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Design, Development And Evaluation Of A New Type Of Continuous Downdraft Gasifier To Generate Producer Gas From Rice Husk

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Abstract— Rice husk is an important agricultural waste, that can be converted into useful fuel through the process called gasification. In this technology, the rice husk is transformed into a mixture of combustible gases in a thermo-chemical process. The producer gas can be used in various applications such as heating production, internal combustion engine application. In the present work, a new prototype of downdraft gasifier is designed and developed of 10 KWth capacity. Fresh rice husk from rice mill is used as a feed stock in the gasifier. It is equipped of a feed system and a drawer ash discharger, which permit continuous run without perturbation. The producer gas was burnt, in order to heat an water heater, and to evaluate its performance. The performance characteristics (the output power rate, the gasifier efficiency, the fuel consumption, conversion rate, calorific value and dynamics behavior) are studied and analyzed at different value of the specific gasification rate. It was found that the best thermal efficiency measured was 34% at specific gasification rate equal to 202 kg/h.m². The maximum power rate was 3800 W at specific gasification rate equal to 275 kg/h.m², and the minimum fuel consumption was 8,87g/kCal at specific gasification rate equal to 202kg/hm². Experiments showed that higher temperature in the reaction zone increases the performance of the gasifier. However, this temperature should not be greater than 900°C to avoid the ash fuse, which is difficult to remove from the gasifier.

Keywords—Renewable energy; Rice husk; downdraft gasifier; Syngas.

I. INTRODUCTION

In Madagascar, the main source of the energy comes from wood, which accounts for 92% of the annual consumption. In second position, the use of petroleum energy represents about 7% or 776 573 TEP [1]. Consequently, the state must face up to the energy problem, because the forest source becomes rare [1], and the dependence of fossil energy is worsening with its high cost and environmental pollution. Therefore, rice husk is very abundant. In fact, the production of the year 2017 is equal to 3.4 million tons, [2] which is equivalent of 378 620 GWH per year. In the country, rice husk is mainly thrown outdoors, is used for bricks cooking, or used as a fertilizer [3].

Nowadays, biomass gasification is attracting researchers for seeking renewable energy [1] [2]. It consists of a thermo-chemical process, in which the biomass is converted into gas [4], [5]. This technology offers a benefic advantage compared to the use of fossil fuel because of its increasing price. Furthermore, the use of biomass as energetic source solves the environmental and climatic problems like air pollution and greenhouse gases emission [4], [5].

Especially, the rice husk gasification can be an applicable solution for energy problem in Madagascar. The producer gas can be used as a fuel for a furnace or burner [5](heating production), for domestic stove [4] [6] [7], or for internal combustion engine to generate electricity or mechanical energy [8] [9]. The syngas can be used with a fuel cell to produce electricity [10]. The objective of this work is to design, realize and test a downdraft gasifier using rice husk as fuel. The producer gas is burnt to warm a water heater at various specific gasification rate. The obtained performance will determine if rice husk gasification, is an applicable technology for energy problem in Madagascar.

II. MATERIAL AND METHODS

A. Design procedure

The gasifier design is based on information available on literature, experience return by researchers and previous experiments, and functional requirements. The useful information are collected, computed and analyzed, in order to establish plans of the gasifier. The following step is the construction of the gasifier. The final step consists of the test of the gasifier, in order to evaluate its performance. Information on literature gives useful data about gasification technology, and gasifier design. To complete the design, functional requirements are listed and took in consideration. These requirements complete the working utilities of the gasifier. Finally the possible troubleshooting, reported during previous experience, and other researchers are considered, to find applicable solution to the gasifier. The requirements corresponding to the chosen solution are summarized in TABLE 1.

TABLE 1 FUNCTIONAL REQUIREMENT AND CHOSEN ARRANGEMENT TO THE DESIGNED GASIFIER

Functional requirement	**Chosen arrangement**	**Material**
The gasifier must gasify of rice husk	Downdraft gasifier, throatless	stainless steel
The gasifier must have a gas duct	Metal round bar 80mm diameter	Metal
The air needed for gasification must be adjustable	Utilization of electric blower, driven by a dimmer	
The gasifier must have a hopper	Construction of a hopper with metal sheet Diameter 650mm, height 800mm	Metal Sheet
The gasifier must have a box to dispose the ash	Construction of a ash container diameter 600mm; Height 500mm	Metal steel
The gasifier must have a lightening door	Utilization of 04 kit muff and bouchon located around the firing zone	Galvanized steel
The height of the firing zone position must be detectable	Monitoring of reactor temperature	K thermocouple
The reactor must be insulated	Insulation of the reactor with glass wool	Glass wool

The troubleshooting reported by other searchers and previous experiments, give also useful information to perform the design of the gasifier, as indicated in Table 2.

TABLE 2 CONSIDERATION OF POSSIBLE TROUBLESHOOTING FOR PERFORMING THE GASIFIER DESIGN

Possible troubleshooting	Chosen arrangement
Bridging of the reaction bed	Installation of a screw conveyor coupled to a steering wheel, at the top of the firing zone
Vitrification of ash due to excessive temperature	Monitoring of reactor temperature
Channel formation	Air flow rate monitoring
Stability of gasification	Utilization of screw conveyor and ash drawer Construction of a char container
Flow reversal	Utilization of an airtight cover for the hopper

B. **Design and construction procedure**

The gasifier is designed, by computing each available information. Its dimension is calculated. The linking between the gasifier and the other apparatus (hopper, char container, ..) are designed according to their shape and dimension. The plan and drawing are established, and the gasifier is constructed. Local material, and local human resource are used during this steps. After the realization, the gasifier is tested in the aim of evaluating its performance. TABLE 3 summarizes the input data needed during the step of design. With the suitable formula, this information allow to determine the gasifier dimension and its capacity, as indicated in TABLE 4.

The machine was built in Ecole Supérieure Polytechnique of Antananarivo (ESPA) with the help of the ARTICOM company (Antananarivo, Madagascar). That enterprise is specialized in apparatus construction. The construction is the result of design, based on data available by literature, and experience return by many researchers, and consideration of functional requirement. **Error! Reference source not found.** shows the schematic of continuous the downdraft gasifier. It consists of a hopper, a screw conveyor, a downdraft gasification reactor, a used char discharge system, a char container, an air blower, and a dimmer. The hopper is made up of metal steel material with 650 mm diameter and 800 mm height. There is a lid at the top and the tightness is assured by a water seal. There is a screw conveyor into the hopper which permit to convey the new fuel into the reactor chamber. The screw is actuated by a steering wheel whose axis passes through the wall of the hopper, with the help of a universal joint. The rice husk is fed through hopper into the reactor. The reactor is a cylinder shape made up of stainless steel 304 material in which the actual reactions take place.

TABLE 3 INPUT DATA USED DURING GASIFIER DESIGN [4]

Input data	Value
Energy needed	$Q_n = 7500$ kCal/h
Low Heating Value of rice husk	$LHV_{RH} = 3273\ kCal/kg$
Bulk Density	$\rho_{RH} = 135\ kg/m^3$
Gasifier efficiency	$\eta = 60\%$
Specific Gasification Rate	SGR =140 kg/hm²
Equivalence ratio	ε=0.3
Stoichiometric air	SA=4.7 kg air/kg rice husk

Time for gasification	Δt =20min
Air density	ρ_{air} = 1.25 kg/m3
Specific resistance of air flow	$S_R = 0.7 cmH_2O/m$ [11]

TABLE 4 OUTPUT DATA, EQUATION, CALCULATED AND RETAINED VALUE FOR GASIFIER DESIGN

Output data	Equation	Calculated value	Retained value
Fuel consumption rate	$\dot{M}_{RH} = \frac{Q_n}{LHV_{RH}.\eta} \left[\frac{kg}{h}\right]$	3.81	3.81
Reactor diameter	$d_{reactor} = 2\sqrt{\frac{\dot{M}_{RH}}{\pi.SGR}} [m]$	0.19	0.20
Reactor Height	$H_{reactor} = \frac{4.\dot{M}_{RH}.\Delta t}{\pi d^2_{reactor}.\rho_{RH}} \quad [m]$	0.52	0.60
Air flow rate	$Q_{v.air} = \frac{\dot{M}_{RH}.\varepsilon.SA}{\rho_{air}} \left[\frac{m^3}{h}\right]$	4.30	4.30
Superficial air velocity	$v_{air} = \frac{4.Q_{v.air}}{\pi.d^2_{reactor}.3600} \quad \left[\frac{m}{s}\right]$	0.04	0.04
Resistance to air flow	$R_f = H_{reactor}.S_R \ [cmH_2O]$	0.42	0.42

Its diameter is 200 mm and the height is 600 mm. The gas is generated in this region and then comes out from the bottom. The reactor is insulated with rice husk ash to prevent heat loss.The feed material is held on horizontal drawer also made of stainless steel. When the reaction of gasification takes place, the firing zone is rising at about 1 to 3 cm per minutes, depending on the gasification rate. In order to maintain the level of reaction at the right height, the used char (mixture of unburnt char and ash) is pushed toward the char container by pushing the drawer. The char container is a cylinder shape which diameter is 500 mm and the height is 700mm. It is equipped of a door at the bottom that permits to remove ash after operation. Removing used char lower the level of the firing zone, and new fuel is added into the reactor chamber by actuating the screw.

A 100 W air blower (Pressure: 2500 Pa, nominal rate: 0.5 m^3/min) is used to supply the primary air needed for gasification. A dimmer drives the blower, to vary its flow rate. As the draft is created, the producer gas crosses through gas duct, which is made of metal round pipe (length 800mm, inner diameter=80mm, cross-section, $S_{duct}=5.10^{-3}$ m². The gas is mixed with secondary air and is burnt . The heat produced by the combustion of the syngas, warms the water heater. The water heater, made of Stainless steel 304, consists on fume/water heat exchanger. Its inner diameter is 300mm, outer diameter is 400mm and height is 600mm. There are tubes inside (40mm diameter) of it to enhance the exchange area. The total exchange area is about 0.82m². The external wall area is about 0.56m².

A chimney is disposed at the top of the water heater, where the fume is rejected to the atmosphere.

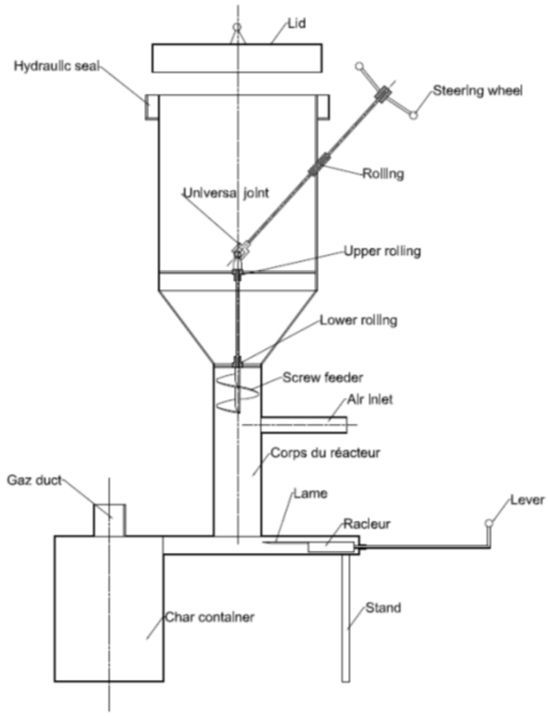

Fig. 1 Schematic drawing of the gasifier

C. **Experimental procedure**

1) **Materials and measurement device**

In the present work, rice husk is transformed into combustible gas, in a continuous downdraft gasifier. The syngas is conveyed and burnt at the water heater. Several parameters from the reactors and the water heater, were recorded and analyzed in the aim of evaluate the gasifier performance. In this way, three K type thermocouples are mounted in different region of the reactor to measure the local temperature. Two sensors are used to record the temperature of the water entering and exiting the water heater. One k type thermocouple is installed on the external wall of the heat water to measure its temperature. Hot wire anemometer (IHM 3880SI) is mounted in the middle of the gas duct. This device measures the velocities of the gas leaving the gasifier in the aim of calculation of the flow rate of the gas. Combustion analyzer (KANE 255) is used to record the O2 concentration and temperature in the fume leaving the water heater, in order to adjust the gas combustion and determine its efficiency. Electronic balance (PCE-BSH 10000) is used to weigh the fresh and the used fuel. The same balance is used to calibrate the flow of water passing through the water heater. In this study, the feed stocks used are fresh rice husk. Its moisture is about 11 to 12 %. Stopwatch is used to measure the time elapsed from the beginning of the experience till its end. The water heater is connected to water supply and is equipped by a tap that adjusts the flow rate.

2) **Method for experience**

The following steps are repeated for each experiment

- First of all, the char container and the reactor are discharged to remove the remaining char from the precedent test.
- The hopper is fed of fresh pre weighed fuel at the top. Then the screw conveyor is actuated on, to add fuel into the reactor. Then the lid is closed and water is added to water seal it.
- The reactor is lighted by presenting torch at lighting door, and the blower is turned on.
- When the reactor is ignited, the lighting door is closed. The gas produced initially which is of low quality, is released to the atmosphere. Near about 15 minutes are required at the initial stage to get a good quality gas continuously. At that

moment, the reactor temperature reaches near to 350º C-600º C. When the quality of the gas is good enough, it is conveyed to the water heater to be burnt. Water is sent through the water heater. Its input and output temperature, and its flow rate are recorded to evaluate the heat produced by the gas.

- Then, the air flow rate is adjusted for each value of the desired gasification rate. When the temperature of the water entering and exiting the water heater is stable, the others parameters are recorded every 2 minutes during the experiment (temperature of the reactor, temperature of the water at the input and output of the water heater). The height of the firing zone is observed and maintained at the right level (350mm from the bottom of the reactor). When it crosses the desired threshold, the drawer is actioned to remove used char at the bottom of the reactor. If so, the screw conveyor is actuated to add fresh fuel into the reactor and to replace the removed char.
- During each experiment, pre-weighed rice husk is added into the hopper to ensure continuous gas production.
- More attention is paid to the syngas combustion, in order to get the best syngas combustion efficiency. The second air supplied is well determine to ensure that the syngas produced by the gasifier, is effectively burnt, without cooling the combustion temperature and avoiding syngas losses. The operating combustion is optimized by the use of the combustion analyzer. The second air supply is adjusted to get the right O_2 concentration in the fume, according to the recommendation described in [11]. In the one hand, insufficient air combustion (less than theoretically amount) causes the decrease of fuel (syngas) efficiency. There is not enough O" to react with the combustible element in the syngas. In the other hand, excess of air combustion increases syngas consumption, reduces its efficiency, because more air cools combustion system by absorbing heat, and throw it out the chimney. Moreover, nitrogen present in the combustion air absorbs heat energy.

3) Characteristic of the raw material

During those experiments, fuel used to gasification is rice husk produced from near mill. The main characteristics of this material is summarized in the following table.

TABLE 5 CHARACTERISTICS OF THE RICE HUSK USED DURING EXPERIMENTS

General characteristics	
Moisture content	11%
Bulk density	135 kg/m3
Low heating value	13 700 KJ/kg
Proximate value (% weight)	
Fixed carbon	20,10 %
Volatile matter	55,60 %
Ash	14 %
Low heating value of rice husk char	12,79MJ/kg

D. Calculated and analyzed parameters

1) Specific gasification rate, SGR

The specific gasification rate (SGR) is defined as the amount of biomass fuel used per unit time per unit reactor area

$$SGR = \frac{\dot{M}_{RH}}{S_{Reactor}} \quad \left[\frac{Kg}{h.m^2}\right] \tag{1}$$

Where:

- $\dot{M}_{RH}$: mass flow of rice husk [Kg/h]
- $S_{Reactor}$: Sectional area of the reactor [m²]

2) **Equivalence ratio, ε**

The equivalence ratio is defined as the ratio between the amount of the air used to gasify the rice husk and the amount of the air needed for stoichiometric combustion.

$$\varepsilon = \frac{\dot{M}_{air}}{\dot{M}_{air,stoic}} = \frac{Q_{v.air}.\rho_{air}}{\dot{M}_{RH}.SA} \qquad (2)$$

- $\dot{M}_{air}$: Mass flow of air used for gasification [Kg]
- $\dot{M}_{air,stoic}$: Mass flow of air needed for stoichiometric gasification of the rice husk
- $\dot{Q}_{v.air}$: Volume flow rate of air [m3/h]
- ρ_{air}: air density [kg/m3]
- $\dot{M}_{RH}$: mass flow of rice husk [Kg/h]
- SA : stoichiometric air for total combustion of the rice husk [4.5 kg air/kg rice husk] [2]

3) **Heat lost in fume, $\dot{Q}_{LF}$**

According to Siegert formula [1], heat loss in fume is evaluated by the rate of produced gas, temperature difference between the fume and ambient air, the nature of the combustible and CO2 concentration in the fume, as described in the following equation:

$$\dot{Q}_{LF} = \dot{Q}_{gas}.\left(\theta_{fume} - \theta_{air}\right).\left(\frac{A_2}{21-[O_2]} + B\right), \qquad \left[\frac{kCal}{h}\right] \qquad (3)$$

Where

- $\dot{Q}_{gas}$: Heat brought by the syngas combustion $\left[\frac{kCal}{h}\right]$
- A_2, B : Siegert constant depending on the nature of the gas (for syngas, $A_2 = 0{,}63$; B=0,011)
- θ_{air} : Temperature of the air supplied in the reactor (equal to ambient air) [°C]
- $[CO_2]$: CO2 Concentration in the fume [%]

4) **Heat received by the water heater, $\dot{Q}_{RWH}$**

It is the amount of the heat needed to warm the water passing through the water heater

$$\dot{Q}_{RWH} = \dot{m}_0.c_{p.0}.(\theta_{OUT} - \theta_{IN}) \quad \left[\frac{kCal}{h}\right] \qquad (4)$$

Where :

- $\dot{m}_0$: mass rate of water passing through the water heater $[kg]$
- $c_{p.0}$: water calorific capacity $\left[\frac{kCal}{kg.°C}\right]$

- $\theta_{OUT}, \theta_{IN}$ Mean temperature of the water measured at output and input of the water heater [°C]

5) **Heat lost through the wall of the water heater, $\dot{Q}_{LW}$**

It is the amount of the heat lost through the wall of the water heater

$$\dot{Q}_{LW} = \alpha_{LW}.S_{E,WH}\left(\theta_{E,WH} - \theta_{air}\right) \quad \left[\frac{kCal}{h}\right] \tag{5}$$

Where :

- α_{LW}: Coefficient heat transfer by convection ($\alpha_{LW} = 12\left[\frac{W}{m^2.°C}\right] = 10{,}3\left[\frac{kCal}{h.m^2.°C}\right]$ outdoor condition with air velocity equal to 0,9m/s [11]
- $\theta_{E,WH}$: Mean temperature recorded at the external wall of water heater [°C]
- θ_{air}: Mean temperature of the ambient air [°C]
- $S_{E,WH}$: External area of the water heater wall [m²]

6) **Output power rate (Heat produced by the syngas combustion) $\dot{Q}_{gaz}$:**

- It is the sum of the heat received by the water heater, the heat wasted in the fume and the heat wasted trough the wall of the water heater.

$$\dot{Q}_{gas} = \dot{Q}_{LF} + \dot{Q}_{RWH} + \dot{Q}_{LW}$$

$$\dot{Q}_{gas} = \dot{Q}_{gas}.\left(\theta_{fume} - \theta_{air}\right).\left(\frac{A_2}{21-[O_2]} + B\right) + \dot{m}_0.c_{p.0}.\left(\theta_{OUT} - \theta_{IN}\right) + \alpha_{LW}.S_{E,WH}\left(\theta_{E,WH} - \theta_{air}\right)$$

$$\dot{Q}_{gaz} = \frac{\dot{m}_0.c_{p.0}.\left(\theta_{OUT} - \theta_{IN}\right) + \alpha_{LW}.S_{E,WH}\left(\theta_{E,WH} - \theta_{air}\right)}{1 - \left(\theta_{fume} - \theta_{air}\right).\left(\frac{A_2}{21-[O_2]} + B\right)} \quad \left[\frac{kcal}{h}\right] \tag{6}$$

7) **Fuel Specific Consumption, FSC**

It is the amount of fuel used to produce one kilocalorie of energy (received by the water heater)

$$FSC = \frac{\dot{M}_{RH}}{\dot{Q}_{gas}} \left[\frac{Kg}{kCal}\right] \tag{7}$$

8) **Energy contained in the residue, $\dot{Q}_{CHAR}$**

It is the energy available in the unburnt residue (char)

$$\dot{Q}_{CHAR} = \dot{M}_{CHAR}.LHV_{CHAR} \left[\frac{kCal}{h}\right] \tag{8}$$

Where :

- $\dot{M}_{CHAR}$: Mass of char produced per hour [kg/h]

- LHV_{CHAR} : Low heating value of the remaining char $LHV_{CHAR} = 3059[kCal/kg]$ [13]

9) **Mass conversion rate, τ_m**

It is the fraction of the fuel, which is really consumed by the gasification.

$$\tau_m = 1 - \frac{\dot{M}_{CHAR}}{\dot{M}_{RH}(1 - FM)} \ [\%] \tag{9}$$

Where :

- FM : Fuel Moisture [%]

10) **Gasifier efficiency, η**

It is the ratio between the heat $\dot{Q}_{gaz}$ contained in the syngas and the heat energy available in the rice husk used during the experiment

$$\eta = \frac{\dot{Q}_{gas}}{\dot{M}_{RH}.LHV_{RH}}$$

$$\eta = \frac{1}{FSC.LHV_{RH}} \ [\%] \tag{10}$$

Where

- η the gasifier efficiency [%]
- $\dot{M}_{RH}$ mass of used fuel [kg]
- LHV_{RH} Lower heating value of rice husk, LHV_{RH}=3273 [kCal/kg]
- FSC: Fuel specific consumption [kg/kCal]

11) **Gas flow rate, GFR**

It is the amount of the syngas produced by the gasifier per time unit

$$GFR = \frac{P.\theta_0.S_{duct}.v_{gas}}{P_0.\theta_{gas}} \left[\frac{m^3}{h}\right] \tag{11}$$

Where:

- $\rho_{gas,0}$: density of the syngas at the temperature of 0°C ($\rho_{gas,0} = 0{,}95 kg/m3$) [13]
- P :actual pressure of the gas [Pa]
- P_0: Normal pressure condition $P_0 = 1{,}013\ [Pa]$
- θ_0: Normal temperature condition θ_0=273 [K]
- θ_{gas}:actual temperature of the syngas [K]
- v_{gas}: velocity of the syngas [m/h]
- S_{duct}:sectional area of the syngas duct [m²]

12) **Approximate heating value of the syngas, LHV_{gas}**

It is the ratio between the sum of the heat produced by the combustion of the producer gas and the gas flow rate.

$$LHV_{gas} = \frac{\dot{Q}_{gas}}{GFR}\left[\frac{kCal}{m^3}\right] \quad (12)$$

III. RESULT AND DISCUSSION

The downdraft gasifier called RAAR.1 was designed, adjusted, and experimented to gasify rice husk, and transform it into producer gas. The rice husk is fed into the hopper, and conveyed into the reaction zone by the help of a vertical screw conveyor. The char formed by the gasification is removed out the gasifier by the help of an ash drawer, and kept into a char container. A steering wheel whose axis passes through the wall of the hopper, is mounted with the screw conveyor by the help of an universal joint. When needed, the char is removed to the char container by pushing the drawer with the hand. Then the drawer is send back to its initial position. An electric blower ensure the draft of the gasification by supplying the necessary air needed for the reaction. A dimmer permits to adjust the blower rate, and the amount of air fed into the gasification reactor.

E. Dynamic behavior

It was necessary to get some skills on the gasifier driving, to ensure normal working of the gasification system and measurement apparatus. For each load, pilot test was conducted to get the exact operating condition and to adjust the gasification rate, the rice husk fed into the gasifier, the rate of char to be removed, and the amount of water, which passes through the water heater.

Starting of the gasifier takes about 5 minutes, then, the producer gas, which have enough quality, is conveyed into the water heater. There, the gas is mixed with enough secondary air and is burnt. The heat produced by the combustion of the gas is recorded on the water heater, in the fume and though the wall of the water heater.

The gasification rate can be adjusted, by regulating the rate of the primary air supplied by the blower, with the help of the dimmer. As the gasification takes place, the rice husk fed into the reactor is transformed into gas and unburnt char mixed with ash. The gas is conveyed into the water heater, while the char is removed out the gasifier by pushing the ash drawer. Fresh fuel is fed into the reactor by actuating the screw feeder. Therefore, the level of the firing zone is kept at the same height during operation. Even if the char is vitrified because of high reaction temperature, the bridge formation is easy to break by the use of the screw feeder and the ash drawer. The screw feeder, connected to a steering wheel, forces the fresh rice husk to push downward the agglomerated char, while, the ash drawer, which slice and push the used layer towards the char container. Fresh fuel can be supplied and the residue in the bottom of the reactor can be removed as desired. The reactor is monitored to ensure that the temperature inside the gasifier doesn't rise more than 800°C. If not the rice husk will fuse and vitrification of the silica can occur. As the lid of the hopper is airtight, no air rises in the reactor. The draft is always kept downward, so the reversal of the draft is avoided.

To get efficient combustion of the producer gas, the amount of air (secondary air) supplied into burner of the water heater, is adjusted with the help of the combustion analyzer. In one hand, if the amount of the secondary air is not enough, the syngas is not entirely burnt. In the other hand, excess of secondary air is not good for the system because it will absorb heat from the combustion.

As the needed skills for driving the gasifier are obtained, and after adjusting the operating parameters, the experiments are conducted. The measurements are taken in steady state. The results is given below.

F. Performance of the Reactors

1) **Specific gasification rate, SGR**

The specific gasification rate is defined as ratio between the amount of rice husk gasified and the cross sectional of the gasifier. The behavior and the results of the gasifier depends mainly of this parameter, because it conditions the preponderance of each gasification reaction and consequently, the quality of the producer gas. During experiments, we noticed that, the setting of the amount of the air blew by the fan, adjusts the specific gasification rate. In practice, the regulation of the air flow rate is obtained by the adjustment of the dimmer value.

When the less air is fed into the gasifier, less rice husk is combusted, and the *SGR* is low. Contrary, as the air used for gasification increases, more fuel is combusted. Considering (1), the augmentation of the rice husk consumption increases the *SGR* . The min value of the *SGR* was 92kg/h.m². Below this limit, the reaction conditions was not enough to obtain burnable syngas. The max value of *SGR* was 292 kg/h.m² was the working limit for the designed gasifier. The min value of the *SGR* was 92kg/h.m². Below this limit, the reaction conditions was not enough to obtain burnable syngas. The max value of *SGR* was 292 kg/h.m² was the working limit for the designed gasifier. With *SGR* greater than the max value, the velocity of the air was too high, which causes fuel fluidization. In this condition, the bed is destroyed and gasification stops. Each parameters is analyzed as a function of the specific gasification rate (*SGR*).

2) **Output power rate, $\dot{Q}_{gaz}$**

The output power rate is the heat rate produced by the combustion of the producer gas ($\dot{Q}_{gaz}$). It is the sum of the heat absorbed by the water heater, the heat lost in the fume and the heat lost in the external wall of the heat exchanger. Radiation heat and conduction heat was neglected. **Error! Reference source not found.** shows the variation of $\dot{Q}_{gaz}$ with *SGR* varying from 92 to 292 kg/hm². Each kind of heat is recorded during the experiment. That is the heat received by the water heater $\dot{Q}_{RWH}$ the heat lost in fume $\dot{Q}_{LF}$ and the heat lost though the wall of the water heater $\dot{Q}_{LW}$. In general, $\dot{Q}_{RWH}$ represents 85% of $\dot{Q}_{gaz}$, while $\dot{Q}_{LF}$ and $\dot{Q}_{LW}$ is equal respectively to 12% and 3%. As the *SGR* is increasing, the $\dot{Q}_{gaz}$ increases, passes to a maximum and then decreases. The minimum power (4214 kCal/h) corresponds with *SGR* equal to 92 kg/hm². The maximum value of $\dot{Q}_{gaz}$ is 9790 kCal/h, which corresponds with an *SGR* equal to 275 kg/hm². For an *SGR* greater than 275 kg/hm², $\dot{Q}_{gaz}$ begins to decrease.

$\dot{Q}_{gaz}$ is equal to the energy contained in the producer gas, and permit to evaluate the performance of gasification. To produce more power, the *SGR* must be increased. This is explained by the following reasons:

- There is an optimal interval, in which the heating value of the producer gas reaches its maximum. The gas is rich in combustible element (CO, H_2, CH_4) and contributes to the high level of the power
- The increase of $\dot{Q}_{gaz}$ is the result of the increase of the gasification rate which produces more gas. More air is supplied into the reactor, so more fuel is combusted, and more fuel is converted into gas.

When the *SGR* is greater than 275 kg/hm², $\dot{Q}_{gaz}$ diminishes. This condition corresponds with an excess of gasification air. The velocity of the air is too high, and destroys the bed reactor. Moreover, the excess of air introduced into the reactor, absorbs more heat, cools the bed temperature, and lower the gas production.

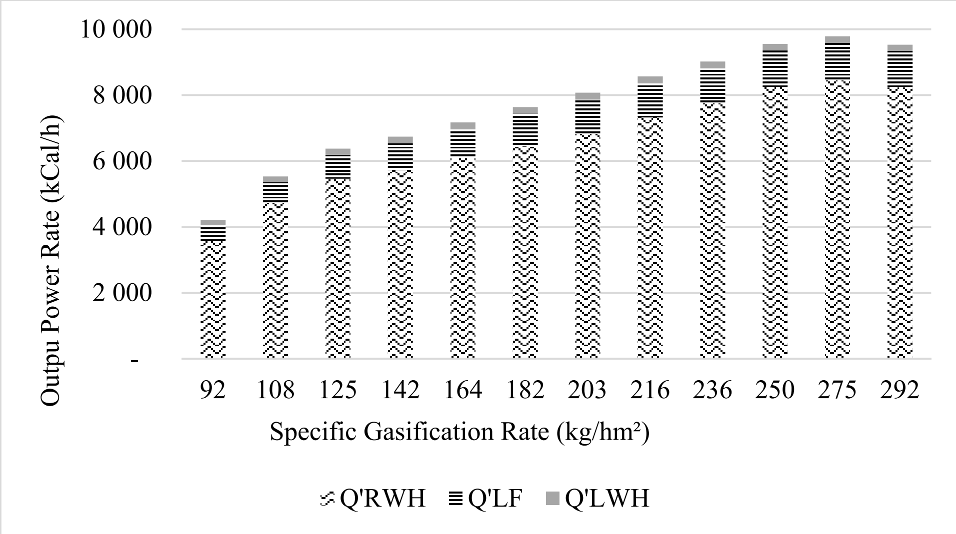

Fig. 2 Variation of the heat produced of the syngas with specific gasification rate

3) **Fuel Specific Consumption , FSC**

Fig. 2 illustrates the variation of *FSC* and $\dot{Q}_{gaz}$ with the *SGR* . First, in the interval of *SGR* 92 to 125 kg/hm², *FSC* decreases up to a minimum value 0.62 kg/kCal, and then increases up to a maximum value 0.96 kg/kCal, for *SGR* greater than 125 Kg/m². There is an optimal value of *SGR* , in which the gasification process is efficient, which corresponds with low fuel consumption.

For an *SGR* less than the optimum value (125 kg/hm²), the reactor condition does not produce high quality of the producer gas. Surely, as a few amounts of air is introduced in the reactor, less fuel is combusted, and the bed temperature is not high enough. Consequently, the gasification reactions, especially reduction reactions are less important. The result is a gas with poor composition, with poor heating value. In this condition, much fuel is needed to produce 1kCal of heat. In this zone, the low value of $\dot{Q}_{gaz}$ is the consequence of a poor quality of the producer gas.

For an *SGR* close to the optimum value (125 kg/hm²), the reaction conditions are well suited to produce gas with good composition. The amount of air is well adjusted, to develop the best temperature condition and to ensure the importance of gasification rate. Consequently, less rice husk is utilized to produce 1kCal of heat. The best *FSC* is given by a good composition of the producer gas that means the best heating value.

As *SGR* value becomes more important, the *FSC* increases with $\dot{Q}_{gaz}$. In this condition, much air is blown into the gasifier, and the formation of CO_2 (complete reaction) is advantaged, instead of formation of CO and CH_4 (Partial reaction). The quality of the gas is lower, because of the low content of combustible element. This observation is in accordance by the result found by [4]. He related that at 1000°C, by raising the equivalence ratio from 0.3 to 0.6, the content of CO drops from 18.6 to 8.6 %, and the percentage of H_2 decreases to 21.5 to 8.7%. Too much air for the gasification will degrade the gas composition, and lower its heating value. Moreover, as the reaction becomes more important, the displacement of the firing zone grows also. To ensure continuous production, and to maintain the reaction zone at the right height, the char must be removed prematurely, without reacting completely. Therefore, the residence time of the rice husk into the reactor is lower. The fuel the consumption raises with the increase of unburnt fuel.

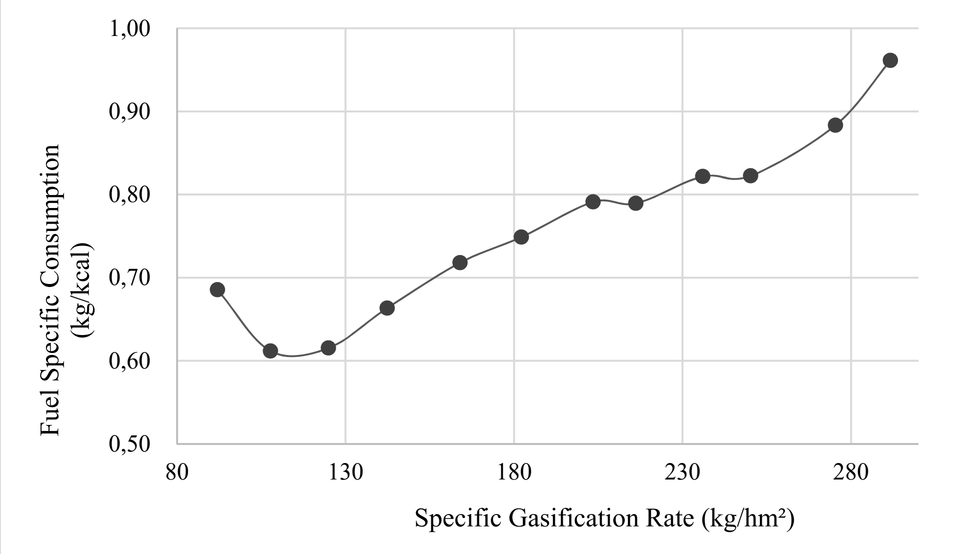

Fig. 3 Variation of FCS with the *SGR*

4) Energy contained in the residue $\dot{Q}_{CHAR}$ and mass conversion rate τ_m

As the gasifier is started, the draft is maintained by the help of the air, blown into the reactor. The different reactions take place (drying, pyrolysis, oxidation, reduction). The predominance of each reaction depends on the air flow, the gasification rate, the reactor temperature and other operating parameters. During gasification, the rice husk is transformed into syngas and char (mix of unburnt fuel and ash). To ensure continuous production, fresh fuel must be supplied continuously, and the reaction product must be removed from the reactor. Fresh fuel is available from the hopper, by actuating the screw conveyor. The producer gas is pushed out the reactor through the gas duct with the help of the draft, while the solid residue (char and ash), stays into the reactor. If the residue is kept into the reactor, the firing zone tends to move towards the fresh fuel, that means in direction of the hopper. The speed of the firing zone depends on the gasification load, and reactor dimension. For a low *SGR* , less air is needed and less fuel is combusted. In this condition, the firing zone moves slowly (1.3 cm/min for *SGR* =92 kg/hm²). Contrary, if the gasification load is higher, more air is supplied, and more fuel is reacting. Consequently, the bed movement is faster (up to 4cm/min for *SGR* =255 kg/hm²). In ideal condition, all the carbon contained in rice husk should be used and transformed in syngas. That means, the residue should be composed of ash only, without any carbon. In real condition, the total consumption of the matter is impossible, because the char must be removed earlier to keep the firing zone at the desired height. The experiments, allows us to study the effect of *SGR* on $\dot{Q}_{CHAR}$ and τ_m, and to determine the best condition which ensure maximum conversion, and minimum energy loss in the residue.

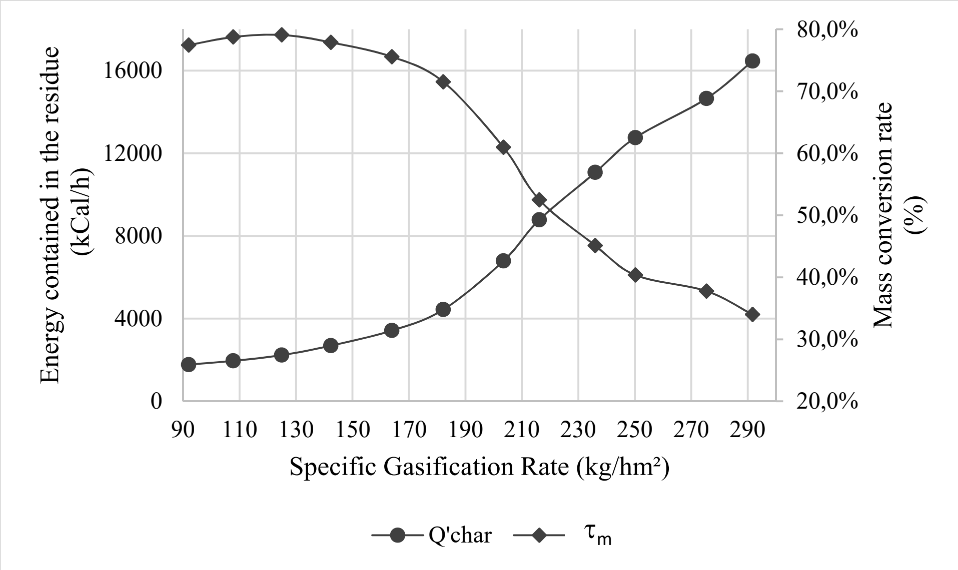

Fig. 4 Variation of $\dot{\boldsymbol{Q}}_{\boldsymbol{CHAR}}$ and $\boldsymbol{\tau_m}$ with *SGR*

As showed in Fig. 4, for an *SGR* comprised between 92 and 164 kg/hm², τ_m is almost constant, whatever the value of *SGR* . The maximum mass conversion is about 78%. That means, for 100 kg of raw material, 78 kg is gasified in the reactor, and the remaining, about 22%, is lost with the solid residue (char mixed with ash). For an *SGR* greater than 164 kg/hm², τ_m decreases suddenly up to 34%. In this range, as seen previously, the drop of τ_m value is explained by the fact that, an important amount of rice husk does not have enough time to react and must be removed out the reactor prematurely, because of the high speed of the firing zone.

$\dot{Q}_{CHAR}$ represents the energy lost in the char, as the rice husk is not entirely used, during gasification process. In the same range, where τ_m is almost constant (92 to 164 kg/m²), $\dot{Q}_{CHAR}$varies proportionally with *SGR* . The increase of $\dot{Q}_{CHAR}$ is the result of augmentation of the amount of gasified rice husk $\dot{M}_{RH}$. For *SGR* greater than 164 kg/m², $\dot{Q}_{CHAR}$ grows rapidly, like explained earlier. The residence time of rice husk into the gasifier is lowered, because of high speed of the firing zone. Consequently, much matter is discarded in the residue, and the energy loss is more important.

A better mass conversion rate is obtained with another kind of gasifier, in which more fuel is combusted and less matter is thrown away in the by product. In comparison with a batch mode gasifier developed by [4], the mass conversion rate was 83.1% (Char produced 16.9 %) with an *SGR* equal to 108 kg/hm².

5) **Approximate low heating value LHV_{gas} and gasification efficiency η**

The variation of gasification efficiency η and the low heating value LHV_{gas} as a function of *SGR* , is depicted in **Error! Reference source not found.**. LHV_{gas} increases first in the range of 92 and 125 kg/hm², peaks to a maximum value (1313 kCal/Nm^3), and decreases in the range of 125 to 292 kg/hm².In the first range, the increasing value of LHV_{gas}, is explained by the fact that, the CO and H_2 content is increasing, while CO_2 concentration is decreasing. Consequently, the gas concentration is performed and so the heating value. The high content of CO and H_2 is the result of the optimum temperature of the reactor. This temperature is high enough to promote the reduction reactions (steam reforming, methane forming, Boudouard reaction) which enhance the content of CO and H_2, and increase the heating value of the gas:

- One part of the incandescent char is reacting with the water in the fuel (in the form of steam) to produce more CO and H_2
- A second part of the char in the reactor reacts with the H_2 to produce more CH_4
- A third part of the char is reacting with the CO_2 and enhance the CO and H_2 yield

When *SGR* becomes greater than 125 kg/hm$_2$, LHV_{gas} diminishes. In fact, as the gasification rate increases, the air introduced into the reactor is more important. The reaction tends to the complete combustion and generates more CO_2 than CO. The concentration of the gas is poor, and the heating value is low. This result agrees with [14] observation. They concluded that optimum temperature of the reactor enhance the gasification yield. [15] found also that higher the feeding rate, the lower is the content of CO and H_2, and the lower is the gas low heating value.

Moreover, the introduction of more air into the reactor increases the amount of N_2, which cools the reaction zone. N_2 does not play any work into gasification process, but it absorbs the heat of the reacting zone. Consequently, the temperature is decreasing, and reduction reaction becomes less effective.

In comparison with standard value, the low heating value of the designed gasifier is lower. The gap is about 6 to 10%, depending on the gasifier design, and operating condition. The difference in value is possibly due to errors in measurement precision, in sampling, and in evaluation of the heat exchange efficiency (because radiation heat transfer was neglected).

In accordance with (10)$\eta = \frac{1}{FSC.LHV_{RH}}$, gasification efficiency η is inversely proportional to *FSC*. When *FSC* is increasing, η is decreasing, and conversely. The maximum value of η corresponds to the minimum value of *FSC*. As indicated in **Error! Reference source not found.**, within the value of 92 to 108 kg/hm², η increases, reaches the maximum value of 49,9%, and then decreases in the range of 125 to 292 kcal/hm². The worst value of η is 31.8%, which corresponds to *SGR* of 292 kCal/hm². The increase of η for an *SGR* less than 125 kg/hm² is due to the improvement of gas composition. The content of CO, H_2 and CH_4 is growing while content of CO_2 is diminishing. The rice husk introduced into the gasifier is converted into gas with the best composition, thanks to the optimal condition for gasification.

A high value of efficiency is also the result of high biomass conversion. The zone where the efficiency is maximum (108 to 125 kg/hm²), is included in the zone where the mass conversion rate is at its highest value (92 to 164 kg/hm²). A good gasification rate combined with high mass conversion rate, gives a maximum efficiency.

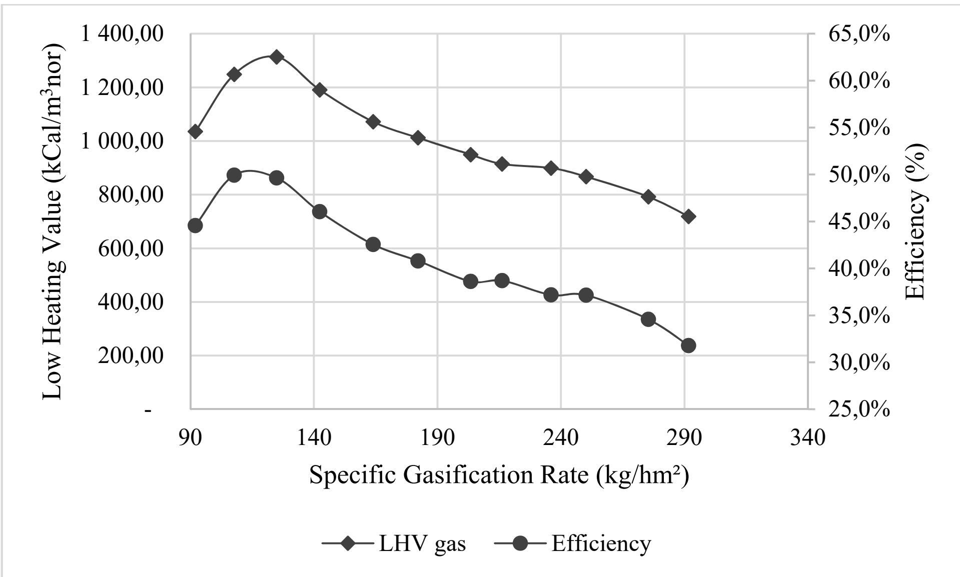

Fig. 5 Variation of LHVgas and η with

Nevertheless, for *SGR* greater than 125 kg/hm², the mass conversion τ_m becomes lower. As seen previously, when the air introduced into the reactor is excessive, the reaction tends to be complete, rather than gasification reaction. Moreover, the bed movement is faster, consequently, the char in the reduction zone must be removed earlier, to ensure continuous production and maintain the firing zone at the right height. The unburnt fuel discarded in the residue, is also one reason of the efficiency drop.

Compared with standard value (Fig. 6), of rice husk gasifier, the efficiency of the designed gasifier is lower, but the performance is acceptable. However, the gasification rate, corresponding to the best efficiency is in accordance with the experiments carried out by [6]. They found that the maximum efficiency of the downdraft gasifier was 54%, corresponding with *SGR* equal to 122 kg/hm². The rice husk gasifier stove designed by [4] have a best efficiency equal to 13% corresponding to *SGR* equal to 107 kg/hm², which is also close to the *SGR* corresponding to the maximum efficiency, for the present work.

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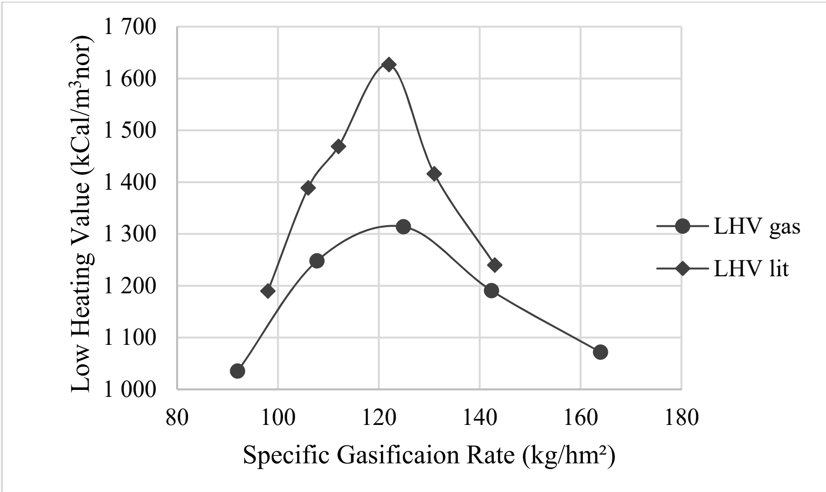

Fig. 6 Comparison of LHVgas with LHV of rice husk syn gas available on literature

IV. Conclusion

This work presented a study about rice husk gasification, which is an applicable solution for energy problem in Madagascar. A downdraft gasifier was designed, developed and tested. The consideration of the functional requirements and the possible troubleshooting reported by previous experiences and other researchers enriched the design process, so that many operating problems were avoided during experiments. The designed gasifier worked successfully. The high capacity to the hopper, with airtight lid ensured continuous feeding of the gasifier, and prevented flow reversal. The continuous operation was also performed, thanks to the arrangement of the char container, the screw conveyor, the ash drawer, which prevented the bridging and facilitated the ash removing from the reactor. Moreover, by monitoring the bed temperature, vitrification of ash was avoided. Results showed that such technologies is affordable by local techniques, and confirmed its applicability as an energy solution, in Madagascar. As the specific gasification rate grew, the output power rate increased and peaked to a maximum value (9 790 kCal/h). The output power rate decreased with load rate greater than 275kg/hm². The best efficiency (49.9%) corresponding to the lowest fuel specific consumption (0.61 kg/kCal), was in the range of 108 to 125 kg/hm². Furthermore, the best mass conversion rate (78%) was in the range of 92 to 164 kg/hm². The maximum low heating value of the gas was 1 313.70 kCal/m^{3}nor, corresponding to a specific gasification rate of 125 kg/hm2. Excessive gasification rate degraded gasifier performance, because complete reaction is favored instead of partial reaction. Moreover, the excess of N_2 brought by the supplied air increases the heat loss.

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