HYDROUS ETHANOL AS A RENEWABLE HOUSEHOLD FUEL FOR LOW-INCOME COUNTRY : CASE STUDY FOR MADAGASCAR

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***Abstract*— 98 % of Malagasy population depend on household solid fuels as their primary cooking fuel. To improve the quality of life of such a large number of people, it is imperative that clean and renewable alternatives are provided for cooking. Low concentration ethanol fuel is considered cleaner because of its inherent characteristics of low pollutant formation and emissions during handling and use. The fuel is easy to distil and can be produced locally. Based on the Water Boiling Test protocol, this paper presents the performance, the safety analysis of the stove, the field tests and policy issues.**

Calculation method showed that the rate of principal pollutant gases such as carbon dioxide and carbon monoxide emission are very low. The greenhouse gas emission and stove capacity increase with increasing ethanol concentrations. The stove gives best results in terms of ease of use and performance with ethanol concentrations ranging from 50 to 75% (v/v).

***Keywords*— Low concentration ethanol, greenhouse, carbon dioxide, thermal efficiency, cooking fuel.**

I. INTRODUCTION

Gaseous fuels like biogas, solid fuels like charcoal and liquid fuels like biodiesel and ethanol are some of the clean and renewable fuels for cooking. However, due to their high energy density, easy transportability, easy storage and local accessibility, the liquid fuels are superior to other renewable alternatives. Most of Malagasy population depends on some form or other of biomass fuels to fulfill its energy requirements. The usually solid fuels like charcoal have been extensively explored as a cooking fuel option. High viscosity, tendency of gumming and formation of soot are problematic. The absence of these drawbacks in ethanol makes it a more attractive possibility.

To solve the 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 use of ethanol fuel to improve the family health (UNHCR, 2013; ITDG, 2004; Battacharya *et al*., 2002; Arimah and Ebohon, 2000) and decrease the actual immense deforestation on Madagascar land toward a clean environment and to reduce the poverty rate related to the household energy demand in Madagascar (Gaia Association, 2010). The culture of the raw materials for the ethanol production is still possible because the exploitable plantation area is enormous. This culture don't entail a deforestation, but the Malagasy land and forest will be protected. To reach this goal, an ethanol stove running on 40 to 94 % 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 low, the fuel is less flammable than pure ethanol, making it safe to handle and hence ideal for household cooking purposes, the other safeties are important, the fuel is easy to distil and can be produced in a one-step distillation process (Vorayos et al., 2006; Rajvanshi et al., 2007), 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 % (v/v) ethanol-water concentration, the price per liter of alcohol will be reasonably than 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 very competitive with the other fuels used for cooking, the bagasse from the cane stalks could be reused instead. No wood fuel will be used to distill alcohol. Due to the extremely low value (4.3 %) of the lower limit of inflammability, the use of pure ethanol for household purposes is dangerous. This problem can be surmount by the use of ethanol mixtures in a suitably designed stove. Tests done at CNRIT (National Centre of Industrial and Technology Research Laboratory of Madagascar) in 2011 showed that 50 -75% (v/v) ethanol-water mixture was a good cooking fuel. The use of this as fuel in the ethanol stove can hopefully help solve both the problems of drinking and cooking. Ethanol, which is rare in domestic use, has the attractive quality of being derived from renewable sources (bio-ethanol) (Bizzo *et al*., 2004; Andrianantenaina, 2014). 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 agriculture land will be saved.

Controlling pollution emission rates from household energy use is one of the most effective ways of ensuring cleaner air in the home, as this addresses the problem at source for the nearly 3 billion of the world's poorest people who still rely on solid fuels (wood, animal dung, charcoal, crop wastes and coal) burned in inefficient and highly polluting stoves for cooking and space heating. The resulting household air pollution (HAP) led to more than 4 million premature deaths among children and adults in 2012 (WHO, 2014). Statistically, the health impacts on people are related to their levels of exposure to indoor air pollution (IAP) (UNHCR , 2013; Battacharya *et al*., 2002). Of the 4.3 million people who die annually from exposure to household air pollutants, most perish from stroke (34%), ischaemic heart disease (26%) and chronic obstructive pulmonary disease (22%). Pneumonia and lung cancer account for 12% and 6% of deaths, respectively (Barregard *et al.*, 2008; WHO, 2014).

Household survey in the work of Metha *et al.* (2006) showed that nearly 98 % of Malagasy population depends on household solid fuels to fulfill its energy requirements. 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 emissions due to formation of products of incomplete combustion such as particulates, carbon monoxide, carbon dioxide, nitrous oxide and sulphur oxide; also, exposure to smoke from these stoves causes serious health problems (IRG, 2005; WWF, 2007; NISM, 2007; ITDG, 2004; Arimah and Ebohon, 2000). In rural households the primary source of energy is fuelwood, followed by charcoal (IRG, 2005). By contrast, in urban areas charcoal is the most commonly used household fuel

To solve the health problems due to the household air pollution, we proposed in this survey to develop a low concentration ethanol stove. The aim of this paper is to determine the thermal efficiency, the carbon dioxide emissions of the stove in maximum and minimum capacity of the stove respectively, to analyze the security and the performance of the stove. Moreover, the Water Boiling Test (WBT) protocol has been adopted to test the stove.

II. ETHANOL STOVE SPECIFICATION

The ethanol stove has been described in our previous work (Andrianantenaina, 2014). The ethanol stove for single pot is composed of (Fig. 1): The cylindrical ethanol burner (Part no. 8) which permitted the ethanol-water to evaporate and ethanol to combust. The burner is designed so that the water in the ethanol converts into vapor. The flame controller (Part no.6) allowed the capacity of stove to be changed from a high to a low power. A fuel regulating valve (Part no.2) has been required to stop fuel from the fuel tank (Part no. 1) toward the cylindrical ethanol burner during the evacuation of the residual water from the burner (Part no. 8) to the exit (Part no. 5).

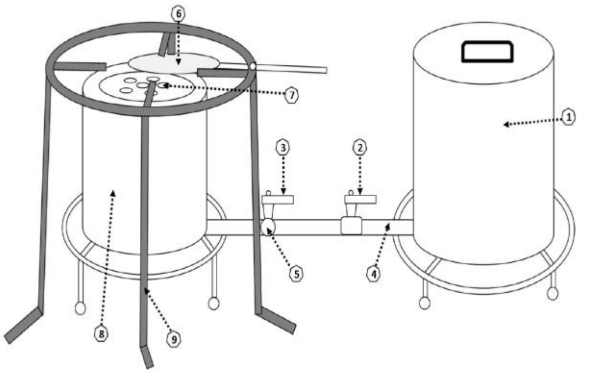

Figure 1. Layout of the "VOAHAJA N°1" ethanol stove (Andrianantenaina, 2014). Parts: 1) Fuel tank, 2) Fuel regulating-valve, 3) Residual output-valve, 4) Fuel tubing, 5) Residual output, 6) Flame controller, 7) Flame output, 8) Burner, 9) Cooking pot support.

However, the stove without fuel tank (Part no. 1) has been studied in this survey. The fuel tank has been disconnected during the tests. Only the fuel that can contain the burner has been used for every test.

The specification details of the ethanol stove in this work according to the research results conducted at the CNRIT are: the design stove capacity ranging from 560 to 1100 W, the thermal efficiency of 35 to 46%, the design fuel composition of 50-75 % (v/v) ethanol-water mixture, the tested fuel composition of 40-94 % (v/v) ethanol-water mixture, the minimum fuel composition that can be used in the stove of 35 % ethanol-water mixture.

III. TESTING METHOD

The Water Boiling Test (WBT) intends to be a simulation of the cooking process that helps stove designers understand how much fuel is needed to complete a cooking task (IRG, 2005; WWF, 2007). During the WBT, the same test is repeated five times using a standard cooking pot. According to the research results conducted at the CNRIT, the calculations were adapted to the Malagasy case of rice and sauce cooking. The time needed to cook food for a Malagasy family is related to the Water Boiling Test time. Also, the cooking procedure is composed of the boiling phase and simmer phase during 40 minutes.

The protocol test consists of three phases: the phase of preparation or before cooking, the phase of cooking and the after cooking.

- In the first phase, 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 second phase, phase of cooking, consists in making some measures of the water temperature increasing in the equipment of cooking and the flame temperature elevation under the pot.

  It is also in this phase that one can appreciate respectively:

  - the behavior of the stove in relation to the used ethanol,

  - the inflammability of the ethanol per alcoholic degree,
  - the state of the flame (in blue flame or in red flame),
  - the temperature of the external body of the stove
- The third phase corresponds to undertake different weighed and measures as:
  - the weight of the tested cooking devices and its content (water),
  - the weight of the remaining alcohol in the burner to determine the real quantity consumed during the boiling point plus 15 minutes,
  - the alcoholic concentration of the remaining solution in the burner.

The power delivered by the burner is calculated by the following formula:

$$P = Q / t \tag{1}$$

with

$$Q = C_{pw} M_{init} \left(T_{boil} - T_{init}\right) + L_v \left(M_{init} - M_R\right) \tag{2}$$

The thermal efficiency of the stove is expressed as:

$$\eta = \frac{Q}{A_{HV} V_{ethanol}} \tag{3}$$

The amount of CO_2 released to boil a given volume of water (in kg/kWh/l) is deducted from the molar balance in the combustion reaction of the fuel (water-ethanol mixture). This study shows that the products of combustion of ethanol are CO_2 and water vapor.

IV. RESULTS AND DISCUSSION

A. Basic future of the ethanol stove

The stove without fuel tank (Part no. 1, Fig. 1) has been analyzed in this survey. The burner has a small fuel chamber and can only take a maximum of 550 ml of water–ethanol mixture. In that case, the stove can be operated for a period of 40 to 60 minutes.

During each phase of test, the ethanol content decreases gradually and the non-evaporated water is enclosed in the burner. The flame is not disrupted but the height of flame decreases. At the end of each phase of test, the final concentration of the remaining fuel was 15 to 18 % v/v of ethanol.

The efficiency (35 to 46%) of the ethanol stove (Figs. 2,3) could be increased with increasing the cylindrical circumference because of the characteristic of the two cylindrical ethanol burner 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. However, in this study this phenomenon occurs in the burner and the combustion of the evaporated ethanol happens on the free surface of the fuel. The resulting flame is blue in color and has no smell.

B. Stove characteristics

Figures 2 and 3 show the influence of increasing ethanol concentrations on the performance of the stove at maximum and minimum capacity respectively. The stove was tested for varying ethanol percentages (40 to 94%). Five tests for each concentration have been performed. During the test, the mass burning rate of the stove is maintained constant and the resulting flame is blue in color. However, the resultant clean flame burns with a yellowish-orange color when one use an ethanol of more than 85%. This latter shows that the combustion is not complete and the greenhouse gas emission increases. The stove capacity increases with increasing ethanol concentrations as shown in Figs. 2 and 3. As the

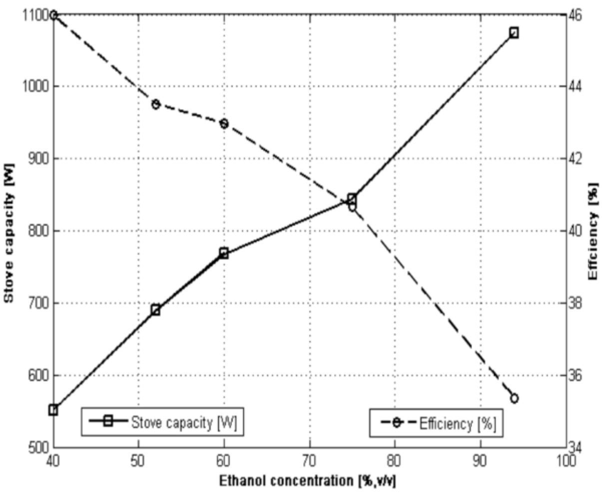

Figure 2. Stove performance with increasing ethanol concentrations (max. capacity)

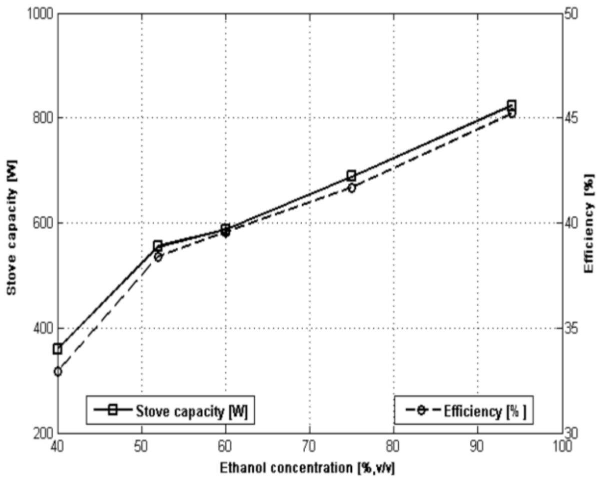

Figure 3. Stove performance with increasing ethanol concentrations (min. capacity).

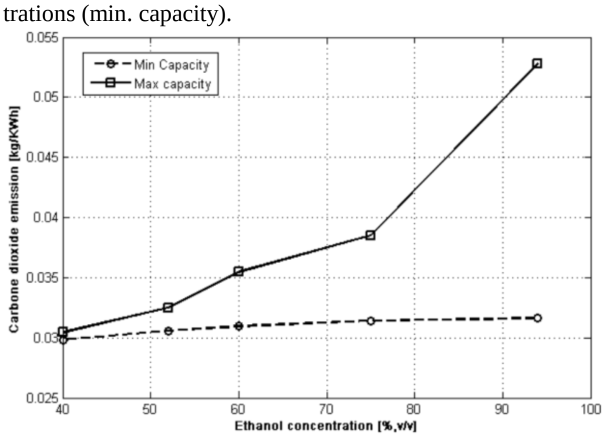

Figure 4. CO_2 emission.

ethanol concentrations increase, the efficiency of the stove drops at maximum capacity (from 46 to 35 %) and increases at minimum capacity (from 32 to 45 %). The drop in efficiency observed at maximum capacity tests is attributed to higher radiation losses and carbon monoxide emissions, 9,027 g/m3 for ethanol (IRG, 2005). This offsets the gain resulting from the reduced water content in the fuel mixture. No such loss occurs at minimum capacity. A minimum of 35 % v/v 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 50 to 75 %, as shown the figures.

Figures 4 and 5 show the calculation results of CO_2 emission according to ethanol concentration. The greenhouse gas emission increases with the ethanol concentration. Besides, the emission of CO_2 in high capacity of the stove increases significantly. This fact is due to the characteristic of the burner. The free surface of the fuel of the burner corresponds to a pool of diameter of 10 cm.

C. Performance of the stove

In terms of performance of the stove VOAHAJA N°1, the power output of the stove depends on the ethanol content of the mixture (Bizzo *et al*., 2004). However, the power output of the stove is a decreasing function of the burning time because of the reduction of the concentration of ethanol in the mixture during the combustion. That influences on the thermal efficiency. The thermal efficiency was calculated taking into account the loss of efficiency with time.

Conversely, the influence of thickness and the nature of vessel walls of the burner have a significant influence to the burner performance. The change of wall thickness improves the burning time and the thermal efficiency. In that case, the products of combustion of ethanol, particularly as the CO_2, decrease. Then, improving the nature of the stove components pick up the performance.

Besides, the cooking pots nature will change the thermal efficiency of the stove. In that case, the heat transfers between the flame and the bottom part of the pot increases with the cooking pot conductivity. The thermal efficiency is enhanced (Andrianantenaina, 2014).

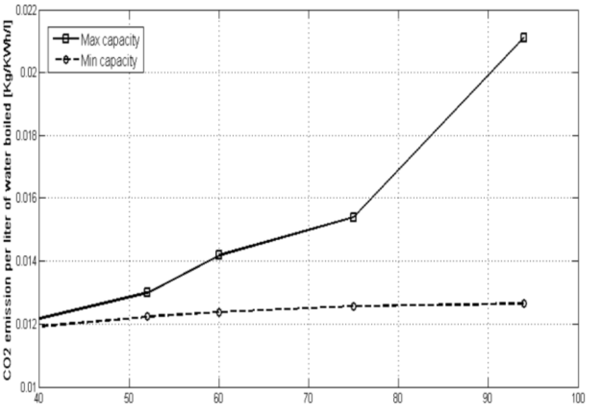

Figure 5. CO_2 emission per liter of water boiled.

The power of our developed burner is less feeble than the power output of the LPG gas burner of about 4 KW and the efficiency of 60% (Battacharya *et al*., 2002), but in relation to the performance of Nimbkar Agricultural Research Institute burner (UNHCR, 2013), the thermal efficiency seems to be the same. A part of heat released by ethanol used to evaporate water in the fuel which does not take part in the combustion process is lowest as the evaporated water quantity is smallest (Andrianantenaina, 2014). It reduces the temperature of the flame and therefore the thermal efficiency (32 to 46%).

D. Safety analysis

The safety analysis has been conducted at the CNRIT. The stove must be located in a steady place to avoid the movement of the fuel in the burner that extinguishes mechanically the flame. This process permits the burner to be thermally steady. Therefore, the use of this stove reduces the risk of fire that frequently occurs in certain rural communities in Madagascar. The mixture of ethanol-water to 50-75% v/v is not very corrosive and ignites with difficulty because of its elevated water content by volume. This has needed a very large surface with a specific condition of ignition to light freely. If there is a flame on the free surface, it turn off very quickly (Andrianantenaina, 2014)

The experience showed that when one opens the output valve of the stove, the fuel coming from the burner moves 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 of the fuel in the burner is surpassed because of the insufficiency of air inside the burner. Also, the flame couldn’t propagate in the tube joining the burner and the output valve due to the absence of the air necessary to the combustion of the ethanol. Besides, as the level of the fuel in the burner goes up until 4 cm below the superior side of the burner, the flame dies out automatically because there is no entry for air. However, while the burner is filled the fuel overflows outside the burner without flame.

While shaking the burner, the movement of the fuel destabilizes the flame. The temperature of the superior layer of the fuel drops suddenly because the movement permits to mix the fuel of the cold bottom part and the hot superior part of the burner. In this case, the ignition temperature is insufficient and the evaporation of the volatile component stops. The height of the flame decreases and the flame is locked inside the combustion chamber. The circulation of the combustion air is disrupted and combustion stops. The same case occurs for a slanted burner. Indeed, there have not an explosion of the stove.

E. Field testing

Field tests (FTs) were conducted on the ethanol stove to demonstrate suitability to the target market and to validate the design. All Tests were conducted in a standard kitchen. The stove's performance was compared with those of standard-used stoves such as TCS (Traditional Charcoal Stove), MWS (Modified Wood Stove) and charcoal and wood stoves. 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 5 persons, is around of 26.38 minutes using the TCS, with a power input of 2.46 KW and a power output of 0.51 KW (Gaia Association, 2010). The thermal efficiency of TCS is of 20.80%. The MWS required less cooking time compared to the TCS. Nevertheless, the power input of MWS is very significant, 5.18 KW, in comparison the power output of TCS, 0.82 KW. Subsequently, the thermal efficiency of MWS is very low, 15.84%. Thus, Malagasy households cook food on inefficient and polluting cook stoves (Gaia Association, 2010). The stove named "VOAHAJA N°1" that we have developed present an opportunity to solve this problem.

The FTs showed that the specific energy required for the ethanol stove is less than that required for the traditional stoves (TCS, MWS, charcoal and wood stove) and the kerosene stove. These values are indicative of the efficiencies of these stoves. The CO emissions recorded during the tests (around 10 ppm near the cook) were found to be acceptable, indicating that ethanol low concentration is a clean and safe fuel. Detailed interviews were conducted during the field-testing of the ethanol stove. The general responses of the users are: It is very easy to light and run. It has no smell and does not give out any smoke; it is much better than the charcoal stove and woodstove. To use this stove is best like using LPG stove seeing as it has easy flame control. The general acceptable cost for the ethanol stove as confirmed by the users was 10 - 15 $.

F. Policy issue

In 2015, the Malagasy government allowed ethanol to be used as a cooking and lighting fuel for rural and urban areas in Madagascar. Actually, 100,000 ethanol stoves running on 85-94% water-ethanol mixture were imported from abroad. However, the use of high concentration ethanol for household purposes is dangerous for rural areas. Besides, the fuel is more flammable than low concentration ethanol, the fuel is not easy to distil in a one-step distillation process. Rectification process will be obligatory. Also, the sophisticate equipments will be required to product a high concentration ethanol. For ethanol to be used as a cooking fuel in households the following policy issues need to be addressed.

- The production and use of low concentration ethanol in rural areas will provide major stimulus to the rural economy,
- Stoves manufacturing is easy to product locally,
- Currently the production and sale of ethanol is controlled by a very rigid excise regime (policeman) primarily because of issues regarding the drinking of this ethanol. However, there is enough chemistry known to mankind to make ethanol non-potable and indigestible. Use of such chemicals will completely prevent drinking ethanol meant for use as fuel,
- The use of low concentration ethanol will reduce its cost and make it a viable alternative to LPG, charcoal, wood and kerosene.

V. CONCLUSIONS

A stove running on low ethanol-water mixture has been developed and tested for varying ethanol percentages (40 to 94%, v/v). Tests results showed as the ethanol concentrations increase, the efficiency of the stove drops at maximum capacity (from 46 to 35 %) and increases at minimum capacity (from 32 to 45 %). The resulting flame is blue in color and has no smell during combustion. The stove pollutant gas emission as carbon dioxide has been calculated. The tests done at CNRIT showed that 50-75 % (v/v) ethanol-water mixture will be a good cooking fuel for Madagascar households. Security of the stove has been analyzed and performance has been evoked. Field tests conducted on the stove show that it is not dangerous to use and suitable for a rural/urban household. Use of chemicals products to make ethanol non-potable and indigestible will completely prevent drinking ethanol meant for use as fuel. One can conclude that the risk of fire is negligible for this kind of stove and for the same type of fuel. The use of low concentration ethanol will reduce its cost and make it a viable alternative to LPG, charcoal, wood and kerosene. However, for this stove to be a viable alternative certain policy issues have been undertaken. Using the developed stove present an opportunity for the rural/urban areas of Madagascar households to solve the cooking problem due to the high greenhouse gas emission by using other biomass solid stoves.

NOMENCLATURE

η :	Thermal efficiency of the stove [%]
A_{HV} :	Average heating value [$J.l^{-1}$]
C_{pw} :	Effective calorific value [$J.kg^{-1}$. °C]
L_v :	Latent heat to vaporize the steam [$J.kg^{-1}$]
M_{init} :	Weight of water before test [kg]
M_R :	Water remaining at end of test [kg]
P :	Firepower [W]
Q :	Energy consumed by the stove [J]
t :	Time to boil pot [s]
$V_{ethanol}$:	Volume of the burned dry fuel [l]

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