Development of a low-cost, electricity-generating Rankine cycle, alcohol-fuelled cooking stove for rural communities

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Abstract

This article describes a novel design and construction of a helical tube flash boiler that uses a 2kW nominal methylated spirit burner to heat an approximately 2.5m long coil of copper pipe fed by a nominal 8 bar electrically operated solenoid water pump. The final embodiment is for superheated steam to be converted to electricity and the waste exit heat from the generator used either for cooking or for ethanol production for low-income families in developing countries. The performance of the flash boiler has been evaluated experimentally based on the well-known “Direct-Method”; by carefully measuring both the flow of the fuel and the steam. It found that the pressure inside the pipe can reach up to 7.4 bar and the temperature of the steam released by the flashing process can reach 255 °C utilising a low-cost water pump. The research results presented in this paper demonstrate that flash boiler stove has a great potential for generating high-temperature steam for developing a low-cost cooking stove.

Keywords: Flash boiler, spirit burner, copper coil, expander, electrical generator

Background

The development of sustainable and clean energy technologies is of ever-growing worldwide interest due to global warming and environmental disorder resulted from fossil fuel sources [1-3]. In the conventional fossil fuel technologies, only 30% of the fuel energy is converted into useful electricity and the rest is wasted and dumped on earth [4]. Recent forecasts predict that a third of new electricity generation added globally by year 2035 will be generated by renewable energy sources. Despite the dramatic evolution of such technologies, the majority of rural communities in the developing countries face problems in the electricity supply and healthy cooking [5]. The Global Alliance for Clean Cookstoves (GACC), hosted by the UN Foundation aims to reduce the estimated 4 million premature deaths per year by introducing 100 million improved stoves by 2020 [6] to improve health standards for women and children. Other work explores the feasibility of generating electricity whilst cooking [7], how it can be afforded [8] and various technologies to achieve this goal [9]. Besides generating electricity, improved cooking stoves reduced fuel demand as well as greenhouse gases and therefore, increase the sustainability of the natural resources. During the last decades, numerous advanced thermodynamic cycles and variations/ combinations of technologies have been developed for waste heat recovery such as Rankine cycle, Stirling Cycle, Organic Rankine Cycle, Kalina Cycle. Recently, Organic Rankine cycle (ORC) has been developed to recover heat from medium grade combined heat power systems [10-13]. ORC solves the problem of the high fluid flow rate associated with the conventional steam Rankine Cycle. However, this technology is costly and has some operational and maintenance drawbacks. The highest temperature the working fluid can reach is below the source temperature due to the existence of a phase change during heating and superheating of the fluid which implies that inefficient heat transfer between the heat source and the fluid. Also, the lowest temperature of the cycle is normally much lower than the lowest temperature reached by the heat source [14]. Many researchers studied and demonstrated small-scale Steam Rankine Cycles (RCs) and several scientists investigated the feasibility of this technology in relation to the additional costs that such systems can involve [15, 16]. The traditional Rankine cycle is efficient for waste heat recovery from exhaust streams with temperatures above about 340-370ºC. The Rankine cycle becomes less cost-effective at low temperatures where bulkier equipment are required at the low-pressure steam. Furthermore, at low waste temperatures, the energy required to superheat the steam is not sufficient to prevent the steam condensation and to avoid erosion of, or example, turbine blades [17]. The major problems related to using turbines as an expander in small-scale water Rankine cycle are the poor efficiency as well as the high production cost, particularly when having multistage turbines.

A flash boiler is one that is widely used to generate steam from combustion gasses to produce electricity through driving steam turbines. In a flash boiler, the heating surface is a single or a series of tubes into which the feed water pumped against the developed pressure. The heat source is usually a petrol, oil or gas flame directed against the tube. The tube is often coiled and housed in a thin lightweight case of metal, frequently stainless steel and the flame is directed through the center of the coil. The development of high-pressure steam is very rapid, hence the term flash steam [18]. The difference between the flash boiler and the mono-tube steam generator is that the mono-tube is permanently filled with water, while the flash boiler is exposed to heat stream (fire is underneath) to keep it hot so that the water feed is quickly flashed into steam and superheated. Flash boilers have many advantages, the most important one is that they take less time to raise steam from a cold start. Also, they are lighter and less bulky than the other types. Problems are that they are more prone to overheat because there is no large reservoir to cool the tubes if the water flow is inadequate or interrupted. Liquid and gaseous fuel are used to fire the boiler in most of the applications. However, some experiments have been run utilizing solid fuel to fire the boiler. The design method of the flash boiler is similar to the evaluation of the heat exchangers, but since a common practice is to recover heat from exhaust gas typical properties for flue gas are required. The aim of this study is to investigate the potential of a flash boiler stove to boil the water to steam and also to identify general design principles of the boiler.

Boiler evaluation

As revealed in the heat balance diagram Figure 1, only part of the heat content of the fuel is converted into useful heat, while the rest of the heat is lost through exhaust gases and radiation losses from the boiler. The efficiency of the boiler is usually rated based on combustion efficiency, thermal efficiency, and overall efficiency.

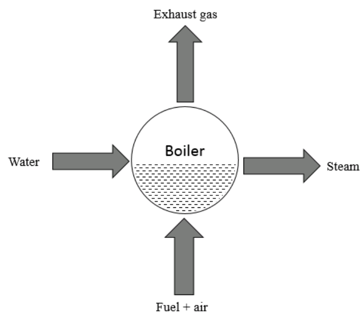

Figure 106. Typical heat flow diagram of a boiler

The typical combustion process in a boiler comprises burning of fuels that contain carbon (oil, gas, and coal) with oxygen to produce heat. Oxygen required for combustion is usually taken from air supplied to the fuel burner of the boiler. Proper heat removal from the flash boiler relies on proper internal distribution and flow of water, proper heat transfer rate in all areas, and proper heat input from the fuel burning.

To evaluate the flash boiler, the well-known "input-output method" is adopted which is based on measuring the mass flow of the burning fuel and the steam generator fluid side conditions necessary to estimate the output. To obtain reliable results from the boiler, the fuel flow, fuel analysis and the steam output must be determined accurately as they are directly proportional to the uncertainty of the boiler efficiency [19].

$$\dot{Q}_f = m_f^0 \times GCV \tag{5}$$

The available heat from burning of the fuel, $\dot{Q}_f$ can be expressed as:
Here: m_f^0 is the average mass rate of the fuel used to bring the water to boiling state (kg/sec),

$$m_f^0 = \frac{m_{f,i} - m_{f,e}}{t} \tag{6}$$

GCV is the gross calorific value of the fuel (kJ/kg)
Where $m_{f,i}$ is the pre-weighed mass of alcohol and $m_{f,e}$ is the mass of alcohol remaining at the end of the test, t is the time to reach the boiling condition.
The heat required to raise the boil the water, $\dot{Q}_w$:

$$\dot{Q}_w = m_w^0 c_{p,w}(T_b - T_w) \tag{7}$$

Where: m_w^0 is the mass rate of the boiled water (kg/sec), $c_{p,w}$ is the specific heat of water (kJ/kg.K), T_b is the boiling temperature of the water (K), T_w is the ambient temperature of

$$m_w^0 = \frac{m_{w,i} - m_{w,e}}{t} \tag{8}$$

water (K) and m_w^0 is the is the mass rate of the boiled water (kg/sec):

Here $m_{w,i}$ is the pre-weighed mass of the water inside the pot and $m_{w,e}$ is the final mass of the water remaining at the end of the test, t is the time to boil the water in the pot
The energy required to evaporate water, $\dot{Q}_{evap.}$

$$\dot{Q}_{evap.} = m_w^0 h_{fg} \tag{9}$$

Where: is the specific evaporation enthalpy for water (kJ/kg).
The heat needed to dry the steam (to be superheated), $\dot{Q}_s$

$$\dot{Q}_s = m_w^0 c_{p,s}(T_s - T_b) \tag{10}$$

Where: $c_{p,s}$ is the specific heat of steam (kJ/kg.K) and T_s is the superheated steam temperature (K)
The boiler efficiency, η_{boiler} is the ratio of the net amount of heat being absorbed by the produced steam to the net amount of heat supplied to the boiler by burning of the fuel [20]. It can be evaluated using the following formula:

$$\eta_{boiler} = \frac{\dot{Q}_w + \dot{Q}_{evap.} + \dot{Q}_s}{\dot{Q}_f} \% \tag{11}$$

Design Concept & Experimental Apparatus
Our analyses show that a low flow rate steam generating flash boiler is able to extract much more heat from combustion than a pot over the flame stoves, even in case of the stoves with improved efficiency modifications such as pot skirts and increasing the speed of the hot gases that scrape against the pot which increase the cooking efficiency by 20%, by forcing hot gases to heat the bottom and the sides of the pot [21].

In this study, the designed flash boiler uses a 2kW nominal methylated spirit burner, to heat an approximately 2.5m long coil of copper pipe fed by a nominal 8 bar water pump. The intent is for superheated steam to be ejected at sonic steam velocity from a small orifice at the end of the pipe to control mass flow. In its final embodiment, the steam will power an electrical generator and the waste exit heat from the generator used either for efficient cooking by or for ethanol production as displayed in Figure 107 and Figure 108 respectively. Heating in the pipe is achieved in three phases. At the first phase, exit combustion gases heat the water inlet from ambient temperature to the boiling temperature. Then, the water is boiled within the horizontal section of the pipe where two-phase flow occurs. At the last phase of the heating process, steam is superheated in the last section of the pipe by the hot combustion gasses from the ethanol burner. It is predicted that heat is transferred by conduction inside and outside the pipe in phase one, while in phase two heat is transferred by a combination of conduction/convection within the pipe and is by radiation/conduction external to the pipe. Phase three heating is by convection within the pipe and mainly by radiation external to the pipe.

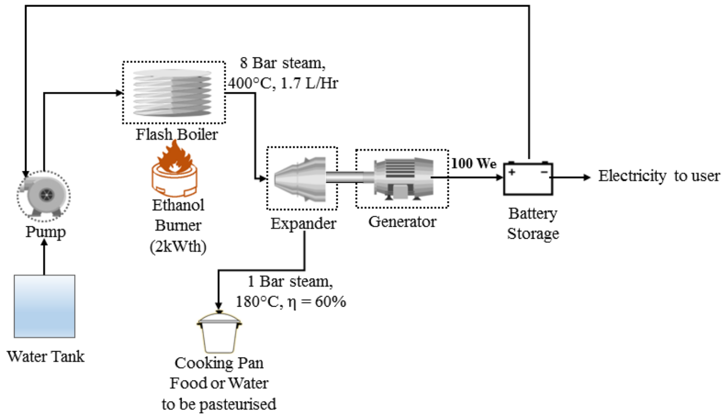

Figure 107. Process of using the flash boiler for cooking purposes

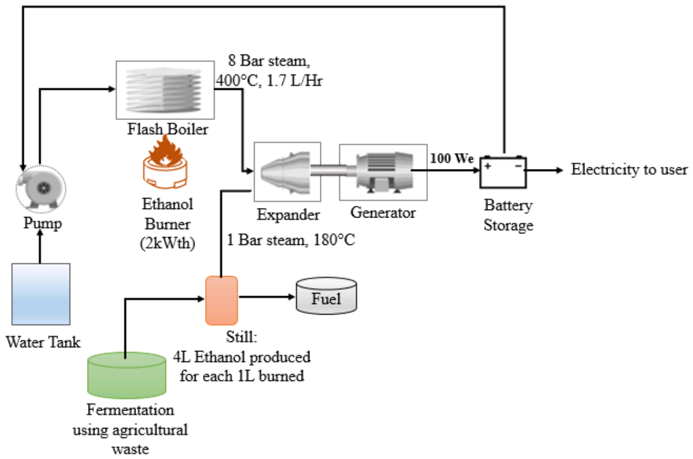

Figure 108. Process of using the flash boiler for fuel production

As shown in Figure 109, the system consists mainly of a 10 mm single copper tube in a multi-layer spiral horizontal configuration with the ethanol burner underneath. The feed water flows inside the tubes after being pumped from a 10L water tank through a 10 mm diameter plastic pipe utilizing a high-pressure diaphragm pump working intermittently to reduce electrical power consumption. (Model HeroNeo® 12V DC 5L/min 60W) The hot gases from combustion flow around the outside of the pipe. The steam is taken out from the system near the roof via steam take-off pipe of 8.2 cm length before is being directed (in the experimental case) to a cooking pot. For insulation purpose, three aluminium foil layers are introduced between the spiral coil and the wooden cover. In the final embodiment, a generator would convert the superheated steam to electricity and the exhaust heat used for cooking. The fuel used to fire is a clean-burning fuel, contains no sulphur and can be produced from renewable feedstocks. Emissions and nitrogen oxides from burning of alcohol are very low.

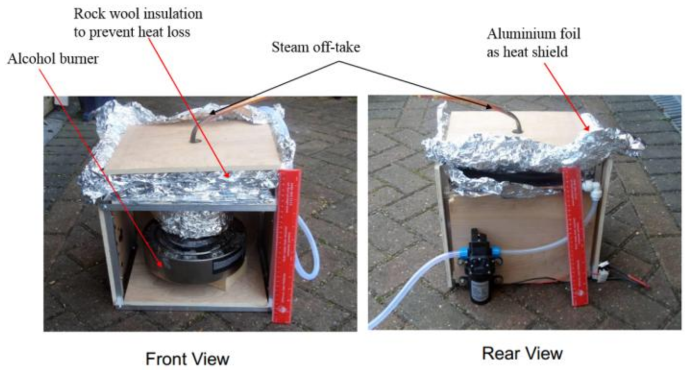

Figure 109. Flash boiler experimental test rig

The copper pipe has a pressure gauge (Model STAUFF 0- 10 bar pressure gauge) at water inlet record pressure, a number of small thermocouples, insulated from gas flow of type-K (RS Components) to capture various temperatures as shown on Figure 5. The LabVIEW platform was used to control the test bench and for Data Acquisition with one thermocouple module (NI 9211) and one bridge module (NI 9237). A scale (OHAUS- Explorer® precision) is used to measure the weight of the fuel and the water before and after the experiment.

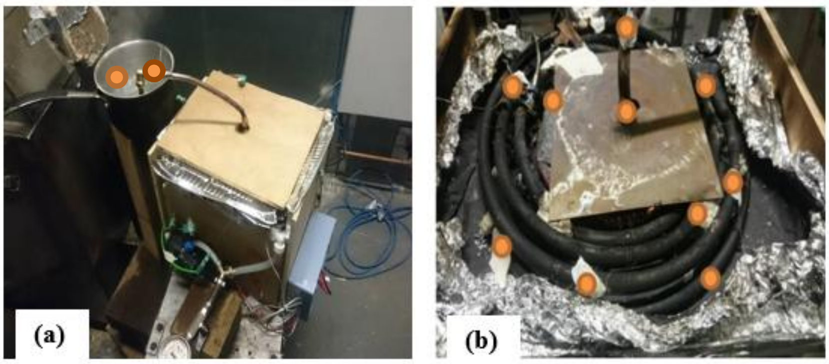

Figure 110. The locations of the thermocouples. (a) At the steam take-off pipe and inside the cooking pot. (b) At the surface of the coil.

Results and discussion

The thermal performance of a flash boiler stove was investigated and measured in terms of combustion input power, thermal output power, specific fuel consumption, fuel ratio and efficiency. At the beginning of the test, 1.3 kg of alcohol was introduced to fire the boiler and water was pumped through the from the clean water tank. Combustion gasses heat the coil and are directed from the super-heated region towards the cold end to create a contra-flow heat exchanger arrangement. A standard efficiency test named the "water boiling test" [22] was carried after 16 minutes of operation using 1.3 Kg of ambient water filled inside a cooking pot. The aim was to measure how efficiently the boiler uses steam (from the steam take-off pipe) to heat the cooking water.

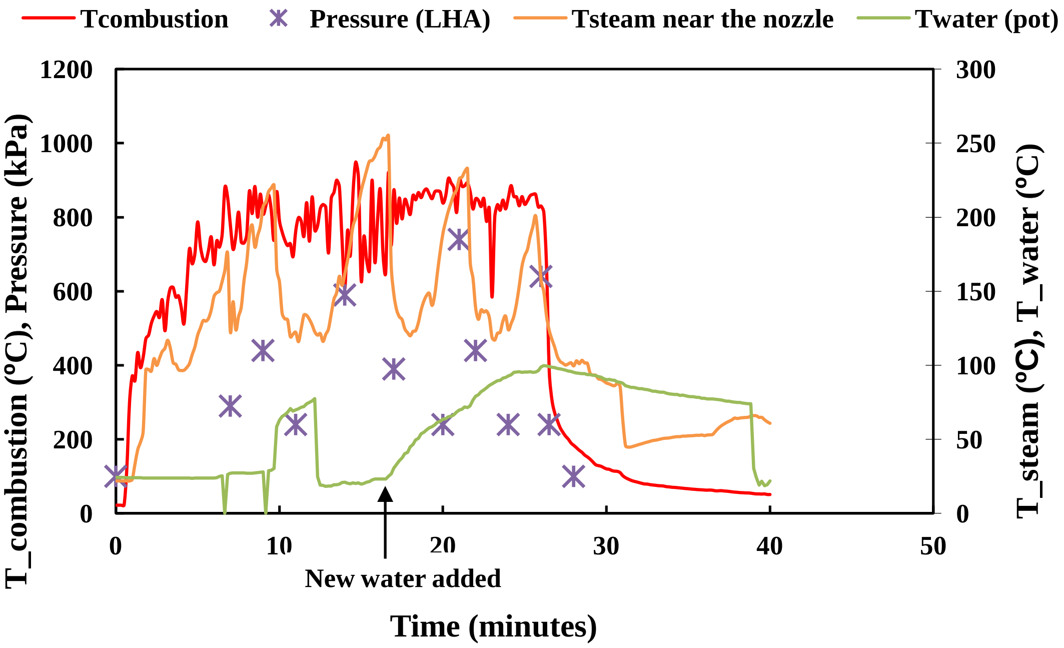

Figure 111. Performance of the flash boiler during the test

The calculated energy output is 0.64kW and the fuel energy input is 1.36kW which gives an efficiency of 47% for the flash boiler stove. Although this is an early non-optimized design, it can bring significant benefits compared to the three stone stove which has a very low thermal efficiency of about 7% and to the other clean-burning stoves of 16 – 42% [7, 23], The measured pressure in the copper pipe was 740 kPa while the maximum temperature of the steam near the nozzle reached 255°C which can be used to drive a Rankine turbine [24]. The important parameters measured during the test are summarized in Table 1.

Table 19. Measured parameters during the experiment

Parameter	Value
Maximum water temperature (°C)	255
Maximum combustion temperature (°C)	949
Mass of alcohol at the beginning (kg)	1.33
Mass of alcohol at the end (kg)	1.23
Mass of the water in the tank at the beginning (kg)	15.5
Mass of the water in the tank at the end (kg)	14
Mass of the water in the pot (kg)	1.32
Maximum pressure in the pipe (bar)	7.4

The thermal efficiency is much higher than conventional cookstoves and may be increased further by better insulation of the top of the wooden cover, which became quite hot, and more gas to pipe surface area. Researchers have noted that the improved insulation can save up to 6–26% [25]. Secondly, there were many leaks from the feed water pipe. Further numerical studies and experiments are required to understand the heat transfer characteristics of the boiler and to quantify the different losses such as: convection and radiation heat loss from the stove, the energy loss from the combustion gases as well as the energy stored in the stove.

Summary

This paper describes the design and development of a copper-pipe flash boiler stove aiming to generate steam at a high pressure to be expanded through a Rankine cycle turbine, and therefore to deliver electrical power to be utilized by the rural communities of the developing countries all around the world and uses alcohol as the fuel. Boiler performance, was evaluated using the well-known "direct- method. The heat supplied to the boiler from the fuel and the heat absorbed by the water in the boiler at a given period of time were calculated. Interestingly, the experimental results show that the generated steam at the exit of the boiler could reach up to 255°C with 7.4 bar pressure inside the copper pipe and 949ºC flame temperature. The efficiency of the boiler was an excellent 47% using 2kW and could be improved with further research. For example, a tesla turbine to expand the steam to generate electrical power.

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