is concerned S4 and S5 seem to be better candidates than S3 that was found to be one of the better ones in Table 3.1.

Table 3.4: Averages and standard deviations of onset of cooking (t_i)

t_i	S2	S3	S4	S5
	12.5	14	11	11
	13	10	10	11
	13	11	10	10
	13	10	10	10
	22	10	10	11
Mean	14.7	11	10.2	10.6
Stdev.	4.1	1.7	0.4	0.5

Table 3.4 depicts the least time of 10.2 minutes by S4 compared to S3 (11 min). The pair treatments indicate that S2 (stove with only one air inlet) has a different average t_i of 14.7 minutes and it was found to be different from the fourth (t_i = 10.2 minutes) and the fifth with t_i = 10.6 minutes. The rest are not significantly different from each other. Such result indicates that the one air inlet stove slightly but significantly delayed the onset of cooking by over four minutes compared to the other stoves. It shows the inadequacy of air supply to the stove when the air inlet is only one. This is either because the surface area of one air inlet of 20 cm^2 is insufficient for combustion volume of 2077 cm^3 ($= \pi(10.5\ cm)^2 \times 6\ cm$) or the air inlet did not get sufficient air because of the frequent change in the direction of the wind.

The result shows a difference between the t_i found from averaged treatment values and the t_i obtained by the statistical method of evaluation. For ANOVA t_is were evaluated from the plots of each replication and tested thereafter (Fig. 3.2). The averages were taken after evaluation of each parameter.

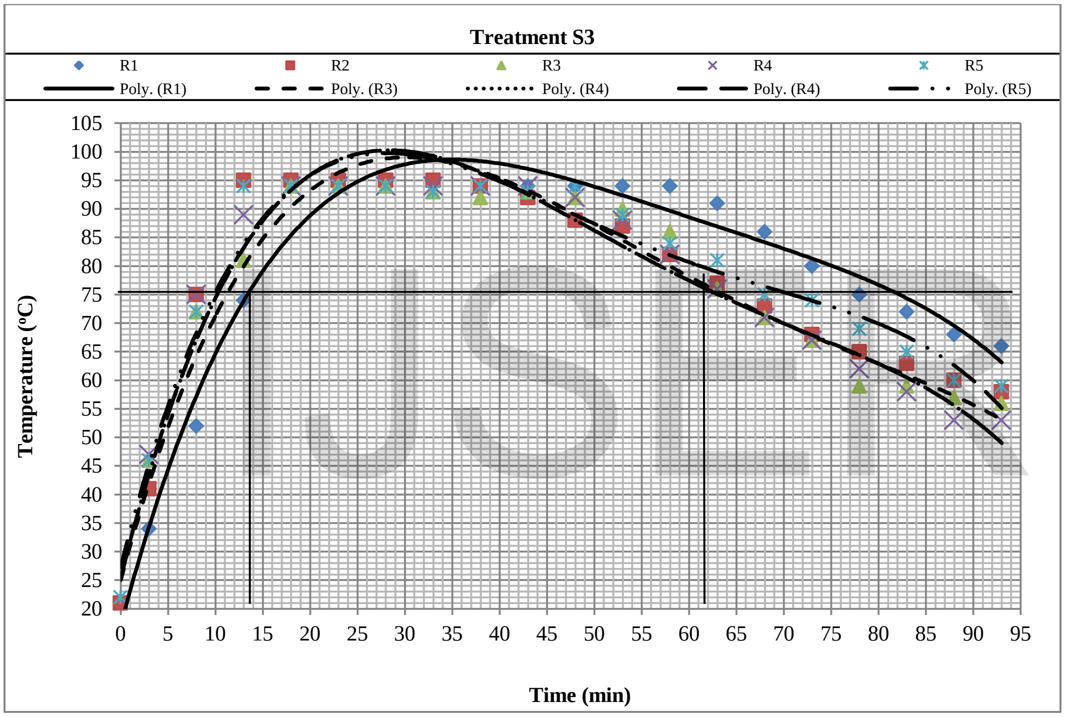

Figure 3.2: Food temperature versus cooking time shown for all the replications of S3

Evaluation of t_i from each replication before averaging the replications gives a different value. This approach reflects the reality than the other method since in actual coking this is what is happening. The averaging method may give us a clue about the treatments but it actually hides the significant differences among treatments.

3.1.3. Statistical test of T_{mx}

The maximum temperature tests were made among four treatments as before. Such tests do not mean much as the treatments all depicted maximum temperatures in excess of 75°C. The ANOVA Table 3.5 did not show significant differences among treatments either. There was no need to make pair comparisons but the averages and the standard deviations (stdev.) values are shown in Table 3.6. This table also shows how close they are in their mean values (between 95.8 and 98°C). The result indicates that air inlets can play roles in terms of delaying or fastening the onset of cooking but have no impact on the maximum temperature reached by the content in the pots.

Table 3.5: One way ANOVA to compare T_{mx} values of the four stoves (S2 –S5)

Source	df	SS	MS	F	F_c	Significance
Treatment	3	15	5	1.9	3.24	NS
Error	16	42.4	2.65			
Total	19	57				

Table 3.6: Averages and standard deviations of maximum temperatures (T_{mx})

T_{mx}	S2	S3	S4	S5
	97	97	100	96
	96	99	98	97
	97	98	99	99
	97	98	97	98
	92	98	95	96
Mean	95.8	98	97.8	97.2
Stdev	2.2	0.7	1.9	1.3

3.1.4. Statistical test of Δt

Perhaps the most important metrics in assessing cookstove is in its effective cooking time. It has a number of implications. A stove that cannot complete the cooking process requires additional load of fuel or it adds cost of fuel. Such a stove requires extra attention to know when to add the fuel, which means it creates inconvenience to the cook. If the extra load of fuel is not accurately known it results in waste some fuel. The extra time required is also going to delay the cooking. A stove that completes the cooking process in one go (without the need of extra fuel) adds convenience, saves time and money.

As for the other parameters, Δt was also determined after determining t_f and t_i from each replication of each treatment. The ANOVA test done on this parameter is shown in Table 3.7.

Table 3.7: One way ANOVA to compare Δt values of the four stoves (S2 –S5)

Source	df	SS	MS	F	F_c	Significance
Treatment	3	146	49	0.8	3.24	NS
Error	16	952	59.5			
Total	19	1098				

The ANOVA test showed no significant differences and therefore there was no need to make pair comparisons. Table 3.8 shows how close the Δt values of the four treatments are and why they are not significantly different. The mean values range from 50.6 to 58.4 minutes. The range is about 8 minutes, which is not small but the differences were confounded because of high variability within replications. Perhaps more replications could have revealed the differences.

Both the average values and the standard deviations reflect important points. High mean value is required to finish cooking without adding more fuel. In this respect S3 (stove with two air inlets) did well. Low standard deviation implies the consistency of the stove in constantly producing nearly the same Δt during every replication. In this regard S5 (the stove with four air inlets) did well. The results are consistent with what was observed in Table 3.1.

Table 3.8: Averages and standard deviations of cooking time (Δt)

Δt	**S2**	**S3**	**S4**	**S5**
	53	69	53	48
	62	54	70	56
	50	53	50	49
	53	54	53	49
	63	62	54	51
Mean	56.2	58.4	56.0	50.6
Stdev	5.9	6.9	8.0	3.2

Summary of food temperature versus time for the onset of effective cooking time shows quadratic fit between the means and the number of air inlets and the standard deviations and the air inlets as shown in Fig. 3.3.

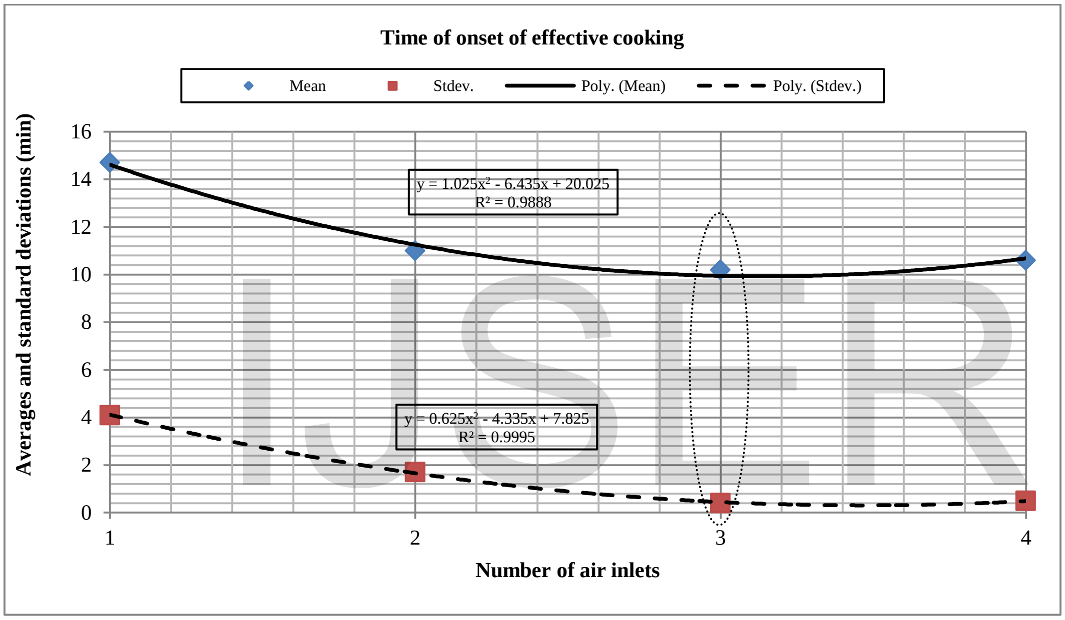

Figure 3.3: Averages and standard deviations versus number of air inlets

In terms of average of t_i, the standard deviation of S3 (stove with two air inlets) showed the least values in both (shown in dotted ellipse). The inflection point on the curve (minimum time of onset of cooking of 10 minutes) is for the stove with three air inlets. Similar plots for Δt are shown in Fig. 3.4.

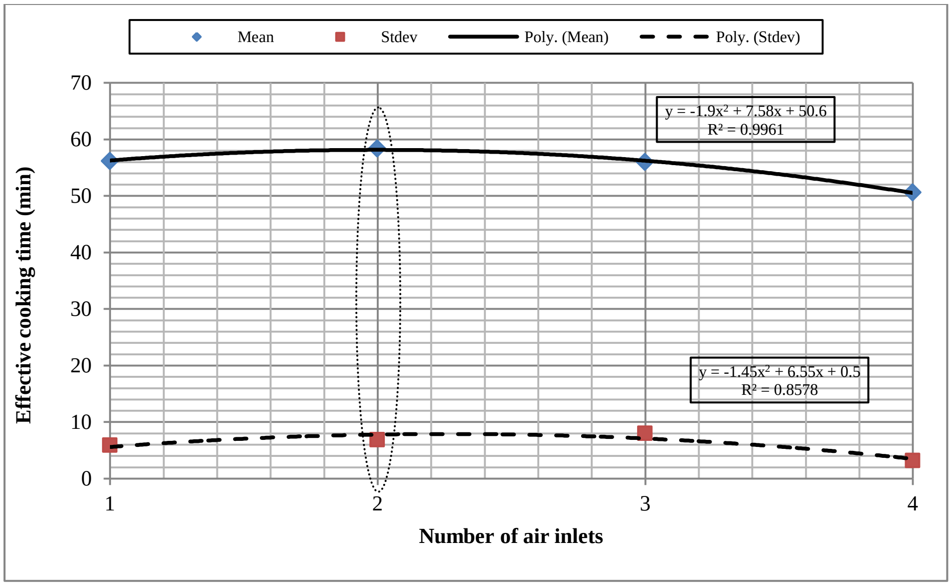

Figure 3.4: Averages and standard deviations versus number of air inlets

As in the case of onset of effective cooking time, Δt also follows quadratic trend with the number of air inlets. In this case the stove with two air inlets (shown in dotted ellipse), has a slight edge over the single and the triple air inlet stoves.

S2 – S5 stoves have almost identical cooking times (Δt). But in two and three air inlets the onset of temperature of 75^{o}C is less by about four minutes than the one air inlet stove (faster by about 28% than the single air inlet stove). Hence in terms of fast cooking, the two and three air inlets are better than the single air inlet stove. With stove of four air-inlets, the cooking time diminished by about 10% compared to the other three stoves. This reduction seems to be due to heat loss by convection set in the air inlets. With four air inlets it is inevitable that the two opposite air inlets face each other and hence a portion of the air entering in one of the air inlets goes out through the opposite air inlet and does not have a chance to go to the combustion chamber. Even if the two and three air inlet stoves are identical in cooking initiation and cooking time, the three air inlets stove has an advantage of letting in air that may come from three different directions. Since the direction of air changes frequently during the time of cooking, the stove with three inlets is better in this sense than the two air inlet stoves, which only has two chances rather than three. But to say more on this it is necessary to see how the two differ in terms of stove body and smoke outlet temperatures.

3.2. Comparisons of stove body temperatures

In order to compare stove body temperatures, first plots of T_b versus cooking time are done for all the treatments together. Such plots for the different air inlets are shown in Fig. 3.5.

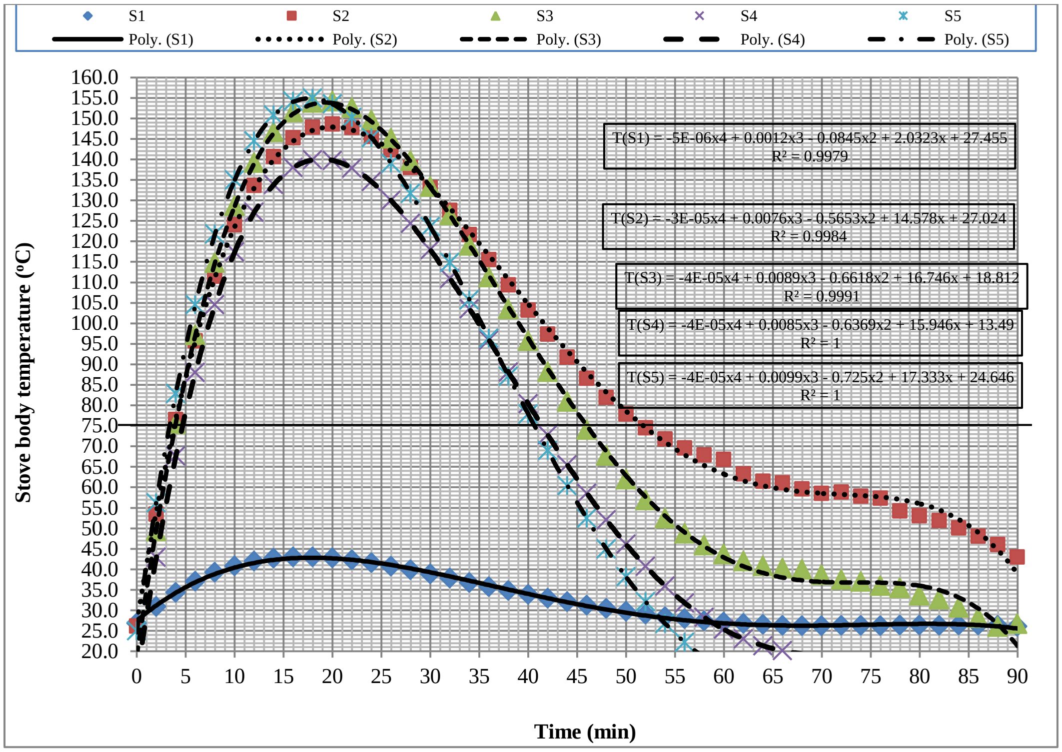

Figure 3.5: Stove body temperature versus cooking time plots for the five stove types

As seen in Fig. 3.5, there was no combustion in S1 (stove with no air inlet) and therefore there was negligible stove body temperature; barely different from ambient temperature. S2 exhibited delayed combustion and as a result it also exhibited delayed release of body temperature.

Looking at the plots of Fig. 3.5, from among the curves S2 had the highest t_f of 52 minutes. Therefore for calculation of the areas under the curves, the upper limit of integration was taken as 52 minutes and the lowest, zero. Performing the integration using the equations given for each of the treatments in Fig. 3.5 gives areas under the curves (in arbitrary units) as summarized in Table 3.9.

Table 3.9: Estimated relative areas of the plots and the percent reduction in stove body heat losses

Treatment	No. of air inlets	Total air inlet area	Fraction of surface area (%)	Area*	Δ W.r.t A_{mx}**	% reduction***
S2	1	20	2.0	5970	0	0
S3	2	40	4.0	5827	-143	-2
S4	3	60	6.1	4905	-1065	-18
S5	4	80	8.1	5790	-180	-3

Area* = area is given in arbitrary units, Δ W.r.t A_{mx}** = difference with respect to A_{mx} of S2; % reduction*** = percent reduction

From among the areas recorded in Table 3.9, S2 has the highest area and thus it is taken as a baseline. With respect to the baseline, S3 and S5 showed nearly identical areas to within 5% of S2. S4 exhibited slightly larger reduction which means more energy was lost by other means than through the body of this stove.

3.3. Comparisons of temperatures stove smoke outlets

Figure 3.6 shows plots of smoke outlet temperatures versus cooking time of the five stoves.

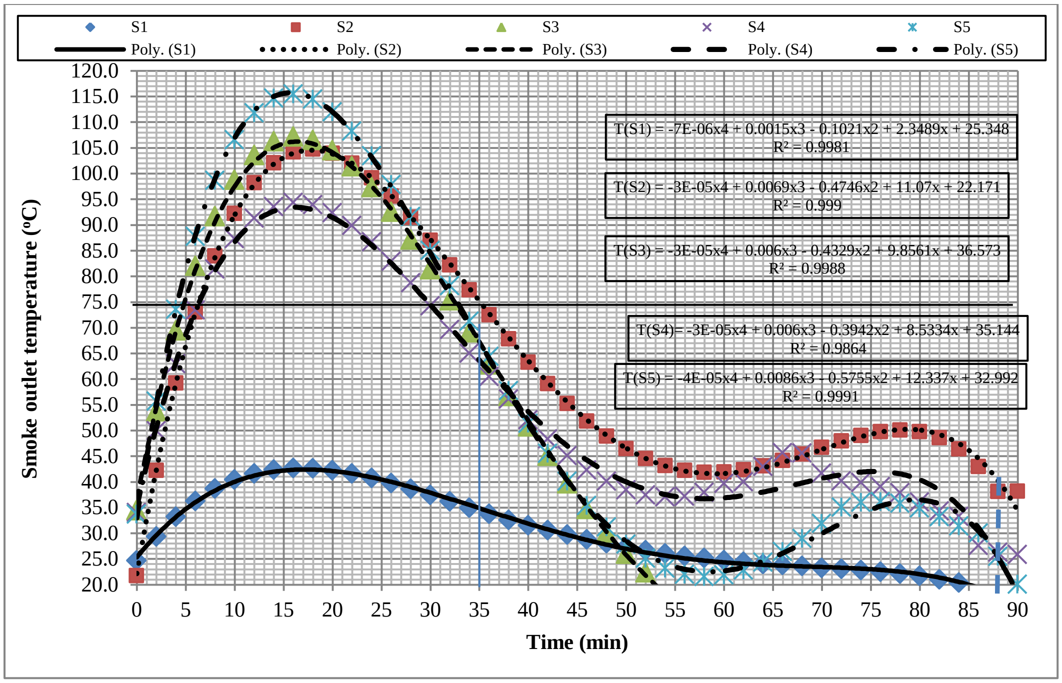

Figure 3.6: Smoke outlet temperature versus cooking time plots of the five types of stoves

Looking at the plots of Fig. 3.6, from among the curves, S5 has the highest t_f of 36 minutes. Therefore for calculating the areas under the curves, the upper limit of integration was taken as 36 minutes and the lowest, zero. Performing the integrations using the equations given for each of the treatments in Fig. 3.6 gives areas under the curves (in arbitrary units) that are as summarized in Table 3.10.

Table 3.10: Estimated areas of the plots and the percent reduction in stove smoke outlet heat losses

Treatment	% moisture	Total air inlet area	Fraction of surface area (%)	Area*	Δ W.r.t A_{mx}**	% reduction***
S2	1	20	2.02	3125	-260	-8
S3	2	40	4.04	3128	-257	-8
S4	3	60	6.07	2821	-564	-17
S5	4	80	8.09	3385	0	0

Area* = area is given in arbitrary units, Δ W.r.t Tb_{mx}** = difference with respect to A_{mx} of S5; % reduction*** = percent reduction

S2 and S3 showed identical smoke outlet temperatures while S4 showed slightly reduced smoke outlet temperature. Comparison of S3 (2 air inlets) and S4 (three air inlets) shows that S4 is slightly better in reducing both stove body temperature and smoke outlet temperatures. S4 is also better in time of onset of cooking than S3. Overall S4 (3 air inlet stove) seems to be slightly better than the two air inlet stove.

3.4. Patterns of food, stove body and smoke outlet temperatures seen together

Energy utilization (in the form of food temperature) and energy loses (in the forms of stove body and smoke outlet temperatures) can be analyzed by drawing the plots of the three together for each treatment. The losses are associated with heat that is transferred into the stove body or out to ambient while the gains are associated with heat that is transferred to the pot. Figure 3.7 shows food, body and smoke outlet temperatures of stoves of one, two, three and four air inlets.

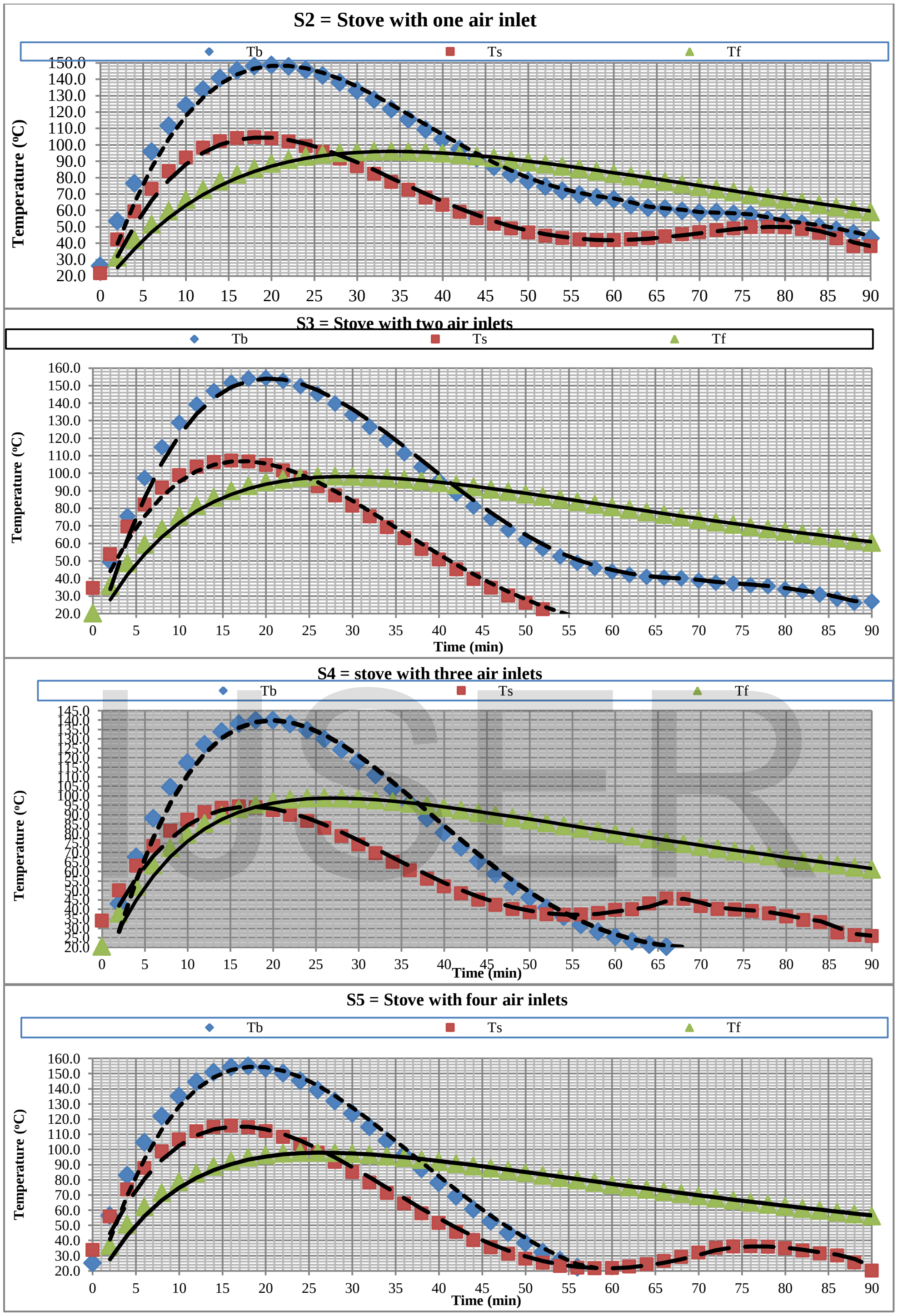

Figure 3.7: Temperatures of food, body and smoke outlets of S2 – S5 stoves

Stove with one air inlet exhibited maximum body, food and smoke outlet temperatures of 147, 97 and 104^{o}C, respectively. From these plots it is easy to realize that much of the energy is lost through the body of the stove. The loss through the smoke outlet cannot be undermined either. The extended tail of the plot of T_b indicates heat loss for a longer time.

The two air inlet stove exhibited maximum body, food and smoke outlet temperatures of 154, 97 and 106^{o}C, respectively. Here again the loss showed slight increment even though the stove performed roughly the same as the single air inlet stove. The loss through the smoke outlet is higher than that of the single air inlet stove. With this stove the tail of T_b dropped faster than that of the smoke outlet and this shows reduction of heat loss during the last minutes of cooking.

The triple air inlets stove exhibited maximum body, food and smoke outlet temperatures of 140, 97 and 94^{o}C, respectively. The reduction in the maximum stove body and smoke outlet temperatures as compared to the single and double air inlets stoves indicates some sort of heat loss to the surrounding. One can say this since the reduction in the maximum body temperature and the rapid falling of the curve during the last minutes of cooking did not manifest in the food temperature. With this stove, the tail of T_b dropped faster than that of the smoke outlet and this shows reduction of heat loss through the body of the stove.

The four air inlets stove exhibited maximum body, food and smoke outlet temperatures of 154, 97 and 115^{o}C, respectively. Both the body and the smoke outlet temperatures increased in this case. Despite that the actual cooking time interval reduced and no benefit was obtained as far as food temperature is concerned. With this stove, the tail of T_b dropped faster than that of the smoke outlet and this shows reduction of heat loss through the body of the stove.

4. Conclusion

In this study five stoves of no air inlet to four air inlets were compared with each other and with the conventional charcoal stove. Tests were performed in terms of food, stove body and stove smoke outlet temperatures. Comparisons were done both graphically and using ANOVA tests followed by pair comparisons.

Stove with no air inlet is completely dysfunctional (could not reach effective cooking temperature). There are no differences between 1 – 3 air inlet stoves in terms of cooking time. The 4 air inlet stove is actually worse since it reduced the effective cooking time. Two and 3 air inlet stoves are beneficial in terms of reaching cooking temperature earlier (23% time reduction). From among 1 -3 air inlet stoves the triple air inlet stove showed the least smoke outlet and stove body temperatures. However, this did not reflect on food temperature, which means there were other ways by which the heat energy was lost. Conventional charcoal stove did not perform as well as others since it took more time to reach cooking temperature and did not stay long at that temperature as well. In general, more air inlets increase the chances of air entry provided that all the air gets into the combustion chamber.

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