Programme for Biomass Energy Conservation in Southern Africa

WATER BOILING TEST (WBT) OF THREE CHARCOAL STOVES AND FOUR FUELWOOD STOVES

Dr. Hassan M Rajabu
Department of Mechanical and Industrial Engineering
University of Dar es Salaam

November 2009

EXECUTIVE SUMMARY

Tanzania Traditional Energy Development and Environment Organization (TaTEDO) and Programme for Biomass Energy Conservation (ProBEC) have been involved in promoting, training, capacity building, and marketing of improved biomass stoves for several years.

The two organizations contacted University of Dar es Salaam to conduct stove performance and emission tests for three charcoal stoves and four fuelwood stoves. The tests were conducted at TaTEDO Center for Sustainable Energy Development at Goba, Dar es Salaam from September 22nd to October 7th 2009.

The stoves that were tested included charcoal stoves (SAHARA and TATEDO jiko bora, and KUUTE stove), and fuelwood stoves (ENVOTEC, M&R, Okoa-1, and Okoa-2). The Water Boiling Test (WBT) and emission results are summarized below for hot- and cold-starts.

<u>WBT results for Charcoal Stoves</u>

	CHARCOAL STOVES					
	COLD START			**HOT START**		
Parameters	SAH	TAT	KUU	SAH	TAT	KUU
Time to boil (mins)	**18.8**	19.3	30.4	**13.4**	14.1	26.6
Burning rate (g/min)	**6.4**	6.2	4.1	**7.3**	7.0	3.7
Thermal efficiency (%)	29%	29%	**35%**	34%	34%	**42%**
Specific fuel consumption (g/liter)	64.8	**63.1**	68.5	**51.3**	51.6	55.5
Firepower (Watts)	**3014**	2921	1915	**3446**	3279	1754

KEY to stove names: SAH = SAHARA stove; TAT = TATEDO stove; KUU = KUUTE stove

WBT results for Fuelwood Stoves

Parameters	FUELWOOD STOVES							
	COLD-START				HOT-START			
	ENV	M&R	OK1	OK2	ENV	M&R	OK1	OK2
Time to boil (mins)	**11.2**	12.9	13.2	11.5	**8.1**	8.9	11.5	9.7
Burning rate (g/min)	18.9	21.7	32.4	**33.1**	24.1	26.1	27.8	**33.6**
Thermal efficiency (%)	**35%**	27%	20%	21%	**39%**	33%	25%	24%
Specific fuel consumption (g/liter)	**85.8**	123.2	129.9	121.2	**79.3**	102.2	97.0	103.1
Firepower (Watts)	5800	6774	10121	**10362**	7403	8132	8699	**10472**

KEY to stove names: ENV = ENVOTEC stove; M&R = M&R stove; OK1 = Okoa-1 stove; OK2 = Okoa-2 stove

Simmer results for Fuelwood Stoves

Parameters	FUELWOOD STOVES (SIMMER TEST)			
	ENV	M&R	OK1	OK2
Burning rate (g/min)	9.2	12.3	**16.4**	12.8
Thermal efficiency (%)	**29%**	23%	20%	18%
Specific fuel consumption (g/liter)	**255.6**	471.5	359.3	267.9
Firepower (Watts)	2809	3857	**5162**	4016
Turn Down Ratio	2.07	1.78	2.07	**2.59**

KEY to stove names: ENV = ENVOTEC stove; M&R = M&R stove; OK1 = Okoa-1 stove; OK2 = Okoa-2 stove

Emission results

Parameters	EMISSION TEST							
	COLD-START				HOT-START			
	ENV	M&R	OK1	OK2	ENV	M&R	OK1	OK2
Carbon monoxide -CO (mg/m^3)	387	**201**	206	236	384	273	**223**	337
Nitrogen oxides -NO_x (mg/m^3)	**15**	16	26	16	**13**	19	17	18

KEY to stove names: ENV = ENVOTEC stove; M&R = M&R stove; OK1 = Okoa-1 stove; OK2 = Okoa-2 stove

1 INTRODUCTION

1.1 Background

In 2005, ProBEC introduced rocket based stoves design in Tanzania that uses imported insulative bricks for boiler furnaces in constructing the combustion chamber of the stove. The bricks were expensive and not easily available locally. In view of that some trained producers of rocket stoves started to experiment locally made insulative bricks in order to compare the bricks performance and the overall stove performance with locally made insulative bricks. The stove producers also made some design modifications on the dimensions for the locally made bricks to suit the design of their stoves and to simplify the construction of stoves.

Tanzania Traditional Energy Development and Environment Organization (TaTEDO) has been involved in improvement and dissemination of both fuelwood and charcoal stoves. Improved Charcoal Stove was first introduced in Tanzania by the Ministry of Energy and Minerals in 1988, with assistance from the World Bank. Adapted from the Kenyan ceramic jiko, this stove consists of a metal outer casing, a ceramic firebox and an insulation collar. The stove has been promoted because it is low-cost, reduces cooking time, and reduces the consumption of charcoal and therefore household expenditure.

In 1992, the Tanzania Traditional Energy Development and Environment Organization (TaTEDO) assumed responsibility for disseminating this technology in the country. Together with efficient fuelwood stoves, TaTEDO has trained artisans to produce the stoves and helped establish workshops and repair centers by offering small loans, training and technical support. In June 2009, ProBEC collaborated with COSTECH and TaTEDO to disseminate KUUTE and Jiko-bora charcoal stoves, respectively. These stoves are produced by stove producers trained by COSTECH and TaTEDO respectively.

In September 2009, the two organizations contacted University of Dar es Salaam (UDSM) to conduct stove performance and emission tests for three charcoal stoves and four fuelwood stoves. The tests were conducted at TaTEDO Center for Sustainable Energy Development at Goba, Dar es Salaam from September 22nd to October 7th 2009.

1.2 Objectives of the Tests

The objectives of conducting the tests are:

- To measure the efficiency of the stoves using the Water Boiling Test (WBT)
- To compare performance characteristics of similar stoves.
- To compare emission performance of fuelwood stoves under similar conditions
- To identify areas that requires further modifications from tested stove.

1.3 Description of the Stoves

Charcoal Stoves

The three charcoal stoves tested are SAHARA, TATEDO –Jikobora, and KUUTE. All three charcoal stoves have metal cladding and ceramic liner and grate. SAHARA and TATEDO-Jikobora have similar tapered firebox design with SAHARA having slightly smaller firebox.

The KUUTE charcoal stove has a different design concept as it does not have the conventional three pot supports above the firebox. When the pot is placed on the stove it seals completely the firebox top, and the hot gases from the burning charcoal exits at the short protruding chimney at the side of the firebox. Material used to construct the KUUTE firebox liner is clay liner made by Vingunguti artisans[1] The illustrations of the three charcoal stoves are shown in Figures 1a-c. The technical drawings of the charcoal stoves are shown in Appendix IV.

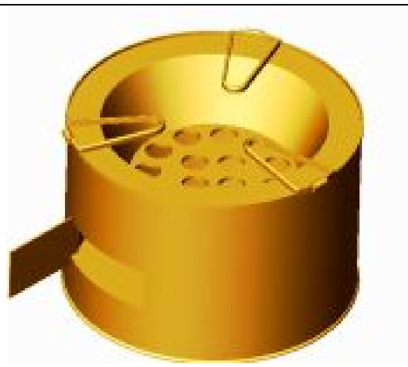
Fuelwood Stoves

The four fuelwood stoves tested are ENVOTEC, M&R, Okoa-1, and Okoa-2. With exception of okoa-1, the other three fuelwood stoves are based on the rocket stove principle, and they have insulative bricks liner in the combustion chamber. Okoa-1 is a tradition improved stove made from clay. Other major differences between Okoa-1 and Okoa-2 are different combustion chamber sizes, and Okoa-2 has 2 primary combustion chambers, with water heating tubing in one combustion chamber. Both Okoa-1 and Okoa-2 are built-in stoves.

[1]Mr. Said Muhunzi. Gerezani, Kariakoo. Mobile: 0715941435

ENVOTECH and M&R are portable rocket stoves. The difference between them is on the major dimensions and combustion chamber design and dimensions. M&R has outer body made of galvanized sheet and cylindrical combustion chamber made by hollow bricks that are made by a mixture of clay from Lungemba (IRINGA) and low mass materials such as sawdust powder or rice husk[2].

ENVOTEC has rectangular chamber made by refractory bricks that are joined by high temperature cement, the outer frame is made by mild steel sheet 1.5 mm[3]. M&R also does not have the extended L-shape fuel magazine and fuel shelf. The illustrations of the four fuelwood stoves are shown in Figures 1d-g. The technical drawings of the fuelwood stoves are shown in Appendix IV.

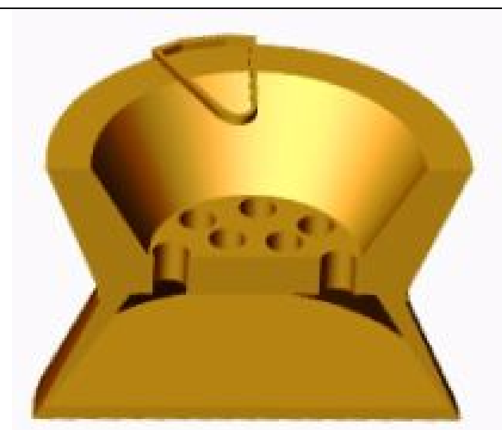


Isometric view

Section

Figure 1a: SAHARA CHARCOAL STOVE: “Jiko bora”, ceramic lined

Isometric view



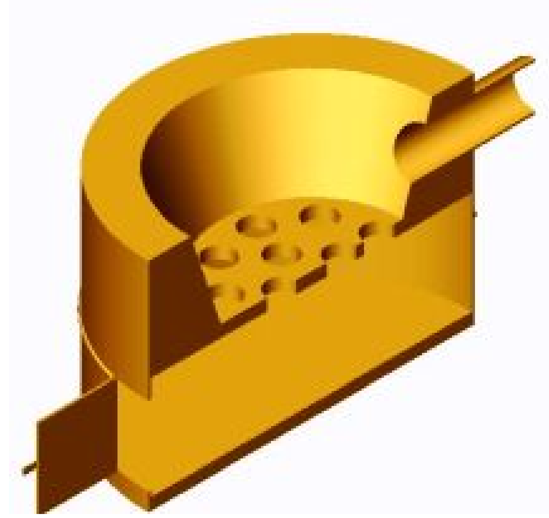
Section

Figure 1b: TATEDO CHARCOAL STOVE: “Jiko bora”, ceramic lined

[2]Dr. L.M.P.Rweyemamu. Mwenge along Bagamoyo road. P.O. Box 75471 DSM. Mobile: 0784478752.

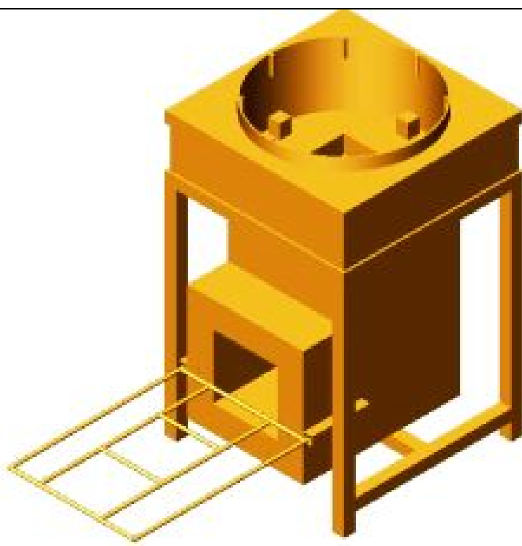
[3]Mr. S. Mwambije. Kinindoni. .P.O. Box 1927 DSM Mobile: 0713605137

Isometric view



Section

Figure 1c: KUUTE CHARCOAL STOVE: “Jiko bora”, ceramic lined



Isometric view

Section

Figure 1d: ENVOTEC FUELWOOD STOVE: “Rocket stove”

 ***Isometric view***	 ***Section***

Figure 1e: M&R FUELWOOD STOVE: “Rocket stove”

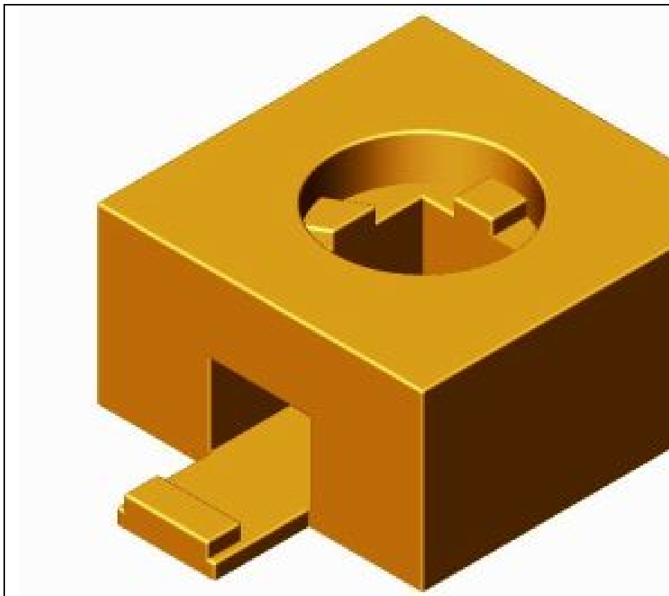
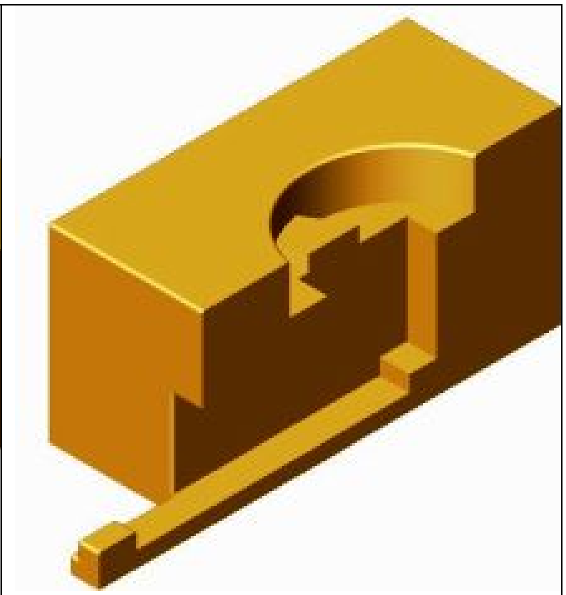
 ***Isometric view***	 ***Section***

Figure 1f: OKOA-1 FUELWOOD STOVE: Built-in mud stove

Isometric view

Section

Figure 1g: OKOA-2 FUELWOOD STOVE: Built-in rocket stove

1.3 Water Boiling Test (WBT)

WBT is a laboratory controlled test which can be used to compare the performance of two or more stoves under similar controlled conditions. It is conducted to measure the cumulative effect of how efficiently chemical energy from the fuel is converted to heat and how efficiently heat energy from the hot gases is transferred to the food through the pot. WBT does not reflect the actual stove performance when food is cooked under normal kitchen conditions, but it gives an indication of a ceiling of maximum achievable efficient the stove can reach under normal kitchen conditions.

WBT was developed in 1980’s by Volunteers in Technical Assistance (VITA). The WBT protocols were then slightly updated in 2003 by Shell Foundation, University of California-Berkeley, and Aprovecho Research Center. The tests conducted followed these procedure which are intended to measure the stove’s performance at both high power (cold and hot starts) for all seven stoves, and low power outputs (simmering) for fuelwood stoves only. The summary of the tests conducted are:

<u>Charcoal stoves</u>

- High power test – cold start
- High power test – Hot start

Fuelwood stoves

- High power test – cold start
- High power test – Hot start
- Simmering test

The above tests generated the following stove performance data for the stoves:

- Stove efficiency
- Average burning rate
- Specific fuel consumption
- Average stove power
- Time to boil
- Turn Down Ratio

1.4 Emission Tests for Fuelwood Stoves

To date, there is no agreed standard procedure for biomass stove emission tests and indoor pollution measurement protocol. The stoves at SEDC are located in a shed at an unsteady windy backyard of SEDC center. The shed is also well ventilated untypical of tradition household kitchens. Hence It was therefore decided that for stoves with no chimney the sampling has to be done just above (about 2 cm) and on the side (3 cm) of the pot. For the stove with chimney (Okoa-2), the sampling was done at the smoke exit of the chimney.

The readings obtained from the tests are therefore only indicative and are for comparing the combustion completeness of the stoves (CO data), and flame temperature (NOx data). The results, therefore, cannot be interpreted or projected to any established Air Quality Guideline for indoor pollution.

1.5 Fuelwood Used for the Tests

In order to minimize the variation that is potentially introduced by variations in fuel type and properties all the tests were conducted using similar type (hardwood) and roughly the same size (1.5 cm x 2.5 cm cross section) prepared from the carpentry shop. The fuelwood selected for the tests were thoroughly air-dried and the moisture content and calorific values of samples of fuelwood used were measured from the samples of fuelwood used.

1.6 Pots Used for the Tests

The dimensions of the pot have an influence on stove performance, especially for the stoves with skirting. The gap between the pot and the skirt in M&R and ENVOTECH fuelwood stoves were carefully maintained to be between 15mm to 20mm by selecting appropriate pots. In charcoal stoves, the same pot was used in all stoves, since they all have approximately the same firebox diameter. The pots used were metal/aluminium pots, and to maintain the emissivity of the pots, they were scrubbed with steel wool after each test run to remove the soot.

2 TEST PROCEDURES AND MEASUREMENTS

2.1 Water Boiling Test

The procedure used for WBT followed Shell Foundation Household Energy and Health Programme (Shell-HEH)4. The details of procedures are attached in Appendix I.

2.2 Emission Tests

The carbon monoxide (CO) and nitrogen oxides (NOx) concentrations from the gases were measured with the Combustion Analizer type CA-CALC Model 6203 Series provided by TATEDO. The equipment was set to average the data for 15 seconds and to record the concentration reading after every two minutes. Both CO and NOx concentrations were measured in mg/m3 units. During the tests the position of the sampling probe was maintained about 2 cm above and 3 cm outside the edge of the pot for stoves with no chimney, and at the chimney for Okoa-2.

2.3 Heat value and Moisture Content Measurements

The calorific value and moisture content of the fuelwood sample used during the tests were determined at the Energy technology Laboratory, University of Dar es Salaam. The procedure used for Heat value and moisture content followed DIN EN22719 and ASTM E871-1982 standards, respectively. For charcoal the value of 29.4 MJ/kg was used for the calorific value which was obtained from literature and used for calculation of results.

[4] www.aprovecho.org

3 RESULTS

3.1 Water Boiling Tests

The WBT conducted for the seven stoves gives results for stove efficiency, average burning rate, specific fuel consumption, average stove power, and time to boil. The values of moisture content (w.b) and calorific value (HHV) of fuelwood used are 10.4% and 20.817 MJ/kg, respectively. The heat value of charcoal used is 29.4 MJ/kg.

Tables of result for each stove are attached in Appendix III. Formulas and description of parameters are shown in Appendix II.

Stoves Efficiency

Figure 2 shows result for stoves efficiency. As expected, all stoves showed higher efficiency when tested as hot-start. For fuelwood stoves lower efficiencies are observed during simmering. KUUTE stove showed highest efficiency in both types of stoves, followed by ENVOTEC which also leads the fuelwood stoves.

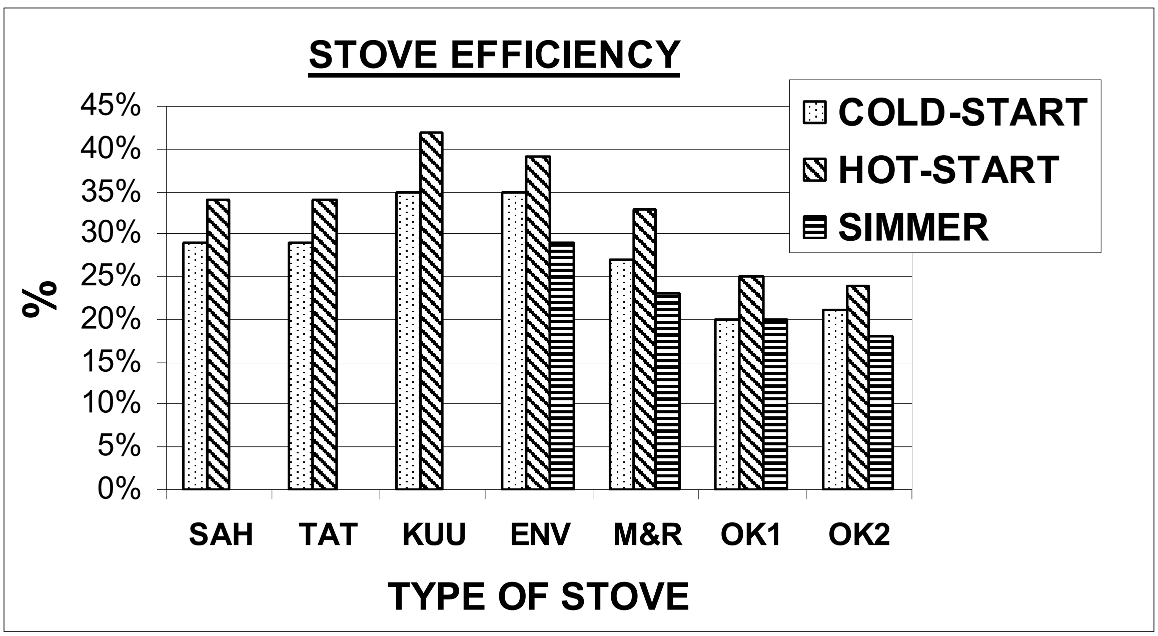


Figure 2: Stoves efficiency of charcoal and fuelwood stoves from WBT

Average Burning Rate

Figure 3 shows the calculated average burning rate of the stoves. From the tests the following can be highlighted:

- The fuel consumption rate in fuelwood stoves is much higher compared to charcoal stoves.
- Okoa-2 produce highest burn rate and KUUTE stove showed the lowest burning rate of all stoves tested

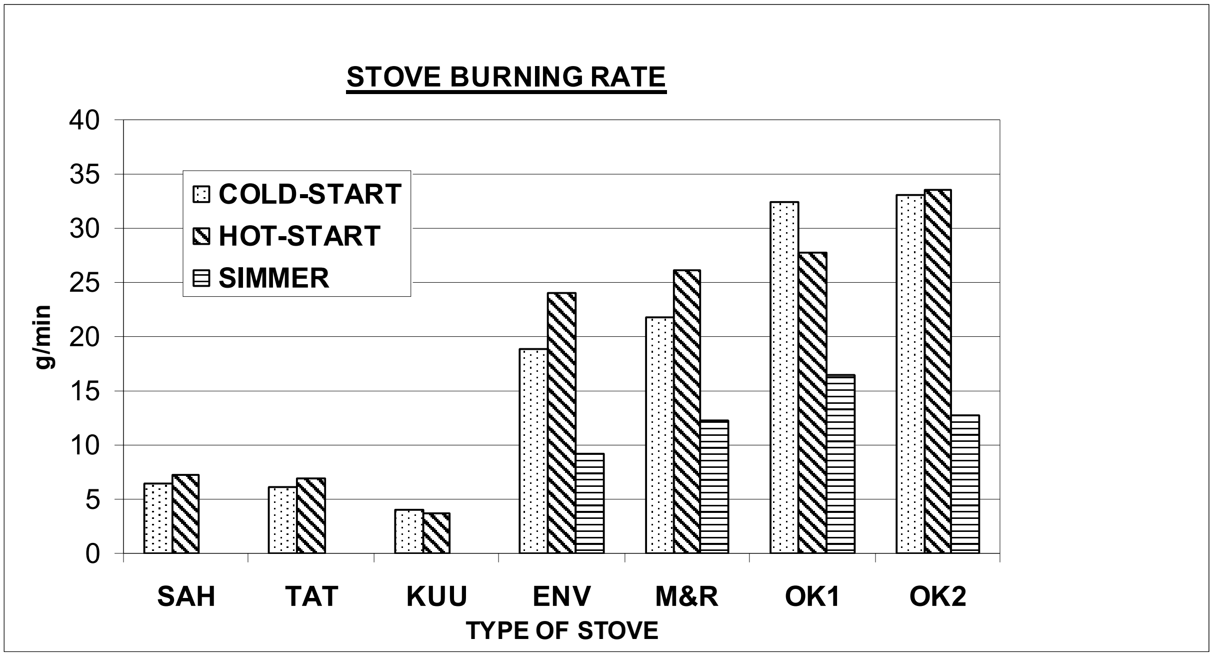


Figure 3: Burning rate of charcoal and fuelwood stoves from WBT

Specific Fuel Consumption (SFC)

Figure 4 shows the SFC of all stoves during cold- and hot-starts. The following can be deduced from the results:

- Charcoal stoves showed similar values of SFC,
- Values of SFC from charcoal stoves are lower compared to SFC in fuelwood stoves.
- In each stove SFC is lower in hot-start compared to cold-start tests, which indicates that more heat is directed to the pot in hot-starts.

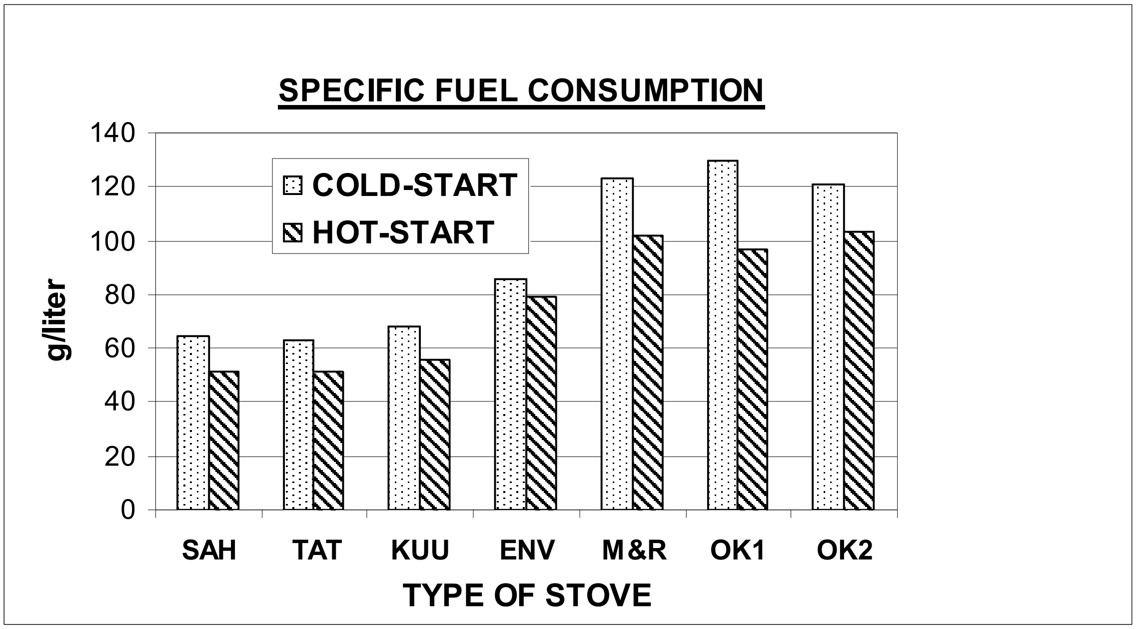


Figure 4: Specific fuel consumption of charcoal and fuelwood stoves from WBT

Average Firepower

Figure 5 shows the firepower of the stoves with fuelwood stoves exhibiting almost 3 times more power compared to charcoal stove. A very low firepower of KUUTE charcoal stove compared to SAHARA and KAKUTE stoves is also noted.

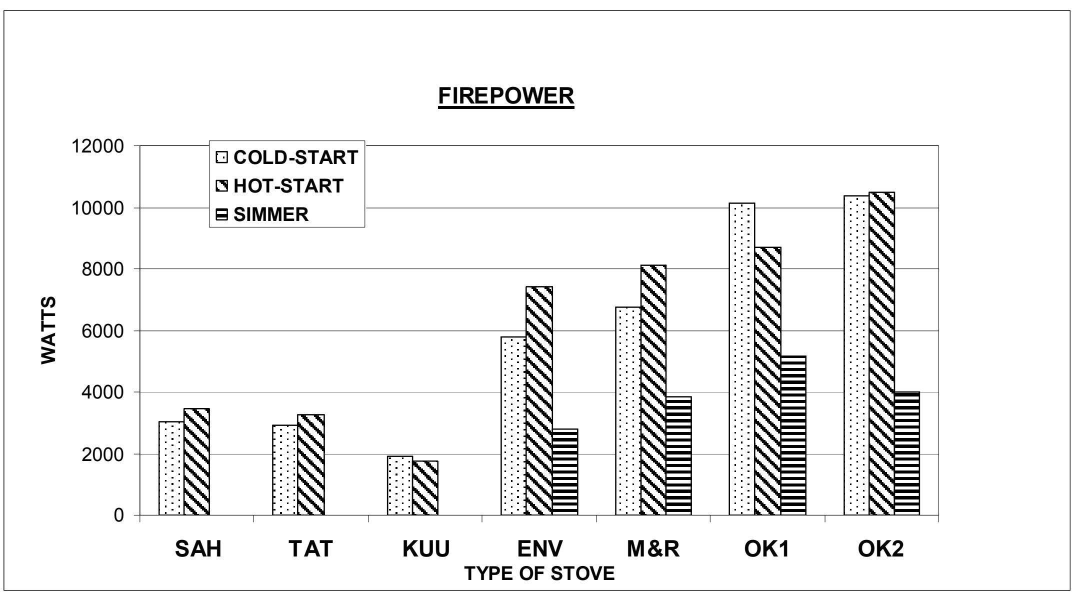


Figure 5: Firepower of charcoal and fuelwood stoves from WBT

Time-to-Boil

From the WBT, the following can be highlighted from the results on time-to-boil shown in figure 6:

- Fuelwood stoves boils water much faster compared to charcoal stoves
- KUUTE stove showed longest time-to-boil. This is attributed to low burn rate of charcoal and hence firepower of the stove.
- In general, stoves with high firepower showed shorter time-to-boil.

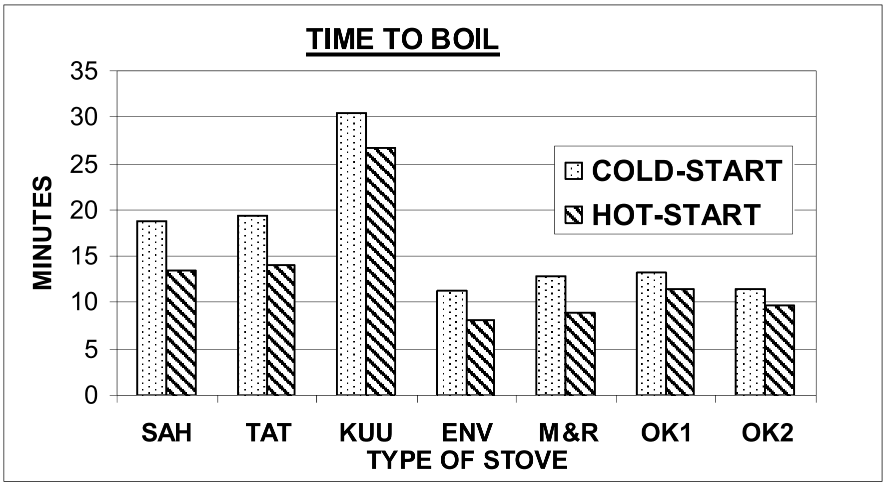


Figure 6: Time to Boil of charcoal and fuelwood stoves from WBT

Turn-down Ratio (TDR)

Turn-down ratio is the ratio of stove's high power to simmering power. From the WBT tests conducted Okoa-2 showed highest TDR. Results for TDR are shown in Figure 7.

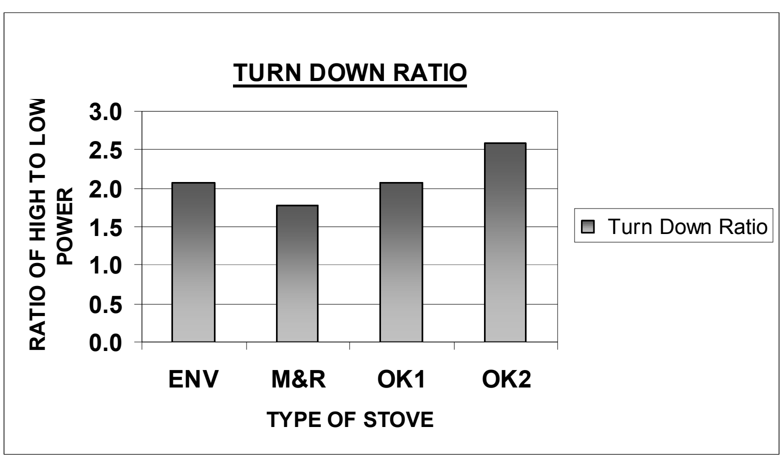


Figure 7: Turn-down ratio of fuelwood stoves from WBT

3.2 Emission Tests

Average Carbon Monoxide (CO) Emissions

The average concentration of carbon monoxide during the WBT revealed that ENVOTEC stove have the highest value, followed by Okoa-2, M&R, and Okoa-1. However, due to uncontrolled conditions at the SEDC stove shed, these results can have induced errors due to positioning of stove during the test, and also wind condition when a particular stove was tested. Figure 8 below show the results from CO measurements.

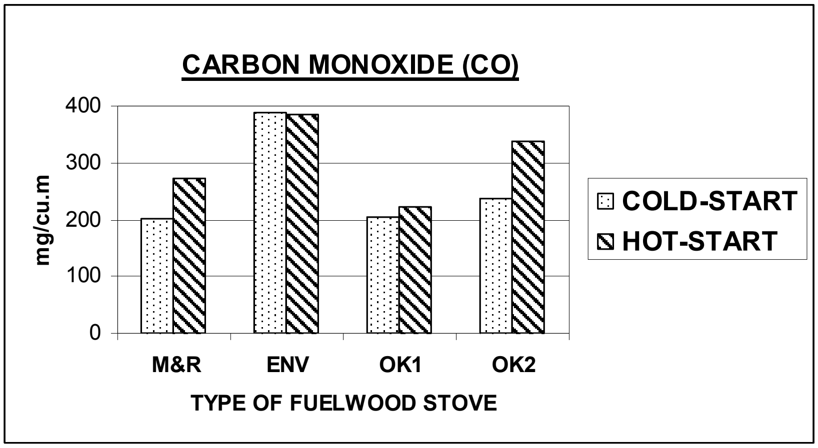


Figure 8: Average carbon monoxide emission from fuelwood stoves from WBT

Nitrogen Oxides Emissions

Results from NOx emissions are shown in Figure 9. Okoa-1 showed highest value, followed by M&R, Okoa-2, and ENVOTEC stoves. The comment made on CO measurement also applies in NOx results.

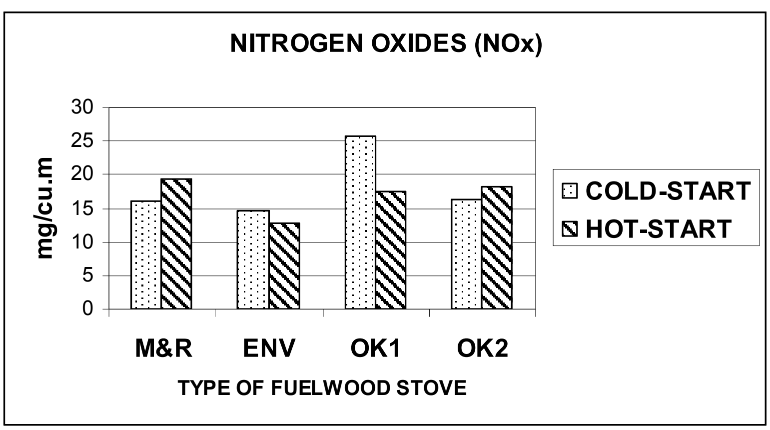


Figure 9: Average nitrogen oxides emission from fuelwood stoves from WBT

4 DISCUSSION AND RECOMMENDATIONS

4.1 Charcoal Stoves

KUUTE stove showed highest efficiency among the charcoal stoves by about 7%. This peculiarity in high efficiency among similar ceramic-lined charcoal stoves is mainly attributed to the design of the KUUTE stove - where the pot completely seals the firebox and the gases from burned charcoal leaves the firebox through the side chimney. This design minimizes heat loss at the top as the main heat transport phenomena from charcoal is through radiation, - unlike fuelwood stoves where heat is transferred mainly by convection via the hot gases from the flame to the pot (refer rocket stove design principle).

With the top of firebox covered by pot in KUUTE stove, radiation heat from the glowing charcoal, plus reflected radiation heat from the sides of the firebox is received by the pot in the upward direction. In the conventional SAHARA and TaTEDO-Jikobora stoves, some radiative heat is lost through the gap created by the pot supports between the pot and the firebox.

Despite the advantage on higher efficiency, the low burning rate of the KUUTE stove is caused mainly by the same reason, i.e., the pot completely sealing the firebox which significantly reducing air draft through the burning charcoal by reducing the hot gases exit area. The side chimney which is provided in this stove is not adequate to make the charcoal burn at the same rate as in the conventional charcoal stoves. Secondly, the diffucion of secondary air through the gap is completely eliminated in KUUTE stove, which together with reduced primary air, reduces the burning rate of charcoal.

The disadvantage of the low burning rate of KUUTE stove causes the time to boil and firepower of the stove to be poor compared to SAHARA and TaTEDO-Jikobora stoves. The time to boil for KUUTE stove is more than 50% longer than SAHARA and TaTEDO-Jikobora stoves. This feature of KUUTE stove can easily make it not to be liked by users, as most users prefer stoves which cook fast than many other good aspects of the stove.

On the other hand, SAHARA and TaTEDO-Jikobora stoves showed reasonably high efficiency for ceramic lined stove. All charcoal stoves, including KUUTE showed good insulative properties as the metal clad sides were not hot to the touch during the tests.

Recommendations for Charcoal Stoves:

- KUUTE stove is an efficient charcoal stove - however, the low burning rate of the charcoal makes it to be not powerful enough compared to other charcoal stoves in the market. More work should be done to increase the burning rate of this stove without compromising the efficiency too much. Such modifications should look into the possibility of increasing air to the burning charcoal by increasing the air inlet area (ash door) to compensate for the small chimney exit area at the side of the firebox. Alternatively, the chimney exit area should be increased, or two or more chimneys should be made to increase the air flow through the burning charcoal. Both alternatives and combinations of alternatives need to be tried to achieve the optimum solution.

- The high efficiency of KUUTE stove compared to SAHARA and TaTEDO-Jikobora stoves demonstrates the influence of the pot distance from the firebox on efficiency. Efficiency is high for KUUTE stove with zero clearance. It can be safely assumed that efficiency decreases as the gap between the pot and the firebox increase. In other words, the less you see the burning charcoal through the gap the more the efficiency of stove. Therefore it is recommended that investigation be done in this area to see the compromise gap which shall give high efficiency without decreasing the firepower of the stove too much.

- Another design feature of conventional charcoal stoves (or is it workmanship?) –which increase the gap is the slight upward projection of the pot support as shown in Figure 10. As discussed above, the increase of the pot distance from the firebox decreases the efficiency of the stove in charcoal stoves. The upward projection of the supports might have been made or designed purposely to compensate for the bending of the supports after use. If that is the case then stronger supports which give the minimum gap clearance should be designed to prevent loss of heat during cooking.

- It is lastly recommended that during the dissemination of charcoal stoves the users should be educated on inefficient practices of using pots with smaller diameter than the firebox, and on overfilling of charcoal in the stove during cooking. Both practices increase the gap and hence heat loss from the stove.

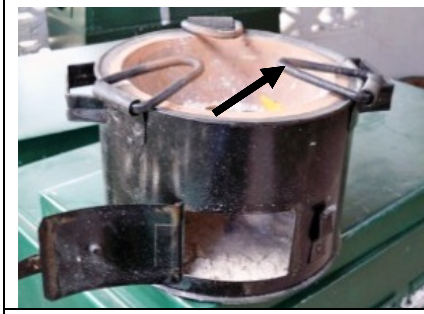


Figure 10: Upward projection of port support (arrow) increase the gap between the pot and the firebox

Figure 11: M&R and ENVOTEC stoves showing the difference in skirt height/diameter ratio

4.2 Fuelwood Stoves

Among the fuelwood stoves tested ENVOTECH stove showed highest efficiency followed by M&R, and lastly Okoa built-in stoves. Okoa-1 and -2 showed same level of efficiency both in cold and hot starts. In general portable rocket stoves showed superior efficiency compared to built-in Okoa stoves. The efficiencies of ENVOTECH and M&R are of the same level to efficiencies exhibited by the ceramic-lined charcoal stoves.

The high efficiency of ENVOTECH compared to other fuelwood stoves, and especially M&R which is very similar in design, is mainly due to the pot skirt dimensions. The port skirt depth for ENVOTECH stove is 110 cm, compared to 70 cm for M&R. This is despite that ENVOTEC takes smaller pot size (skirt diameter 260 cm), compared to M&R (330 cm). These dimensions make the skirt depth-to-diameter ratio to be 0.42 and 0.21, for ENVOTECH and M&R, respectively. Hence, more convective heat from the rising hot gases is transferred to the pot in ENVOTECH compared to M&R stove. Figure 11 depicts the two stoves, with high percentage of surface area of the pot inside the skirt for ENVOTECH stove.

Despite the better design, materials of construction and better workmanship, Okoa-2 showed the same level of efficiency as Okoa-1. Okoa-2 has two primary combustion chambers with one side accommodating water-heating tubes, and both sides share a common chimney. During the tests only the side without water-heating tubes was used for the test.

The size and mass of Okoa-2 and hence the heat capacity, is much bigger compared to Okoa-1. This fact might have contributed in lowering the efficiency of Okoa-2, as more heat from the fuel is robbed to raise the stove mass temperature in the big stove (Okoa-2) due to bigger heat capacity as compared to Okoa-1. Furthermore, the external surface area of Okoa-2 is much larger and more heat is lost to the surroundings compared to the compact Okoa-1. The efficiency of Okoa-2 should be expected to increase if both sides of the stove are used.

In average, the burning rate and firepower of fuelwood stoves are more than 3 times higher than those showed by charcoal stoves. However, this is due to the bigger sizes of the fuelwood stoves tested. Furthermore, the reactive nature of fuelwood compared to charcoal contributes further to the high burn rates in fuelwood stoves.

Recommendation from Fuelwood Stoves

The following recommendations are made for the fuelwood stoves:

- The skirt height for M&R to be increased slightly to improve its efficiency.

- The efficiency of Okoa-2 can be increased if the heat capacity of the stove is reduced. Another option to contain the heat on the side which is used is to create internal separation of the two combustion chambers. Such a separation should be made of insulating materials or an air gap to thermally separate the two combustion chambers. The thermal separation will reduce the heat flow from one side of the stove to the other during the time when only one side is used for cooking.

4.3 Emissions

The average concentration of carbon monoxide during the WBT revealed that ENVOTEC stove have the highest value, followed by Okoa-2, M&R, and Okoa-1. However, due to uncontrolled conditions at the SEDC stove shed, the reliability of measurements was poor and results can have induced errors due to the relative position of stove during the test, and the influence of continuously changing wind condition which affects the results when a particular stove was tested.

APPENDICES

Appendix I: Water Boiling Test Measurements and Procedure

Measurements

Variables measured BEFORE each test run	
f_{ci}	Weight of fuel before test (grams)
P_{ci}	Weight of Pot with water before test (grams)
T_{ci}	Water temperature before test (ºC)
t_{ci}	Time at start of test (min)
Variables measured AFTER each test run	
f_{cf}	Weight of wood after test (grams)
c_c	Weight of charcoal and container after test (grams)
P_{cf}	Weight of Pot with water after test (grams)
T_{cf}	Water temperature after test (ºC)
t_{cf}	Time at end of test (min)

During the test the water temperature is recorded after every 2 minutes (tct)

Procedure (Cold-start)

- Fill the pot to 2/3 full with cold clean water and record the weight of pot and water (P_{ci})
- Insert the thermometer attached to wood holder in water and record the initial water temperature (T_{ci})
- Record the weight of fuel before the test (f_{ci})
-
- Start the fire with methylated spirit, and place the pot with water immediately and record the starting time (t_{ci})
- Record the water temperature and time after every 2-3 minutes (t_{ct})
- Throughout the following "high power" phase of the test, control the fire to bring the water rapidly to a boil.
- Record the time when the water in the pot reaches the pre-determined local boiling temperature as shown by the thermometer (T_{cf})
- Remove all wood from the stove and extinguish the flames

- Knock off all loose charcoal from the ends of the wood into the container for weighing charcoal
- Weigh the unburned wood removed from the stove (f_{cf})
- Weigh pot with its water (P_{cf})
- Extract all remaining charcoal from the stove, place it with the charcoal that was knocked off the fuelwood and weigh (c_c).

Procedure (Hot-start)

After finishing the "cold-start" test proceed to "hot-start" immediately, before the stove gets cold. Repeat the measurements and same procedure as for "cold-start"

Procedure (Simmering tests)

Simmering test begins by repeating the hot-start high power test. When the water is about to boil (3-5oC below local boiling point), initial measurements are taken and time is set to start the test for additional 45 minutes maintaining the water temperature just below boiling.

- Remove the fuelwood from the stove and weigh it. Record this weight as the weight of wood at the start of the simmer phase. Return the wood to the stove. The weight of the charcoal is not measured and will be assumed to be the same at the end of the test.
- Remove the pot of water from the stove, weigh it and return it to the stove.
- Monitor the temperature of water in the pot to be just below boiling by controlling the firepower, keeping the water as close to 3 degrees below the established boiling point as possible.
- After 45 minutes rapidly record the finish time of the test.
- Remove all fuelwood from the stove and knock loose charcoal into the charcoal container. Weigh the remaining wood.
- Weigh the pot with the remaining water.
- Extract all remaining charcoal from the stove and weigh it (including charcoal which was knocked off the sticks). Record the weight of pan plus charcoal.

Appendix II: Formulas and Description of Parameters

High power test (cold start)

Variables that are directly measured		Variables that are calculated	
f_{ci}	Weight of fuel before test (grams)	f_{cm}	Fuel consumed, moist (grams)
P_{ci}	Weight of Pot with water before test (grams)	Δc_c	Change in char during test phase (grams)
T_{ci}	Water temperature before test (ºC)	f_{cd}	Equivalent dry fuel consumed (grams)
t_{ci}	Time at start of test (min)	w_{cv}	Water vaporized (grams)
f_{cf}	Weight of fuel after test (grams)	w_{cr}	Water remaining at end of test (grams)
c_c	Weight of charcoal and container after test (grams)	Δt_c	Duration of phase (min)
P_{cf}	Weight of Pot with water after test (grams)	h_c	Thermal efficiency
T_{cf}	Water temperature after test (ºC)	r_{cb}	Burning rate (grams/min)
t_{cf}	Time at end of test (min)	SC_c	Specific fuel consumption (grams fuel/grams water)
		SC^T_h	Temp-corrected specific consumption (grams fuel/grams water)
		FP_c	Firepower (W)

f_{cm} - Fuel consumed (moist): This is the mass of fuel that was used to bring the water to a boil found by taking the difference of the pre-weighed fuel and the fuel remaining at the end of the test phase:

$f_{cm} = f_{cf} - f_{ci}$

Δc_c - Net change in char during test phase: This is the mass of char created during the test found by removing the char from the stove at the end of the test phase. C_c is the weight of the char + container, and k is the weight of the container.

$\Delta c_c = c_c - k$

f_{cd} - Equivalent dry fuel consumed: This is a calculation that adjusts the amount of fuel that was burned in order to account for two factors: (1) the energy that was needed to remove the moisture in the fuel and (2) the amount of char remaining unburned. The calculation is done in the following way:

$$f_{cd} = f_{cm} * (1 - (1.12 * m)) - 1.5 * \Delta c_c$$

The factor of $1 - (1.12 * m)$ adjusts the mass of fuel burned by the amount of fuel required to heat and evaporate $m * f_{cm}$ grams of water. It takes roughly 2260 kJ to evaporate a kilogram of water, which is roughly 12% of the calorific value of dry fuel. Thus if fuel consists of m% moisture, the mass of fuel that can effectively heat the pot of water is reduced by roughly $1 - (1.12 * m)$ because the water must be boiled away before fuelwood burns.

The factor of $1.5 * \Delta c_c$ accounts for the fuelwood converted into unburned char. Char has roughly 150% the calorific content of fuelwood, thus the amount of fuelwood heating the pot of water should be adjusted by $1.5 * \Delta c_c$ to account for the remaining char. Note, in the simmer phase it is possible that there will be a net loss in the amount of char before and after the test, in which case Δc is negative and the equivalent dry fuelwood increases rather than decreases.

w_{cv} - Water vaporized: This is a measure of the amount of water lost through evaporation during the test. It is calculated by simple subtraction of initial weight of pot and water minus final weight of pot and water.

$$w_{cv} = P_{ci} - P_{cf}$$

w_{cr} - Water remaining at end of test: This is a measure of the amount of water heated to boiling. It is calculated by simple subtraction of final weight of pot and water minus the weight of the pot.

$$w_{cr} = P_{cf} - P$$

Δt_c – Duration of phase: This is simply the time taken to perform the test. It is a simple clock difference:

$$\Delta t_c = t_{cf} - t_{ci}$$

h_c - Thermal efficiency: This is a ratio of the work done by heating and evaporating water to the energy consumed by burning fuel.

$$h_c = \frac{4.186 * (P_{ci} - P) * (T_{cf} - T_{ci}) + 2260 * (w_{cv})}{f_{cd} * LHV}$$

In this calculation, the work done by heating water is determined by adding two quantities: (1) the product of the mass of water in the pot, $(P_{ci} - P)$, the specific heat of water (4.186 J/g^{o}C), and the change in water temperature $(T_{cf} - T_{ci})$ and (2) the product of the amount of water evaporated from the pot and the latent heat of evaporation of water (2260 J/g). The denominator (bottom of the ratio) is determined by taking the product of the dry-fuel equivalent consumed during this phase of the test and the LHV.

r_{cb} - Burning rate: This is a measure of the rate of fuel consumption while bringing water to a boil. It is calculated by dividing the equivalent dry fuel consumed by the time of the test.

$$r_{cb} = \frac{f_{cd}}{t_{ci} - t_{cf}}$$

SC_c - Specific fuel consumption: Is a measure of the amount of fuel required to produce one liter (or kilo) of boiling water starting with cold stove.

$$SC_c = \frac{f_{cd}}{P_{cf} - P}$$

$SC^T{}_c$ – Temperature corrected specific fuel consumption: This corrects specific consumption to account for differences in initial water temperatures. This facilitates comparison of stoves tested on different days or in different environmental conditions. The correction is a simple factor that "normalizes" the temperature change observed in test conditions to a "standard" temperature change of 75 ºC (from 25 to 100).

$$SC^T{}_c = \frac{f_{cd}}{P_{cf} - P} * \frac{75}{T_{cf} - T_{ci}}$$

FP_c – Firepower: This is a ratio of the fuel energy consumed by the stove per unit time. It tells the average power output of the stove (in Watts) during the high-power test.

$$FP_c = \frac{f_{cd} * LHV}{60 * (t_{ci} - t_{cf})}$$

Note, by using f_{cd} in this calculation, both the remaining char and the fuelwood moisture content have been accounted for.

High power test (hot start)

In this test, measurements and calculations are identical to the cold start test. Simply substitute the subscript ‘h’ for the subscript ‘c’ in each variable as in the table below.

Variables that are directly measured

f_{hi}	Weight of fuel before test (grams)
P_{hi}	Weight of Pot with water before test (grams)
T_{hi}	Water temperature before test (ºC)
t_{hi}	Time at start of test (min)
f_{hf}	Weight of fuel after test (grams)
c_h	Weight of charcoal and container after test (grams)
P_{hf}	Weight of Pot with water after test (grams)
T_{hf}	Water temperature after test (ºC)
t_{hf}	Time at end of test (min)

Variables that are calculated

f_{hm}	Fuel consumed, moist (grams)	$f_{hm} = f_{hf} - f_{hi}$
Δc_h	Net change in char during test phase (grams)	$\Delta c_h = c_h - k$
f_{hd}	Equivalent dry fuel consumed (grams)	$f_{hd} = f_{hm} * (1 - (1.12 * m)) - 1.5 * \Delta c_h$
w_{hv}	Water vaporized (grams)	$w_{hv} = P_{hi} - P_{hf}$
w_{hr}	Water remaining at end of test (grams)	$w_{hr} = P_{hf} - P$
Δt_h	Duration of phase (min)	$\Delta t_h = t_{hf} - t_{hi}$
h_h	Thermal efficiency	$h_h = \frac{4.186 * (P_{hi} - P) * (T_{hf} - T_{hi}) + 2260 * (w_{hv})}{f_{hd} * LHV}$
r_{hb}	Burning rate (grams/min)	$r_{hb} = \frac{f_{hd}}{t_{hi} - t_{hf}}$

SC_h	Specific fuel consumption (grams fuel/grams water)	$SC_h = \frac{f_{hd}}{P_{hf} - P}$
$SC^T{}_h$	Temp-corrected specific consumption (grams fuel/grams water)	$SC^T{}_h = \frac{f_{hd}}{P_{hf} - P} * \frac{75}{T_{hf} - T_{hi}}$
FP_h	Firepower (W)	$FP_h = \frac{f_{hd} * LHV}{60 * (t_{hi} - t_{hf})}$

Low power (simmering) test

Variables that are directly measured

f_{si} Weight of unused fuel when the water first boils (grams)

P_{si} Weight of Pot with water when the water first boils (grams)

T_{si} Water temperature at boiling ($T_{si} = T_b$) (ºC)

t_{si} Time at start of simmer phase test (min)

f_{sf} Weight of unburned fuelwood remaining after test (grams)

c_s Weight of charcoal and container after test (grams)

P_{sf} Weight of Pot with water after test (grams)

T_{sf} Water temperature at end of test (ºC)

t_{sf} Time at end of test (min)

Variables that are calculated

f_{sm}	Fuelwood consumed, moist (grams)	$f_{sm} = f_{sf} - f_{si}$
Δc_s	Net change in char during test phase (grams)	$\Delta c_s = c_s - k - \Delta c_h$
f_{sd}	Equivalent dry fuelwood consumed (grams)	$f_{sd} = f_{sm} * (1 - (1.12 * m)) - 1.5 * \Delta c_s$
w_{sv}	Water vaporized (grams)	$w_{sv} = P_{si} - P_{sf}$
w_{sr}	Water remaining at end of test (grams)	$w_{sr} = P_{sf} - P$
Δt_s	Duration of phase (min)	$\Delta t_s = t_{sf} - t_{si}$
h_s	Thermal efficiency	$h_s = \dfrac{4.186 * (P_{si} - P) * (T_{sf} - T_{si}) + 2260 * (w_{sv})}{f_{sd} * LHV}$
r_{sb}	Burning rate (grams/min)	$r_{sb} = \dfrac{f_{sd}}{t_{si} - t_{sf}}$
SC_s	Specific fuel consumption (grams fuel/grams water)	$SC_s = \dfrac{f_{sd}}{P_{sf} - P}$
FP_s	Firepower (W)	$FP_s = \dfrac{f_{sd} * LHV}{60 * (t_{si} - t_{sf})}$
TDR	Turn-down ratio	$TDR = \dfrac{FP_h}{FP_s}$

Appendix III: Test Results

SAHARA CHARCOAL STOVE

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Average	St Dev
Temp-corrected time to boil Pot # 1	min	18.8	18.8	18.8	**18.8**	0.1
Burning rate	g/min	6.6	5.9	6.8	**6.4**	0.5
Thermal efficiency	%	31.5%	27.1%	27.9%	**28.8%**	2.3%
Temp-corrected specific consumption	g/liter	67.7	57.2	69.5	**64.8**	6.6
Firepower	watts	3088.6	2751.2	3203.6	**3014.5**	235.1
2. HIGH POWER TEST (HOT START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Temp-corrected time to boil Pot # 1	min	13.4	13.5	13.2	**13.4**	0.2
Burning rate	g/min	7.0	7.1	7.8	**7.3**	0.4
Thermal efficiency	%	33.1%	34.8%	33.1%	**33.7%**	1.0%
Temp-corrected specific consumption	g/liter	48.8	51.1	54.0	**51.3**	2.6
Firepower	watts	3312.8	3342.2	3683.5	**3446.1**	206.1

TATEDO CHARCOAL STOVE

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Average	St Dev
Temp-corrected time to boil Pot # 1	min	18.8	19.8	19.4	**19.3**	0.5
Burning rate	g/min	6.2	6.2	6.3	**6.2**	0.1
Thermal efficiency	%	30.0%	29.3%	29.0%	**29.4%**	0.5%
Temp-corrected specific consumption	g/liter	60.7	64.3	64.2	**63.1**	2.1
Firepower	watts	2906.9	2901.5	2953.3	**2920.6**	28.5
2. HIGH POWER TEST (HOT START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Temp-corrected time to boil Pot # 1	min	14.0	14.1	14.3	**14.1**	0.1
Burning rate	g/min	7.3	6.3	7.4	**7.0**	0.6

Thermal efficiency	%	32.0%	36.7%	33.1%	**33.9%**	2.5%
Temp-corrected specific consumption	g/liter	53.4	45.4	56.1	**51.6**	5.6
Firepower	watts	3412.5	2941.5	3482.6	**3278.9**	294.2

KUUTE CHARCOAL STOVE

1. HIGH POWER TEST (COLD START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Temp-corrected time to boil Pot # 1	min	30.5	30.2	30.6	**30.4**	0.2
Burning rate	g/min	4.2	3.8	4.2	**4.1**	0.2
Thermal efficiency	%	33.8%	37.6%	34.3%	**35.2%**	2.1%
Temp-corrected specific consumption	g/liter	71.0	64.1	70.5	**68.5**	3.8
Firepower	watts	1980.5	1804.3	1959.0	**1914.6**	96.1
2. HIGH POWER TEST (HOT START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Temp-corrected time to boil Pot # 1	min	27.1	26.2	26.0	**26.4**	0.6
Burning rate	g/min	3.7	3.8	4.0	**3.8**	0.2
Thermal efficiency	%	42.6%	42.7%	40.9%	**42.1%**	1.0%
Temp-corrected specific consumption	g/liter	54.5	54.5	57.5	**55.5**	1.7
Firepower	watts	1725.0	1782.1	1887.4	**1798.2**	82.4

ENVOTEC FUELWOOD STOVE

1. HIGH POWER TEST (COLD START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Temp-corrected time to boil Pot # 1	min	11.1	11.1	11.5	**11.2**	0.2
Burning rate	g/min	19.0	19.2	18.4	**18.9**	0.4
Thermal efficiency	%	34.8%	34.4%	35.2%	**34.8%**	0.4%
Temp-corrected specific consumption	g/liter	85.3	86.7	85.5	**85.8**	0.8
Firepower	watts	5846.3	5904.5	5649.5	**5800.1**	133.6

2. HIGH POWER TEST (HOT START)	units	Test 1	Test 2	Test 3	Average	St Dev
Temp-corrected time to boil Pot # 1	min	7.8	8.1	8.3	**8.1**	0.3
Burning rate	g/min	25.3	23.9	23.1	**24.1**	1.1
Thermal efficiency	%	38.5%	40.1%	38.7%	**39.1%**	0.9%
Temp-corrected specific consumption	g/liter	80.7	78.9	78.2	**79.3**	1.3
Firepower	watts	7774.9	7329.7	7103.2	**7402.6**	341.7
3. LOW POWER (SIMMER)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Burning rate	g/min	9.0	9.2	9.3	**9.2**	0.1
Thermal efficiency	%	29.2%	28.6%	28.3%	**28.7%**	0.5%
Specific fuel consumption	g/liter	252.1	254.6	260.0	**255.6**	4.1
Firepower	watts	2766.1	2811.5	2849.9	**2809.2**	41.9
Turn down ratio	--	2.1	2.1	2.0	**2.1**	0.1

M&R FUELWOOD STOVE

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Average	St Dev
Temp-corrected time to boil Pot # 1	min	12.5	12.6	13.5	**12.9**	0.6
Burning rate	g/min	21.1	21.7	22.2	**21.7**	0.5
Thermal efficiency	%	26.6%	27.9%	27.6%	**27.4%**	0.7%
Temp-corrected specific consumption	g/liter	118.7	111.8	139.0	**123.2**	14.1
Firepower	watts	6864.8	6655.2	6803.1	**6774.4**	107.7
2. HIGH POWER TEST (HOT START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Temp-corrected time to boil Pot # 1	min	9.4	9.1	8.3	**8.9**	0.5
Burning rate	g/min	22.5	27.2	28.5	**26.1**	3.1
Thermal efficiency	%	33.0%	33.2%	33.8%	**33.3%**	0.4%
Temp-corrected specific consumption	g/liter	94.6	103.2	108.8	**102.2**	7.2
Firepower	watts	7311.1	8344.1	8739.7	**8131.6**	

						737.6
3. LOW POWER (SIMMER)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Burning rate	g/min	13.3	13.1	10.5	**12.3**	1.6
Thermal efficiency	%	22.6%	24.7%	22.9%	**23.4%**	1.1%
Specific fuel consumption	g/liter	539.9	445.2	429.4	**471.5**	59.8
Firepower	watts	4330.7	4017.2	3223.7	**3857.2**	570.6
Turn down ratio	--	13.3	13.1	10.5	**12.3**	1.6

OKOA-1 FUELWOOD STOVE

1. HIGH POWER TEST (COLD START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Temp-corrected time to boil Pot # 1	min	13.5	13.4	12.5	**13.2**	0.6
Burning rate	g/min	31.0	31.7	34.5	**32.4**	1.9
Thermal efficiency	%	19.6%	20.5%	18.8%	**19.6%**	0.8%
Temp-corrected specific consumption	g/liter	128.7	130.4	130.6	**129.9**	1.0
Firepower	watts	10062.0	9716.0	10586.1	**10121.4**	438.1
2. HIGH POWER TEST (HOT START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Temp-corrected time to boil Pot # 1	min	11.5	11.5	11.5	**11.5**	0.0
Burning rate	g/min	25.4	28.1	30.1	**27.8**	2.4
Thermal efficiency	%	26.3%	25.7%	24.4%	**25.5%**	1.0%
Temp-corrected specific consumption	g/liter	87.9	97.8	105.2	**97.0**	8.6
Firepower	watts	8240.5	8617.3	9238.1	**8698.6**	503.8
3. LOW POWER (SIMMER)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Burning rate	g/min	19.0	18.2	12.2	**16.4**	3.7
Thermal efficiency	%	17.7%	19.5%	22.8%	**20.0%**	2.6%
Specific fuel consumption	g/liter	426.5	410.2	241.1	**359.3**	102.6
Firepower	watts	6169.5	5585.4	3729.7	**5161.5**	

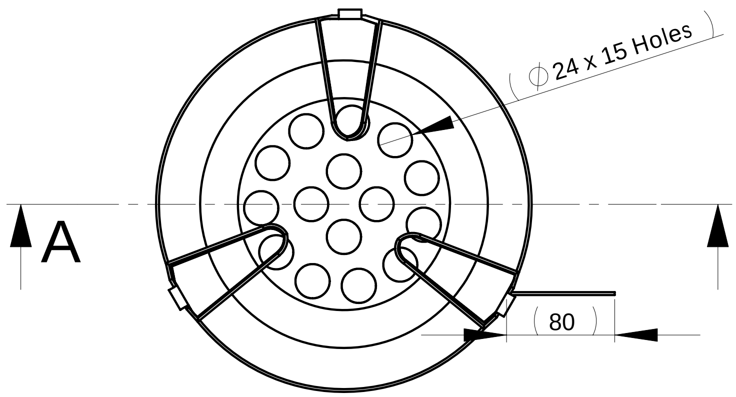
						1,273.9
Turn down ratio	--	1.6	1.7	2.8	**2.1**	0.7

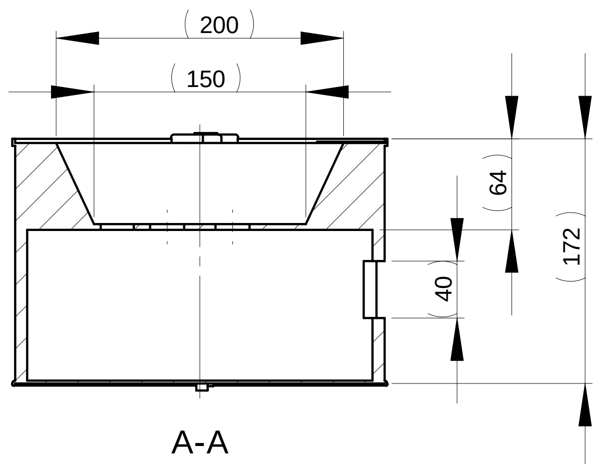
OKOA-2 FUELWOOD STOVE

1. HIGH POWER TEST (COLD START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Temp-corrected time to boil Pot # 1	min	11.5	11.5	11.5	**11.5**	0.0
Burning rate	g/min	32.8	32.5	34.0	**33.1**	0.8
Thermal efficiency	%	19.4%	22.3%	21.2%	**21.0%**	1.4%
Temp-corrected specific consumption	g/liter	118.9	119.6	125.1	**121.2**	3.4
Firepower	watts	10653.1	9985.0	10448.5	**10362.2**	342.3
2. HIGH POWER TEST (HOT START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Temp-corrected time to boil Pot # 1	min	10.4	9.4	9.4	**9.7**	0.6
Burning rate	g/min	28.6	35.2	36.9	**33.6**	4.4
Thermal efficiency	%	24.2%	23.8%	23.5%	**23.8%**	0.4%
Temp-corrected specific consumption	g/liter	94.0	104.8	110.4	**103.1**	8.3
Firepower	watts	9290.3	10811.0	11315.6	**10472.3**	1,054.3
3. LOW POWER (SIMMER)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**
Burning rate	g/min	12.7	13.5	12.4	**12.8**	0.6
Thermal efficiency	%	20.5%	20.4%	11.6%	**17.5%**	5.1%
Specific fuel consumption	g/liter	264.4	281.6	257.8	**267.9**	12.3
Firepower	watts	4124.8	4129.3	3793.4	**4015.8**	192.7
Turn down ratio	--	2.6	2.4	2.8	**2.6**	0.2

Appendix IV: Technical Drawings

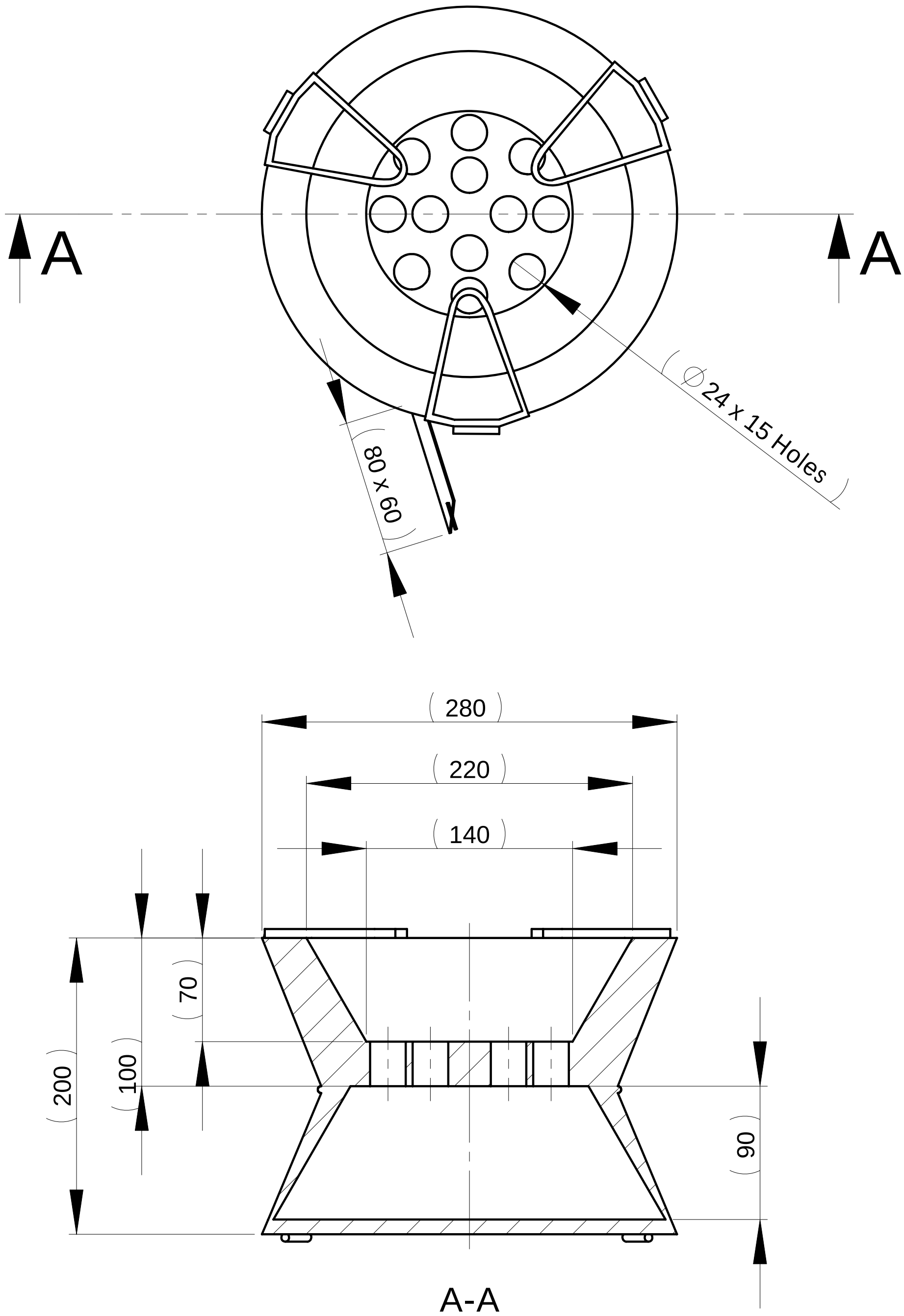
- SAHARA
- TATEDO jiko bora
- KUUTE
- ENVOTEC
- M&R
- Okoa-1
- Okoa-2





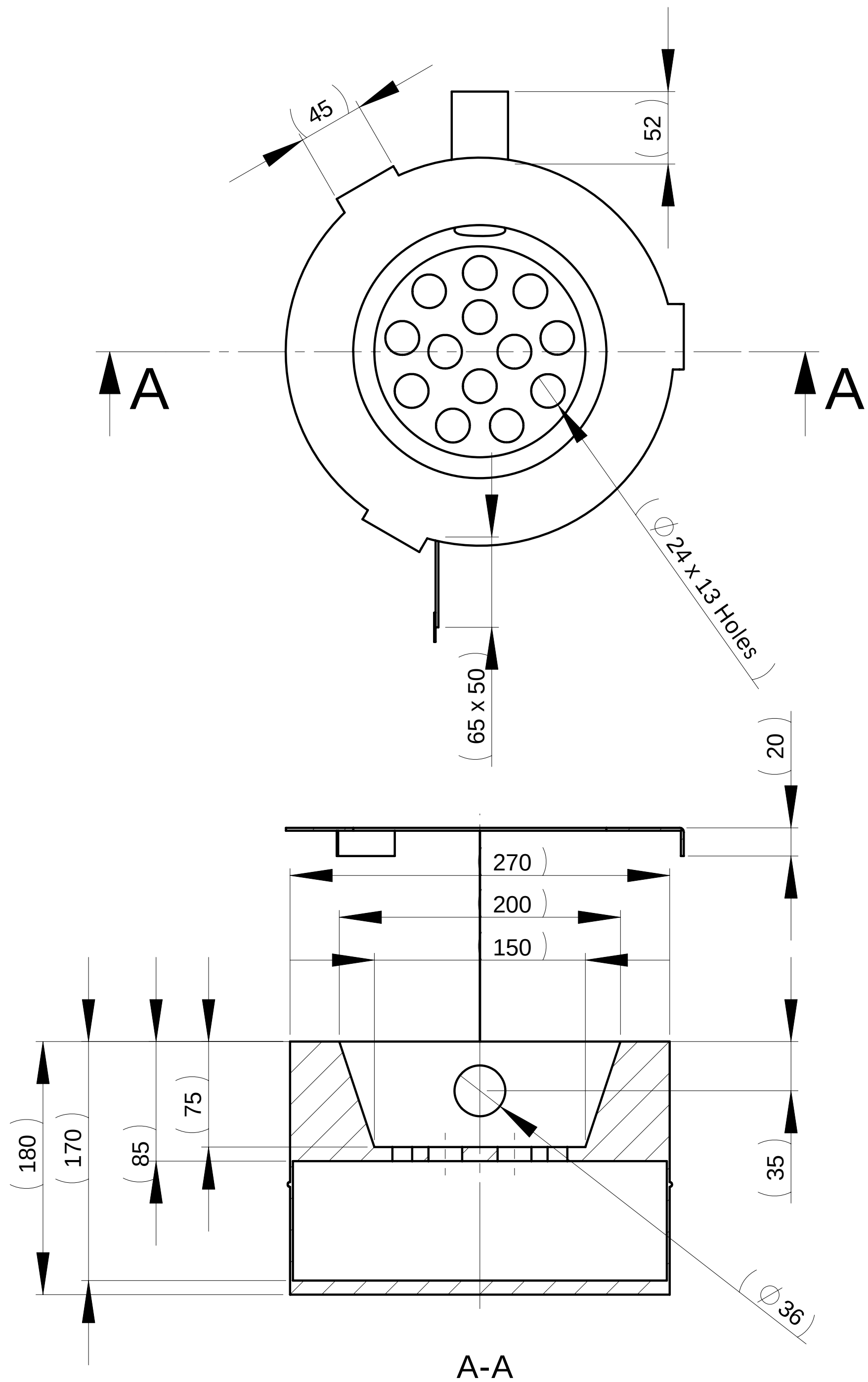
A-A

PROJECTION THIRD ANGLE	SCALE: 1:5 DIMENSION:mm	DRAWN: DR. H. M. RAJABU	REMARKS
PLACE: SEDC	SAHARA		SHEET 1 OF 1

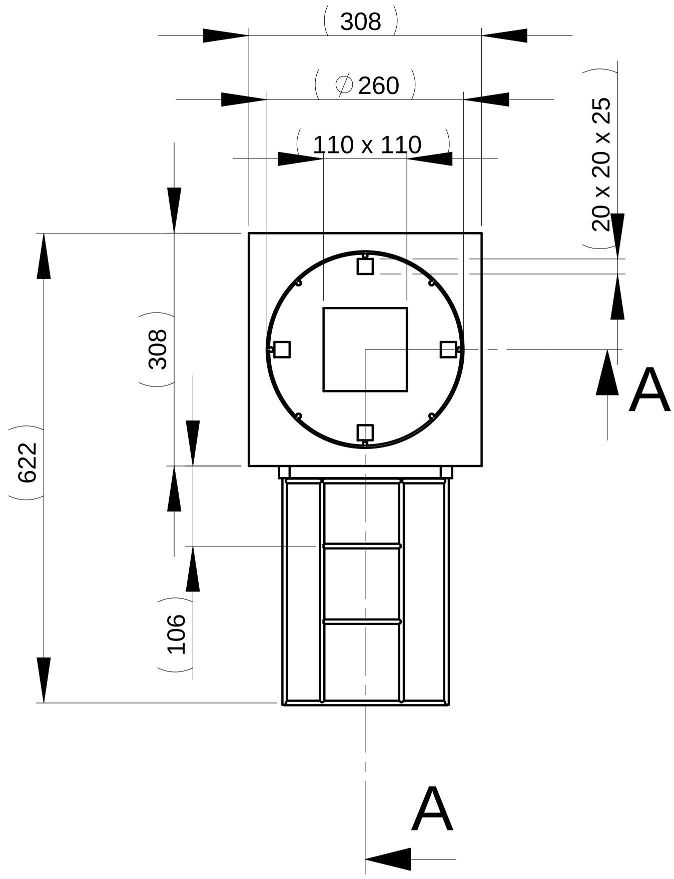


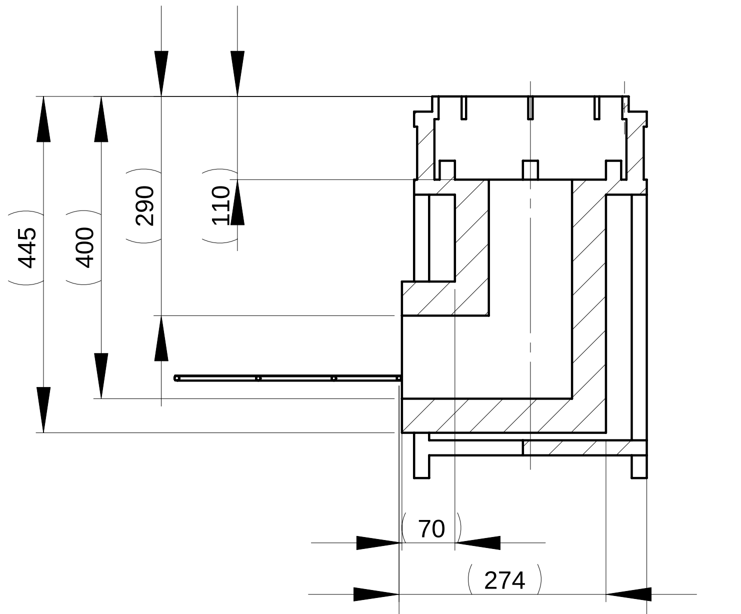
A-A

PROJECTION THIRD ANGLE	SCALE: 1:5 DIMENSION:mm	DRAWN: DR. H. M. RAJABU	REMARKS
PLACE: SEDC	TATEDO		SHEET 1 OF 1



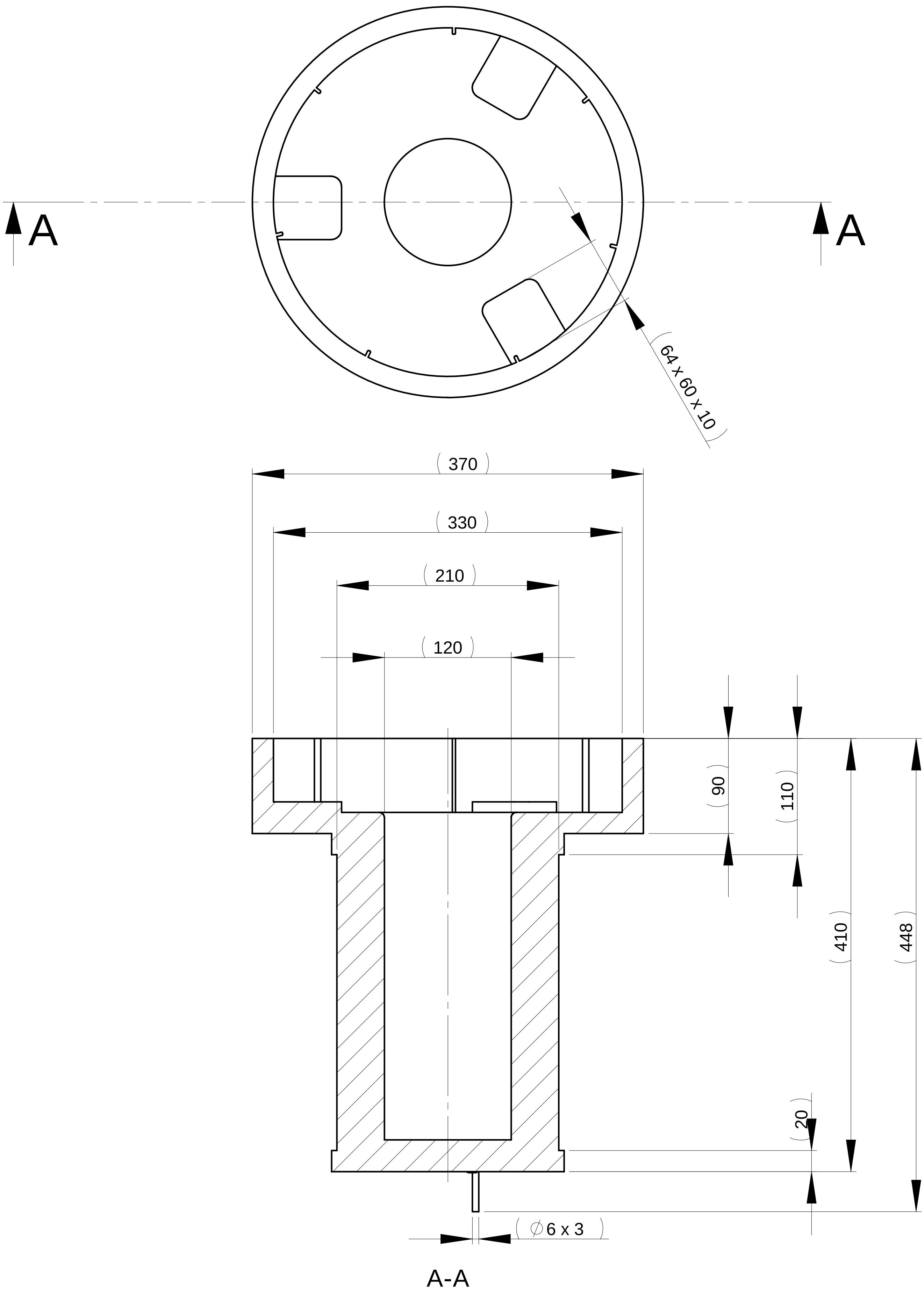
PROJECTION THIRD ANGLE	SCALE: 1:5 DIMENSION:mm	DRAWN: DR. H. M. RAJABU	REMARKS
PLACE: SEDC		KUUTE	SHEET 1 OF 1



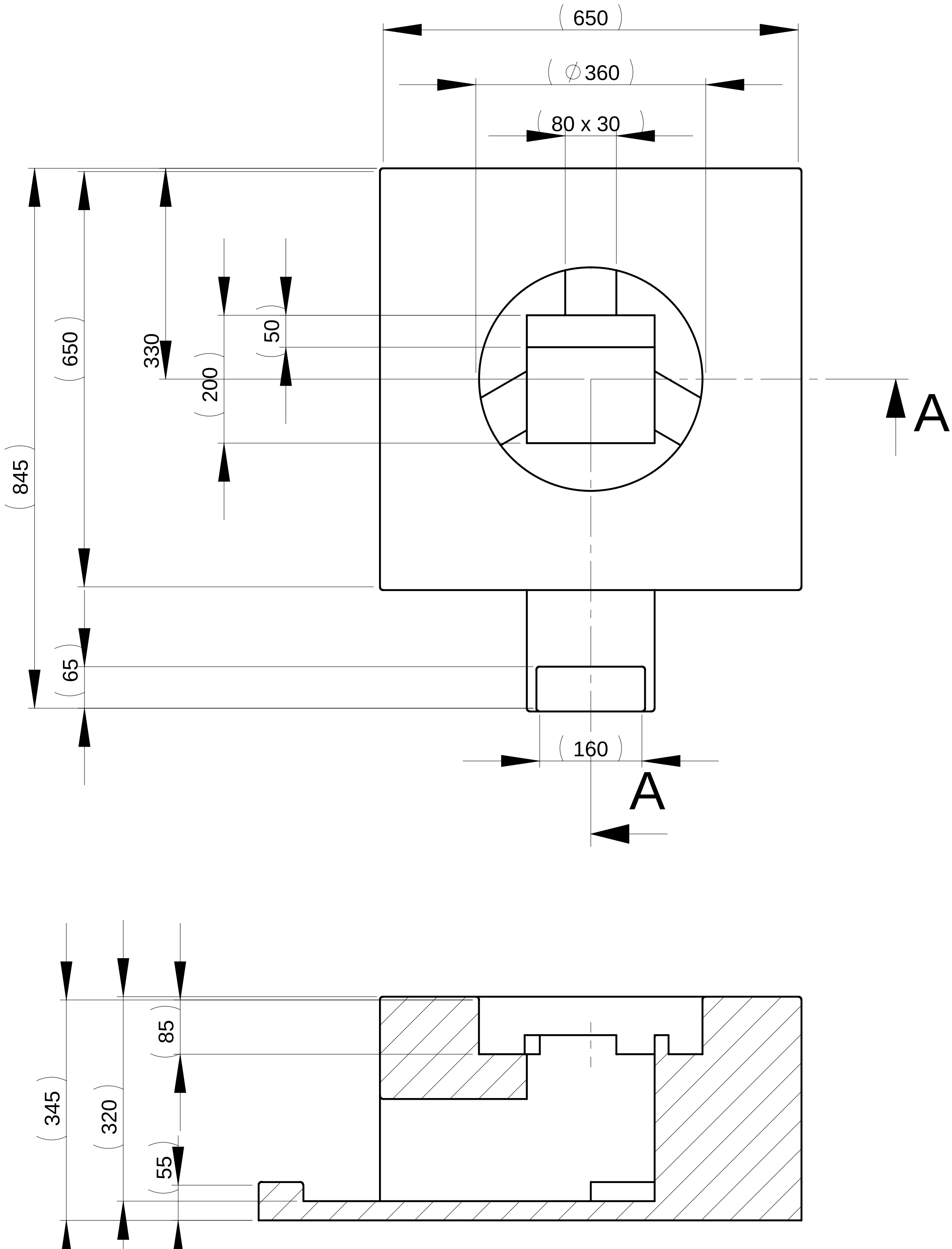


A-A

PROJECTION THIRD ANGLE	SCALE: 1:5 DIMENSION:mm	DRAWN: DR. H. M. RAJABU	REMARKS
PLACE: SEDC	ENVOTECH		SHEET 1 OF 1

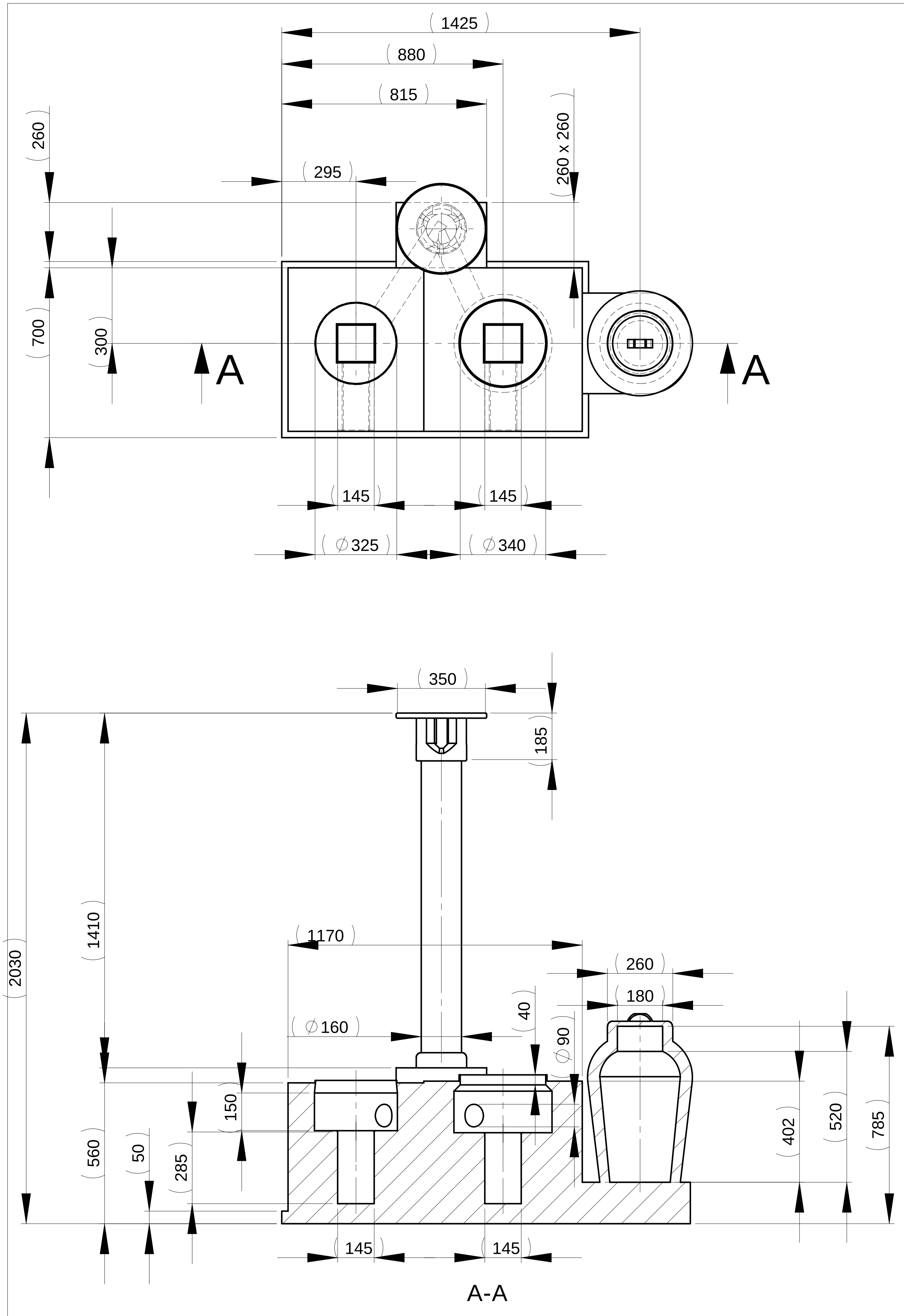


PROJECTION THIRD ANGLE	SCALE: 1:5 DIMENSION:mm	DRAWN: DR. H. M. RAJABU	REMARKS
PLACE: SEDC	M & R		SHEET 1 OF 1



A-A

PROJECTION THIRD ANGLE	SCALE: 1:10 DIMENSION:mm	DRAWN: DR. H. M. RAJABU	REMARKS
PLACE: SEDC	OKOA 1		SHEET 1 OF 1



PROJECTION THIRD ANGLE	SCALE: 1:20 DIMENSION:mm	DRAWN: DR. H. M. RAJABU	REMARKS
PLACE: SEDC	OKOA 2		SHEET 1 OF 1