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ACKNOWLEDGEMENTS. We thank the Director, Wadia Institute of Himalayan Geology (WIHG), Dehra Dun, for providing the necessary facilities. We also thank Sri Deepak Srivastava (Consultant) for discussions and valuable suggestions; Dr Rakesh Bhambri and Dr Indra Karakoti (WIHG) for help during manuscript preparation and the Department of Science and Technology, New Delhi for financial support.

Received 7 November 2013; revised accepted 18 May 2014

Thermal performance of a low-concentration ethanol stove without pressure system

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We report here the thermal performance of a new burner running on low-concentration ethanol (50°GL) without pressure system. The experimental method based on the water boiling point of water developed by Shell Foundation, consists of three phases of test used to study the performance of the stove. Test and calculation results show that the time to boil 2.5 l of water is 19.6 min in cold start and 18.4 min in hot start. The specific consumption is 25.55 g/l for the boiling task and 29.4 g/l for the simmering task. The thermal efficiency calculation of the stove is 55.75% in high power and 58.3% in simmer with a turndown ratio of 2.24. The average thermal output of the stove is from a high of 1575 W to a low of 694 W. The optimal thermal output is 694 W, with a thermal efficiency of 59%. The results show that the burner can transform gradually the low ethanol–water mixture of 50% (w/w) to a vapour of ethanol–water mixture concentration of 68.55% (w/w) in cold start, 73.71% (w/w) in hot start and 68.47% (w/w) in simmer. Improving the nature of the burner components helps improve the performance of the stove and also has an impact on its lifespan. The performance of the stove depends on the variation of the concentration of ethanol fuel during the test. The experimental study showed that the stove running on 50% v/v ethanol–water mixture is a no smoking stove, with no danger of fires.

Keywords: Burner, ethanol stove, thermal efficiency, water boiling test.

MALAGASY forest resources have been in a state of regression for several decades. The principal causes of deforestation are land clearance for agriculture, wild fires, fuelwood use for household energy, wood for construction and wood fuel for energy[1]. Forest cover constitutes less than 25% of the total land area of Madagascar. The country has already lost 80% of its natural area, and continues to lose an estimated 200,000 ha annually to deforestation. If the rate of forest reduction remains at the current level, i.e. 0.55% per annum, all of Madagascar's forests will be lost within 40 years[2]. In this context careful zoning and planning of agricultural encroachment into new areas would have to be integrated into a policy aimed at expanding sugarcane ethanol production in Madagascar

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at any scale to ensure that the appropriate balance is reached.

According to Madagascar's National Energy Policy, the country remains almost entirely dependent upon biomass fuel, which accounts for 95% of total energy consumption. This biomass comprises firewood, charcoal and crop residues. In rural households the primary source of energy is fuelwood, followed by charcoal[1]. By contrast, in urban areas charcoal is the most commonly used household fuel. Madagascan families annually consume approximately 9.026 million m^3 of wood as firewood and 8.575 million m^3 as charcoal[3]. Most of households in Madagascar cook food on the traditional charcoal stove (TCS) and the modified wood stove (MWS) based on biomass fuel. Although biomass is a renewable source of energy, traditional biomass-fired stoves like TCS and MWS cause significant greenhouse gas (GHG) emissions due to the formation of products of incomplete combustion such as particulates, carbon monoxide, nitrous oxide and sulphur oxide; also, exposure to smoke from these stoves causes serious health problems[4,5]. Statistically, the health impacts on people are related to their levels of exposure to indoor air pollution (IAP)[6,7]. The detrimental effects of smoky indoor environments have been illustrated by experimental exposure to human subjects, which caused inflammatory response and signs of increased oxidative response in the lower airways of the respiratory tract[8].

For a standard rice-cooking procedure, the research results conducted at the Aprovecho Stove Research Laboratory financed by the Tany Meva Foundation, Madagascar showed that the time needed to cook rice, for a Malagasy family size about five persons, is around of 26.38 min using the TCS, with a power input of 2.46 kW and a power output of 0.51 kW. The calculated thermal efficiency is of 20.80%. The MWS required less cooking time compared to TCS. Nevertheless, the power input is significant, 5.18 kW, in comparison with the power output of 0.82 kW. Subsequently, the thermal efficiency is very low, 15.84%. Charcoal and wood stoves may take up to 10–15 min to light, with constant tending, depending on fuel moisture[9]. Thus, Malagasy households cook food on inefficient and polluting cookstoves.

To solve these energy fuel and cooking fuel problems, clean and renewable alternatives have to be promoted. However, the cost and availability of cleaner cooking fuels such as liquefied petroleum gas (LPG) and natural gas keep them out of the reach of most Madagascan families. Besides, these fuels are non-renewable and hence present only a short-term solution. A proposed lasting solution is the used of ethanol fuel to improve the family health and decrease the immense deforestation on Madagascar land toward a clean environment and to reduce the poverty rate related to the household energy demand in Madagascar[9].

To reach this goal, an ethanol stove running on 50% ethanol–water mixture has been developed and studied. The main reasons for the choice were the following:

- The stove pollutant gas emission (GHG emissions) is very low.
- The fuel is less flammable than pure ethanol, making it safe to handle and hence ideal for household cooking purposes.
- The fuel is easy to distil and can be produced in a one-step distillation process[10,11], in rural areas of Madagascar; a substantial amount of illicit liquor production takes place in make-shift backyard and rudimentary distillation units, which produce alcohol with 40–60% (w/w) ethanol–water concentration.
- The price of a litre of ethanol will be reasonable compared to the actual charcoal and fuel-wood prices because of the low cost and abundant availability of raw materials for the production of ethanol will make it competitive with the other fuels used for cooking.
- The bagasse from the cane stalks could be reused. No wood fuel will be used to distil alcohol.

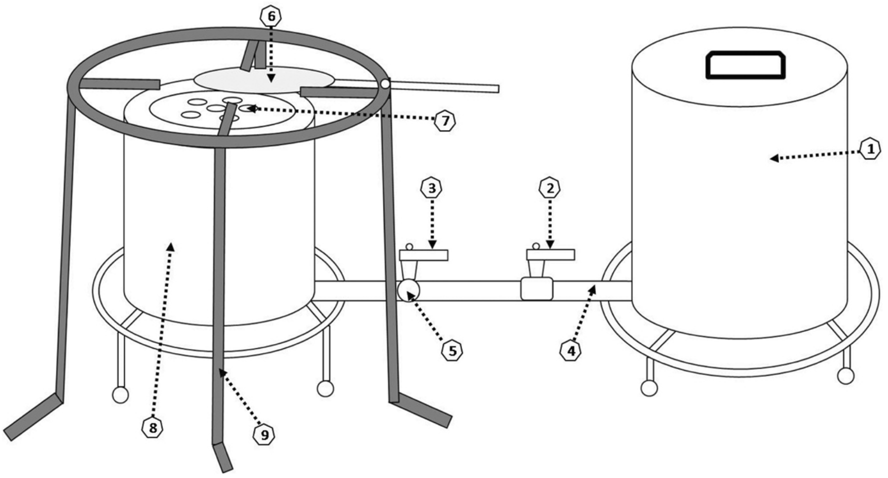
The use of this as fuel in the ethanol stove may help solve both the problems of drinking and cooking. Also, production and use of ethanol locally will create significant employment in Madagascar, through the development of a local industry in ethanol production, manufacturing of ethanol production equipment and in stoves and fuel distribution. The Malagasy agricultural land will be saved.

In the present study, a stove system has been developed, with a cylindrical burner and a tank constituting a communicating vase. The burner has a small fuel chamber and can only take a maximum of 550 ml of water–ethanol mixture. The tank is used exclusively to facilitate the replenishment of alcohol in the burner at the beginning of each phase of the test, that is, burner and the tank are not connected permanently during the test. The burner functions regardless of the tank. The thermal performance of the burner is the main part of this study.

The aim of this communication is to determine the thermal efficiency thermal output, corrected time to boil, corrected specific fuel consumption, burning rate of the burner and turn-down ratio based on the water boiling test (WBT) data calculation[12,13], in cold start, hot start and simmer test.

The ethanol stove for single pot is composed of the following (Figures 1 and 2):

- The flame controller with control settings – high power to simmer. This allowed the capacity of stove to be changed from a high to a low power.
- The cylindrical ethanol burner as a fuel tank which allows the ethanol–water to evaporate and ethanol to combust. The burner is designed so that the water in the ethanol converts into steam. The resulting flame is



Part	Component
1	Fuel tank
2	Fuel regulating valve
3	Residual output valve
4	Fuel tubing
5	Residual output
6	Flame controller
7	Flame output
8	Burner
9	Cooking pot support

Figure 1. Layout of the VOAHAJA ethanol stove.

Figure 2. Flame of the VOAHAJA ethanol stove burning 50% ethanol–water mixture without pressure system.

blue in colour and has no smell. Two aluminum standard pots in the region are used during the test and have a volume of about 3.5 l with thicknesses of 5–6 mm. For each size, one should choose a standard shape (height and circumference) that is used in our area.

According to the research results conducted at the Aprovecho Stove Research Laboratory, the calculations were adapted to the Malagasy case of rice and sauce cooking. Rice is normally served with beef sauce, which is boiled meat with vegetables and onion. There were thus two major cooking tasks: preparation of the sauce, which has a number of steps and takes on average 80–98 min, and preparation of rice which takes, on average, about 35 min to cook. The time needed to cook food for a Malagasy family is related to WBT time. Also, the cooking procedure is composed of the boiling phase and the simmer phase. For this reason, the WBT[12] is used, in this study, as a method to test the performance of the stove.

WBT is a simulation of the cooking process that helps stove designers understand how much fuel is needed to complete a cooking task[12].

WBT consists of three phases that immediately follow each other.

- In the first phase, the cold-start high-power test, the tester begins with the stove at room temperature and uses a pre-weighed bundle of ethanol fuel to boil a measured quantity of water in an aluminum standard pot. The tester then replaces the boiled water with a fresh pot of cold water to perform the second phase of the test.
- The second phase, the hot-start high-power test, follows immediately after the first test while the stove is still hot. Again, the tester uses a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. Repeating the test with a hot stove helps identify differences in performance when a stove is cold and when it is hot.
- The third phase follows immediately after the second phase. Here, we determine the amount of fuel required to simmer a measured amount of water at just below boiling point for 45 min.

The same test is repeated three times using three standard cooking pots.

For every test, one weighs the amount of fuel remaining and the pot with water, and measures the concentration of fuel remaining in the burner after each phase of the test. WBT should be conducted without lids. However, lids retain heat and vapour in the pot and can complicate WBT by increasing the variability of the outcome and making it harder to compare results from different tests. If a lid is used then the amount of water evaporated and escaping is dependent on tight the lid fits the pot, and also on the fire power. If the fire power is so low that the temperature is maintained a few degrees below boiling, effectively no water vapour will escape. If the firepower is high enough so that the water boils, the escaping steam will push the lid open and escape[14]. Finally, we put a hole about 8 cm in diameter in the middle of the lid. This should have little impact on the high-power testing phase.

The tests were performed by burning the stove in a tightly closed room of volume approximated at 12 m^3 that resembled a typical size kitchen in urban areas and a room in rural areas.

The local boiling point of water is the point at which the temperature no longer rises, no matter how much heat is applied. For a given altitude h (in m), the boiling point of water may be estimated by the following formula[12]

$$T_{\text{boil}} = \left(100 - \frac{h}{300}\right). \tag{1}$$

It is important to note that the calculation of water content by volume is different than the moisture content on a wet mass basis as used in WBT calculations. Given that the density of water is 1 g/ml and the density of pure ethanol is 0.789 g/ml, moisture content on a wet basis is calculated as follows[9]

$$MC_{\text{wet}} = 100\frac{(\rho_{\text{wp}}V_{\text{wp}} + \rho_{\text{wA}}V_{\text{wA}})}{(\rho_{\text{wp}}V_{\text{wp}} + \rho_{\text{wA}}V_{\text{wA}} + \rho_{\text{E}}V_{\text{Ep}})}. \tag{2}$$

A simple energy balance for the fire, stove and cooking pot is presented in this study. The energy transferred to the water is the sum of the latent heat, sensible heat and the heat transferred away from the pot via convection conduction and radiation. This latter heat is not accounted for in the WBT calculation, but it is important: at simmering, the stove's mission is to counterbalance this heat loss, not to evaporate water from the pot. Yet, the evaporation of water, rather than the heat loss from the pot, is measured. This mismatch between the measured quantity and the desired service also occurs during the high-power, water-heating tests, but the impact is not as great.

For the high-power test, the thermal efficiency of the stove, in cold start or in hot start, is calculated by the formula

$$\eta_{\text{HP}} = \frac{\Delta E_{\text{H}_2\text{O,HP}}}{E_{\text{released, HP}}}, \tag{3}$$

where $\Delta E_{\text{H}_2\text{O,HP}}$ is the sensible heat required to bring the water to boil and the latent heat to vaporize the steam.

$$\Delta E_{\text{H}_2\text{O, HP}} = m_{\text{H}_2\text{O, HP}, i}C_{\text{p}}(T_{\text{boil}} - T_{\text{H}_2\text{O}, i}) + m_{\text{H}_2\text{O, HP, vap}}\Delta h_{\text{H}_2\text{O, fg}}. \tag{4}$$

And $E_{\text{released,HP}}$ is the energy released by the fuel during the test[9]

$$E_{\text{released,HP}} = m_{\text{fuel, dry, HP}}\text{LHV}. \tag{5}$$

The fuel used had a lower heating value (LHV) of 26.7 mJ/kg (ref. 12).

The equivalent dry fuel consumed adjusts the amount of fuel that was burned in order to account for two factors: the energy needed to remove the moisture in the fuel and the amount of fuel remaining unburned. During the high-power test, $m_{\text{fuel,dry, HP}}$ is calculated by

$$m_{\text{fuel,dry,HP}} = m_{\text{fuel,wet,HP}}(1 - MC_{\text{wet}}) - \frac{MC_{\text{wet}}m_{\text{fuel,wet,HP}}(4.186(T_{\text{boil}} - T_{\text{fuel},i}) + L_{\text{V}})}{\text{LHV}}. \tag{6}$$

The time to boil the pot is the difference between start and finish times

$$\Delta t_{\text{HP}} = t_{\text{HP},f} - t_{\text{HP},i}. \tag{7}$$

The temperature-corrected time to boil the pot is the same as above, but adjusts the result to a standard 75°C temperature change (25–100°C). This adjustment standardizes the results and facilitates a comparison between tests that may have used water with higher or lower initial temperatures.

$$\Delta t_{\text{HP}}^{T} = 75\frac{t_{\text{HP},f} - t_{\text{HP},i}}{T_{\text{HP},f} - T_{\text{HP},i}}. \tag{8}$$

The burning rate 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.

$$R_{\text{b,HP}} = \frac{m_{\text{fuel, dry, HP}}}{\Delta t_{\text{HP}}}. \tag{9}$$

Specific consumption can be defined for any number of cooking tasks and should be considered as 'the fuel required to produce a unit output', whether the output is boiled water, cooked beans, or loaves of bread. In the case of the cold-start high-power WBT, it is a measure of the amount of fuel required to produce 1 litre (or kilogram) of boiling water starting with a cold stove. It is calculated as

$$SC_{\text{HP}} = \frac{m_{\text{fuel, dry, HP}}}{m_{\text{H}_2\text{O, HP}, i}}. \tag{10}$$

The temperature-corrected specific fuel consumption corrects specific consumption to account for differences in initial water temperature. 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°C (25–100°C). It is calculated in the following way.

$$SC_{\mathrm{HP}}^{\mathrm{T}} = SC_{\mathrm{HP}} \frac{75}{T_{\mathrm{HP},f} - T_{\mathrm{HP},i}}. \tag{11}$$

The fire power is a ratio of the fuel energy consumed by the stove per unit time. It gives the average power output of the stove (in W) during the high-power test.

$$FP_{\mathrm{HP}} = \frac{m_{\mathrm{fuel,\,dry,\,HP}} \mathrm{LHV}}{60 \Delta t_{\mathrm{HP}}}. \tag{12}$$

In the low-power test (simmer test), the temperatures vary up and down, but we must vigilantly try to keep the simmering water as close as possible to 3°C below the local boiling point; the test is invalid if the temperature in the pot drops more than 6°C below the local boiling temperature.

The initial measurements are the same as in the high-power tests; however, the goal of this test is to maintain water at a high temperature with minimal power output from the stove. The turn-down ratio is calculated by

$$\mathrm{TDR} = \frac{\mathrm{FP_h}}{\mathrm{FP_s}}, \tag{13}$$

where $\mathrm{FP_h}$ is the fire power during the high-power phase, hot start and $\mathrm{FP_s}$ is the fire power during the simmer test.

A summary of results from the WBT protocols is given in Tables 1–3. The test is designed to yield several quantitative outputs which are a good predictor of stove performance. The outputs are:

- time to boil (adjusted for starting temperature);
- burning rate (adjusted for starting temperature);
- specific fuel consumption (adjusted for starting temperature);
- fire power;
- turn-down ratio (ratio of the stove's high-power output to its low-power output);
- thermal efficiency.

The average time to boil 2.5 l of water during the high-power phase is 18.75 min, around of 7.5 min/l (Tables 1 and 2). There is a significant difference between the time taken to boil water during cold and hot start which is 1.2 min. This difference is not important within the recorded standard deviation ± 0.6 STD. The coefficient of variation (COV) is 1% and 1.71% for the cold and hot start respectively.

Specific fuel consumption is a function of the thermal efficiency and the fire power levels at which the stove is operated during the cooking period. The WBT shows a specific consumption of 25.55 g/l for the boiling task; and 29.4 g/l for the simmering task (Table 3). This is because the stove was performing two different tasks (bringing water to a quick boil and maintaining a simmer for 45 min). The specific consumption measures have a higher COV of 3.32%.

During the hot start test, the water boils more quickly in 18.4 min (Table 2). The cold water is put directly in the hot pot. This reduces the time to boil water. Besides, the stove is still hot and the fuel is preheated. The ethanol in the fuel evaporates more quickly, and it entails a fast reduction of its concentration in relation to the cold start. The thermal efficiency in hot start is only 57.1% (Table 2). This marks the difference between the two thermal efficiencies in cold and hot start.

To keep the water simmering at 3–6°C below boiling, it was necessary to set the flame control at a minimum position. The output of the flame is almost closed. This reduces the surface of the pot reached by the flame and the average temperature of the fuel surface (84.6°C)[15,16] which allows the evaporation of a certain quantity of fuel into the burner to a more elevated concentration (73.71%). Therefore, the power delivered by the burner reduces nearly to half (Table 3). The average water temperature during the simmering test is 92.4°C (± 0.30 STD, 0.33% COV) with an equivalent thermal efficiency of 58.3%.

Values shown in Tables 1–3 present the accuracy of the test during the measurements. COV is not superior to 5.97% for all results.

Table 4 shows the specification details of the ethanol stove. The stove can be operated for a continuous period of 40–60 min without further fuel tank filling and 2–3 h if the fuel tank (Figure 1 *a*) is filled. After 1–2 h of combustion, the remaining water in the burner must be evacuated toward the outside while closing the valve connecting the tank and the burner. During this time, the flame is not disrupted but the height of flame decreases.

A minimum of 35% (w/w) ethanol in the solution can be utilized in the stove. However, the stove gives best results in terms of ease of use and performance with ethanol concentrations ranging from 45% to 50%.

The efficiency (54.4–58.3%) of the ethanol stove can be increased with increasing cylindrical circumference because of the characteristic of the two-cylindrical ethanol burner which allows the ethanol into the mixture to evaporate and to combust. This system is equivalent to the principle of distillation in continuous rectification to separate the water–ethanol mixture. However, this phenomenon occurs in the burner and the combustion of the evaporated ethanol is on the free surface of the mixture.

The combustion is full but the energy lost through the lateral partition of the burner is greater. A part of the heat released by ethanol used to evaporate water in the fuel which does not take part in the combustion process is

Table 1. Results from the water boiling test, high power (cold start)

High power test (cold start)	Units	Average	SD	COV (%)
Time to boil pot	min	19.2	0.6	3.25
Temperature-corrected time to boil pot	min	19.6	0.2	1.00
Burning rate	g/min	3.3	0.0	0.77
Thermal efficiency	%	54.4	1.4	2.67
Specific fuel consumption	g/l	25.3	0.7	2.60
Temperature-corrected specific consumption	g/l	25.7	0.1	0.37
Temperature-corrected specific energy consumption	J/l	9.5	0.5	5.71
Firepower	W	1464.2	11.3	0.77

SD, Standard deviation; COV, Coefficient of variation.

Table 2. Results from the water boiling test, high power (hot start)

High power test (hot start)	Units	Average	SD	COV (%)
Time to boil pot	min	18.3	0.6	3.41
Temperature-corrected time to boil pot	min	18.4	0.3	1.71
Burning rate	g/min	3.5	0.0	0.55
Thermal efficiency	%	57.1	0.3	0.50
Specific fuel consumption	g/l	25.8	0.9	3.32
Temperature-corrected specific consumption	g/l	25.9	0.4	1.70
Temperature-corrected specific energy consumption	J/l	8.1	0.2	2.91
Firepower	W	1567.7	8.6	0.55

Table 3. Results from the water boiling test, low power (simmering test)

Low power (simmer)	Units	Average	SD	COV (%)
Burning rate	g/min	1.6	0.0	1.21
Thermal efficiency	%	58.3	0.6	1.04
Specific fuel consumption	g/l	29.4	0.3	0.91
Temperature-corrected specific energy consumption	J/l	10.9	0.7	5.97
Firepower	W	701	8.5	1.21
Turn-down ratio	–	2.24	0.0	1.34

Table 4. Stove specification

Item	Specification
Design stove capacity	694–1575 W (or turn-down ratio of 2.24)
Efficiency	54.4–59%
Design fuel composition	50% (w/w) ethanol–water mixture
Tested fuel composition	50% (w/w) ethanol–water mixture
Minimum fuel composition that can be used in the stove	35% ethanol–water mixture
Fuel tank capacity	Small tank – 2 l, big tank – 10 l
Fuel tank operating pressure	0 kPa
Overall dimensions	44 × 16 × 21 cm
Weight	2.1 kg (empty) and 16.1 kg (filled)
Construction materials	Mainly stainless steel
Estimated mass production cost	US$ 15–30 per stove

lowest as the evaporated water quantity is smallest. The maximum part of heat released by ethanol is used to boil the water in the cooking pot during the test.

In the present study, the stove performed the simmer task in which the optimal power of the stove was 694 W which corresponds to a thermal efficiency of 59%, calculated using eq. (12). The burning rate of the stove was 3.4 g/min at high power and 1.6 g/min at low power. The model of the stove used in the pilot study has one burner which provides a maximum of 1575 W power output. This is related to the heat output of a typical LP gas burner, 1500 to 2000 W (refs 13, 14).

The calculation of power output of the stove depends on the total quantity of dry fuel during the test (WBT calculation) for pure ethanol[14]. However, the real power output of the stove running on 50% (w/w) ethanol–water mixture is a decreasing function of the burning time because of the reduction in the rate of ethanol in the mixture during the combustion. This has an influence on the thermal efficiency.

Conversely, the thickness and nature of vessel walls of the burner have a significant influence on burner performance. The change of wall thickness increases the burning time and thermal efficiency. The pollutant gas emission (CO, CO_2,…) decreases. Improving the nature of the stove components helps improve the performance of the stove and also has an impact on its lifespan.

Besides, the nature of the cooking pots will change the thermal efficiency of the stove. In that case, the heat transfer between the flame and the bottom part of the pot increases with the cooking pot conductivity. The thermal efficiency is enhanced. This marks a drop of the GHG emission.

For each phase of the test, the concentration of the unburned fuel is measured. The difference between the initial and final concentrations of the fuel is presented in Table 5. The concentration of the fuel burned is also calculated (Table 6).

Table 5 shows the burner performance. The final concentration of the ethanol–water mixture after boiling task of 2.5 l of water is 44.4°GL in high power. The decrease of the ethanol–water mixture concentration during the WBT in high power is 5.6°GL and at simmer 6.28°GL (Table 5). Thermal efficiency is influenced by the variation in concentration. The thermal efficiency of the stove is an increasing function of the concentration of the unburned fuel. The performance of the stove depends on the variation in concentration of the fuel during the test.

Experimental measures show that the flame burns even though the concentration of the ethanol–water mixture inside the burner is greater than 15–20°GL. Consequently, the acceptable maximal diminution of the concentration during the phase of the test for the stove is 30–35°GL. Beyond this value, the burner does not perform.

Table 5. Variation in the concentration of fuel during each phase of the test

Test phase	Average	SD	COV
High power test (cold start, °GL)	5.22	0.19	3.69
High power test (hot start, °GL)	6.00	0.33	5.56
Low power (simmer, °GL)	6.28	0.42	6.68

Table 6. Concentration of the fuel burned

Test phase	Average	SD	COV
High power test (cold start, °GL)	68.55	2.89	4.22
High power test (hot start, °GL)	73.71	1.23	1.67
Low power (simmer, °GL)	68.47	2.76	4.03

The results show that the burner can transform gradually the low ethanol–water mixture of 50% (w/w) to a vapour of ethanol–water mixture concentration of 68.55% (w/w) in cold start, 73.71% (w/w) in hot start and 68.47% (w/w) in simmer, to combust after evaporation and the alcohol–water mixture fuel burns with a clean blue flame (Table 6). In this case, the combustion of the ethanol is full.

The security analysis conducted at the National Center of Industrial and Technological Research Laboratory of the Malagasy Scientific Research Ministry is summarized in Table 7.

The stove must be located so as to avoid the movement of the fuel in the burner that mechanically extinguishes the flame. This process permits the burner to be thermally steady and secure. Therefore, the use of this stove reduces the risk of fire that frequently occurs in certain rural areas in Madagascar.

The mixture of ethanol–water at 50% v/v is not corrosive because of its elevated water content by volume. This mixture ignites with difficulty to air pressure because its ignition temperature is higher. It needs a very large surface with a specific condition of ignition to light freely. If there is a flame on the free surface, it dies out quickly.

Experience showed that when one opens the output valve of the stove, two cases occur:

– Once the valve connecting the tank and the burner is open, the fuels coming from the burner and the tank move toward the exit through the output valve. During this time, the flame of the burner is lit again. The volume of the fuel in the burner decreases and the flame dies out automatically when the minimal level required for the fuel in the burner is surpassed because of the insufficiency of air inside the burner. Also, the flame could not propagate in the tube joining the burner and the output valve due to the absence of air necessary for the combustion of ethanol.
– The output valve is closed, when the level of the fuel goes up considerably until 4 cm of the superior side of the burner. The flame dies out automatically because there is no entry for air anymore. However, the fuel overflows outside the burner without the flame.

While shaking the burner, the movement of fuel destabilizes the ethanol combustion. The temperature of the superior layer of the fuel changes suddenly because turbulence permits mixing of fuel of the cold bottom part and the hot superior part of the burner. The gradient of temperature through the fuel is equal to zero. This phenomenon reduces the temperature of the free surface of the fuel. In this case, the ignition temperature is insufficient and evaporation of the volatile component stops. The height of the flame decreases and the flame is locked inside the combustion chamber. Circulation of the

Table 7. Security analysis of the stove

Category	Notes	Observation
Stability	Satisfying	Detachable (tank and burner in two parts)
Ergonomics	Good	Portability: simple, removable, light, Design: presentable
Insulation	Satisfying	Without system of thermal insulation, the surroundings of the stove vessel is very hot
Finish	Medium	Tubing joining burner and fuel tank prepared from plumbing 21/27 (nipple, floodgate of stop in *t*-square) not proportioned in relation to the whole
Ignition time	Good	Easy by preheating with ethanol concentration more than 70°GL, using a flame aspiration cylinder
Power regulation	Satisfying	No regulating of debit (invariable, unique debit)
Turn-off	Good	Easy using a removable horizontal valve to the superior part of the burner (two positions: open, close)
Capacity of the filled tank	Good	Small tank of 2 l, big tank of 10 l
Practicability	Very good	Loading at will (in continuous) in full cooking
Durability	Good	Construction materials: stainless steel, lifespan: about 6 years

combustion air is disrupted; and the combustion stops and the flame dies out. The same occurs for a slanted burner as well.

One can conclude that the risk fire does not exist for this type of burner and fuel.

A practical stove running on 50% (w/w) ethanol–water mixture without pressure system has been developed. WBT protocol is used to manage the performance of the burner in the laboratory. The flame is controllable and the optimal capacity of the stove is 694 W, with a thermal efficiency of 59% in cold start and TDR of 2.24. The maximal capacity of the burner is of 1575 W. WBT showed a fire power of 701 W and a specific consumption of 29.4 g/l at simmer. One litre of water will boil in 7.5 min. The burner can transform the ethanol–water mixture of 50% to a vapour of ethanol–water mixture of 73.7% (w/w) in high power. The performance and the security of the stove have been evaluated. The influence of thickness and nature of the vessels of the burner and of the cooking pot have also been analysed.

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ACKNOWLEDGEMENTS. I thank Pr. B. O. A. Ramamonijisoa (LAPAUF, University of Fianarantsoa), Dr A. Ravoninjatovo (CNRIT, National Laboratory of Madagascar) for technical support. I also thank referees for providing useful suggestions.

Received 6 November 2013; revised accepted 30 April 2014