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# Evaluation of the conversion efficiency of the 180Nm$^3$/h Johansson Biomass Gasifier™

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**Abstract**
Biomass gasification is the thermochemical conversion of biomass materials into a producer gas, which is a mixture of carbon monoxide, carbon dioxide, methane, hydrogen, nitrogen and water vapour. The 180Nm$^3$/h System Johansson Biomass Gasifier (SJBG) at Eskom research and Innovation Centre is used for research and development initiatives, and also for demonstration purposes. The aim of this research was to investigate the efficiency of the gasifier and. This is done through an analysis of the gas profiles at the gasifier using a custom-built gas and temperature measurement system. Non-Dispersive Infrared gas detection technique is applied to monitor the volume and quality of producer gas. Palladium/Nickel gas sensing is applied to monitor the hydrogen content in the gas stream. Temperature in the gasifier is monitored through the use of type K thermocouples. The gas and temperature sensors are connected to the data logger interfaced to a computer. The heating value of the producer gas was determined from the percentage composition of the combustible gases. Evaluation of the efficiency of this gasifier was done before the installation of a 300Nm$^3$/h at a rural village. The gasifier achieved an efficiency of 75% with an average gas heating value of 6MJ/Nm$^3$.


**Keywords:** Biomass waste, Conversion efficiency, Gasification, Gas analysis, Gas heating value.

## 1. Introduction
Biomass gasification is an old concept that is starting to gain popularity due to the search for renewable energy sources that could improve the global carbon footprint. Gasifier efficiency is an important factor used in determining the technical and economic viability of using a gasifier system [1]. There exist various types of biomass gasifier technologies, each designed for specific fuel types. The efficiency and effectiveness of these gasifiers is dependent on, amongst other things, the gasifier type/design. Fluidized bed gasifiers achieve higher efficiencies than fixed bed and other gasifier types but they are not preferred for electricity generation because of their high levels of tar production. Amongst the fixed bed gasifiers, updraft gasifiers are more efficient but generally fixed bed downdraft gasifiers are preferred for electricity generation using gas engines or turbines; this is basically because they produce gas with very little quantities of tar compared to their updraft counterparts. The tar in the gas poses major operational challenges because it clogs in the engine valves resulting in high engine maintenance costs. There are tar removal processes that also increase the cost of operating biomass gasifier systems.
The 180 Nm$^3$/h Johansson biomass gasifier system was investigated to establish its performance prior to installation of a 300Nm$^3$/h gasifier system for electricity generation to support community economic development in the rural Eastern Cape Province, South Africa. The pilot plant was meant to demonstrate

the use of renewable energy sources to improve the socio-economic status of rural communities, which constitute the majority of people living in South Africa. The project was also meant to contribute towards the 10000GW renewable energy contribution to final energy target set by the South African government. South Africa is endowed with large quantities of biomass waste resulting from industrial processes such as saw mills, pulp and paper industries as well as the sugar industries. Most of these industries are situated in rural areas with people who either cannot afford the energy services or are not connected to the electricity grid. Biomass gasification could therefore be used to provide such communities with low cost electricity for domestic and/or small business enterprises.

## 2. Description of the system Johansson Biomass Gasifier

The System Johansson Biomass Gasifier (SJBG) is based on the German Imbert downdraft gasifier. K. G. Johansson (South African) modified the Imbert gasifier into a tar free gasifier. He developed an internal air pre-heater system making it possible to attain sufficient high temperature (1500°C) and long enough residence time for tar cracking. Figure 1 shows the schematic diagram of the SJBG. The SJBG consists of the gas producer, purification unit and the generator. The gas producer is an 180Nm$^3$/h gas production unit. The purification unit consists of the cyclone, the gas scrubber/cooler with cooling pond, the particle interference filter and the engine safety filter. The gas is used to run a gas engine that drive generators for electricity generation. The gas is produced in the gas producer and channeled through the purification unit that removes the fine carbon particles before it is used to fuel the gas engine. This research focuses on the conversion efficiency of the gasifier without looking at the downstream processes and associated components.

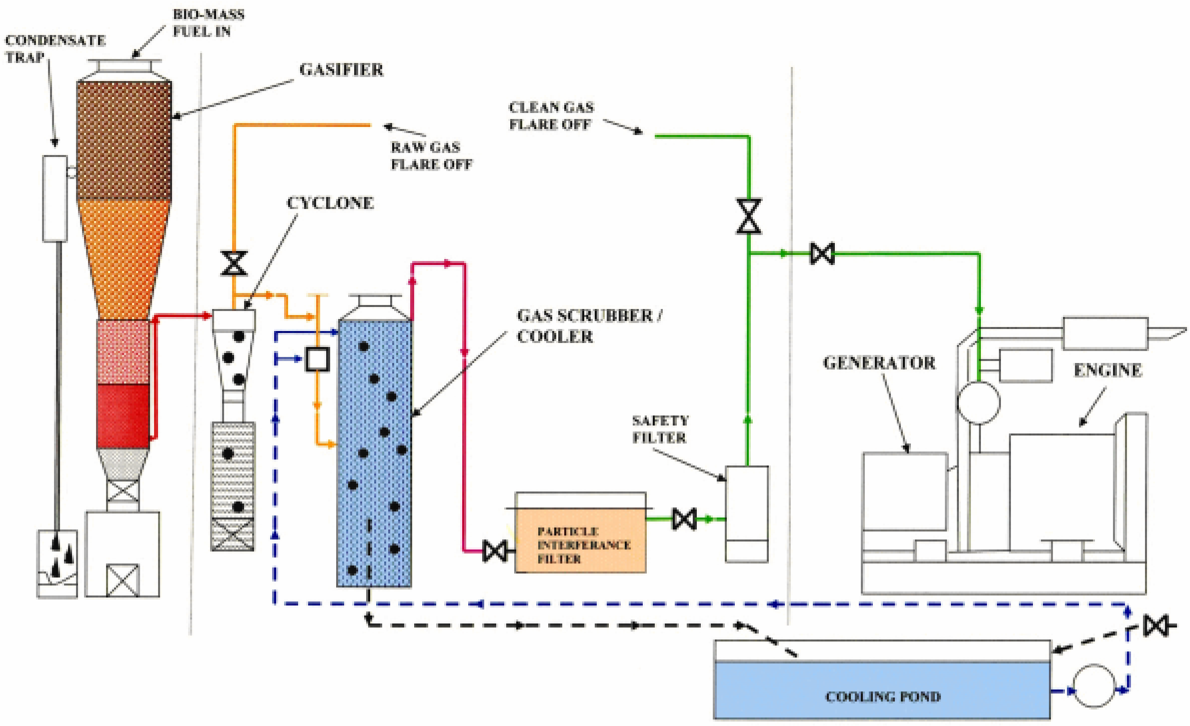


Figure 1. Schematic diagram of the system Johansson Biomass Gasifier

Figure 2 shows the photo of the 180Nm$^3$/h gasifier. When the fuel is introduced into the gasifier, it first passes through the fuel hopper/drying zone where it is dried at temperatures above 100°C; it then goes into the carbonization zone where it is converted to charcoal at temperatures above 500°C giving gas as a by product. The fuel then gets combusted in the oxidation zone with air supply from the surrounding environment. The temperature in this zone reaches a maximum of 1500°C converting the tar into useful gases. This is because the ambient air is pre-heated to about 500°C through the internal air pre-heater system raising the temperature inside the reactor. Reduction reactions take place below the combustion zone resulting in a number of useful gases.

Figure 2. Photo showing the gasifier

The process taking place in the gasifier is as follows:
Combustion occurs in the oxidation zone. Introduced air in the oxidation zone contains (besides oxygen and water vapours) inert gases such as nitrogen and argon. These inert gases are considered to be non-reactive with fuel constituents. Oxidation takes place at temperature between 700-2000°C. Heterogeneous reactions take place between oxygen in the air and solid carbonized fuel (Charcoal), producing carbon monoxide. Hydrogen in the fuel reacts with oxygen in the air, producing steam. Combustion is described by the following chemical formulae:

$$C + O_2 \rightleftharpoons CO_2 + 401.9 \text{kJ/mol} \tag{1}$$

$$H_2 + ½O_2 \rightleftharpoons H_2O + 241.1 \text{ kJ/mol} \tag{2}$$

The gas forming reactions that take place in the reduction zone of the gasifier are as follows:
Boudouard reaction

$$CO_2 + C + 164.9 \text{kJ/mol} \rightleftharpoons 2CO \tag{3}$$

Water-gas reaction

$$C + H_2O + 122.6 \text{kJ/mol} \rightleftharpoons CO \quad + H_2 \tag{4}$$

Water shift reaction

$$C + H_2 + 42.3 \text{kJ/mol} \rightleftharpoons CO + H_2O \tag{5}$$

Methane production reaction

$$C + 2H_2 \rightleftharpoons CH_4 + 75 \text{kJ/mol} \tag{6}$$

$$C + 3H_2 \rightleftharpoons CH_4 + H_2O + 205.9 \text{kJ/mol} \tag{7}$$

Reduction reactions, Eqs (3) and (4) are the main reactions taking place in the reduction zone and they are endothermic, this results in temperature decreasing during these reactions [2-4].

## 3. Research methodology

The method employed involved simulation of the gasifier operating performance using a command based downdraft biomass gasifier modeling program developed by T.H. Jayah [5]. A custom built Gas and Temperature Monitoring System (GTMS) [6] was used to establish the gas volumes and temperature inside the gasifier. The GTMS employs Non Dispersive Infrared (NDIR) gas sensors for measurement of CO, $CO_2$ and $CH_4$; it employs the use of Palladium/Nickel (Pd/Ni) sensor for measurement of hydrogen content. Temperature is measured through the use of type K thermocouples. The NDIR and Pd/Ni sensors were selected due to their selective sensitivity to the particular gas species without cross sensitivity. In this case NDIR sensors with gas correlation filter were used to avoid cross sensitivity amongst hydrocarbons. The gas heating value and gasifier conversion efficiency were then calculated from the percentage composition of combustible gases [7]. The following equation was used to calculate the gas heating value:

$$CV = \frac{(H_{2Vol} \times CV_{H_2}) + (CO_{Vol} \times CV_{CO}) + (CH_{4Vol} \times CV_{CH_4})}{100\%} \tag{8}$$

where $CV$ is the gas calorific value/heating value (MJ/Nm$^3$), $H_{2vol}$ is the volume concentration of hydrogen gas (%), $CV_{H_2}$ is the calorific value of hydrogen as reflected in the standard gas table (MJ/Nm$^3$), $CO_{vol}$ is the volume concentration of carbon monoxide (%), $CV_{CO}$ is the calorific value of carbon monoxide gas as reflected in the standard gas table (MJ/Nm$^3$), $CH_{4vol}$ is the volume concentration of methane gas (%) and $CV_{CH_4}$ is the calorific value of methane gas as reflected in the standard gas table (MJ/Nm$^3$).

The following equation was used to determine the conversion efficiency of the gasifier:

$$\eta = \frac{H_g \times 2Nm^3/h}{H_w} \times 100\% \tag{9}$$

where η is the cold gas efficiency, $H_g$ is the gas heating value and $H_w$ is the average calorific value of wood. The 2Nm$^3$/h is the gas flow rate from the gasifier.

## 4. Results and discussions

### *4.1 Simulated results*

Figure 3 shows the gas compositions obtained through simulations. The average gas compositions were found to be 25% CO, 26% $H_2$, 8% $CO_2$, 1.8% $CH_4$ and 37% $N_2$. The quantity of Nitrogen is higher because the gasifier is air blown. Figure 4 shows the simulated gas heating value and gasifier efficiency calculated from the percentage contribution of combustible gases viz carbon monoxide, carbon dioxide and methane. The heating values of these gases were obtained from the standard gas table; they are 10.1MJ/Nm$^3$ for hydrogen, 12.64MJ/Nm$^3$ for carbon monoxide and 38MJ/Nm$^3$ for methane. Although methane has a higher heating value than carbon monoxide and hydrogen, its contribution to the producer gas heating value is outweighed by that of hydrogen and carbon monoxide because the latter gases are produced in larger quantities than methane.

The gasifier conversion efficiency was calculated using equation 9. A gas flow rate of 2Nm$^3$/h was assumed, which is the gas flow rate in the 180Nm$^3$/h gasifier; and a wood heating value of 17.5MJ/kg was used because it is the average calorific value of the wood used during the experiment. It was established that the conversion efficiency of the gasifier is directly proportional to the gas heating value. This is clearly observed in Figure 4. This is basically because the conversion of energy is from a solid (wood) to a gaseous (producer gas) energy carrier. This represented the cold gas efficiency of the gasifier. An average efficiency of 75% was achieved from the simulation data, this efficiency is within the known cold gas efficiencies of biomass gasifier systems [8], which ranges between 65% and 75% with some gasifiers reaching as high as 90%. However the high conversion efficiencies are achieved by other gasifier types that are not suitable for electricity generation using gas engines/turbines. This is because of their high levels of tar production.

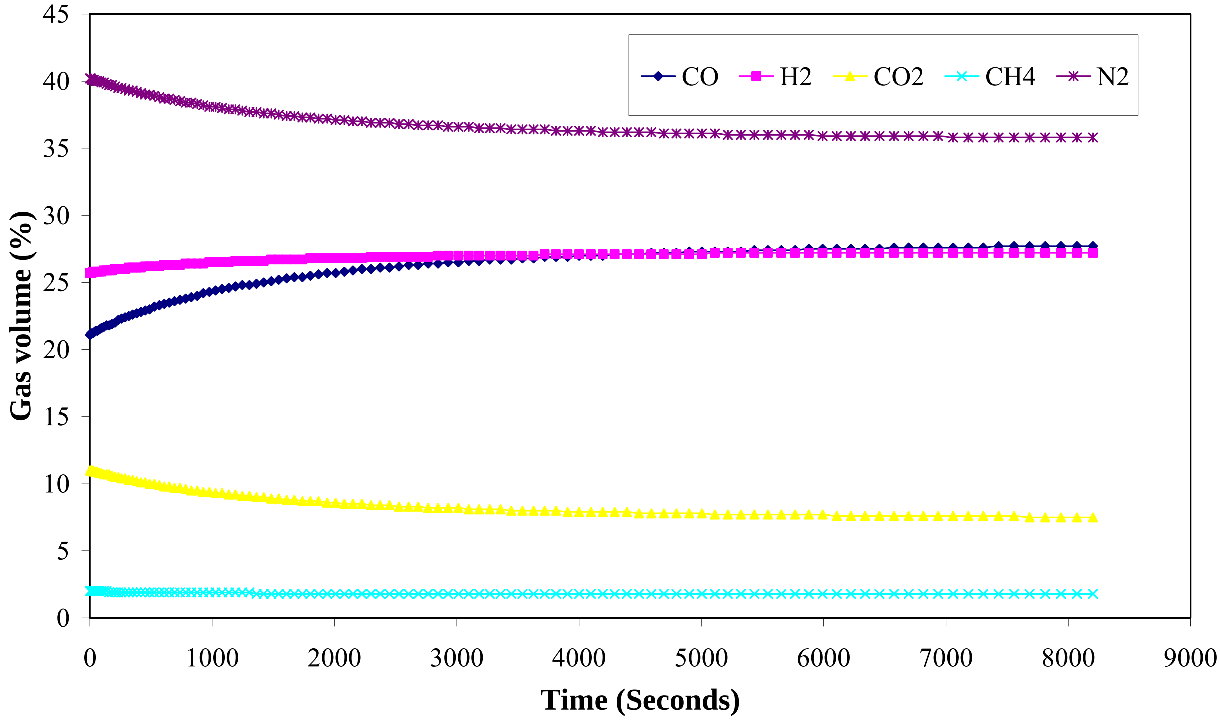


Figure 3. Simulated gas compositions

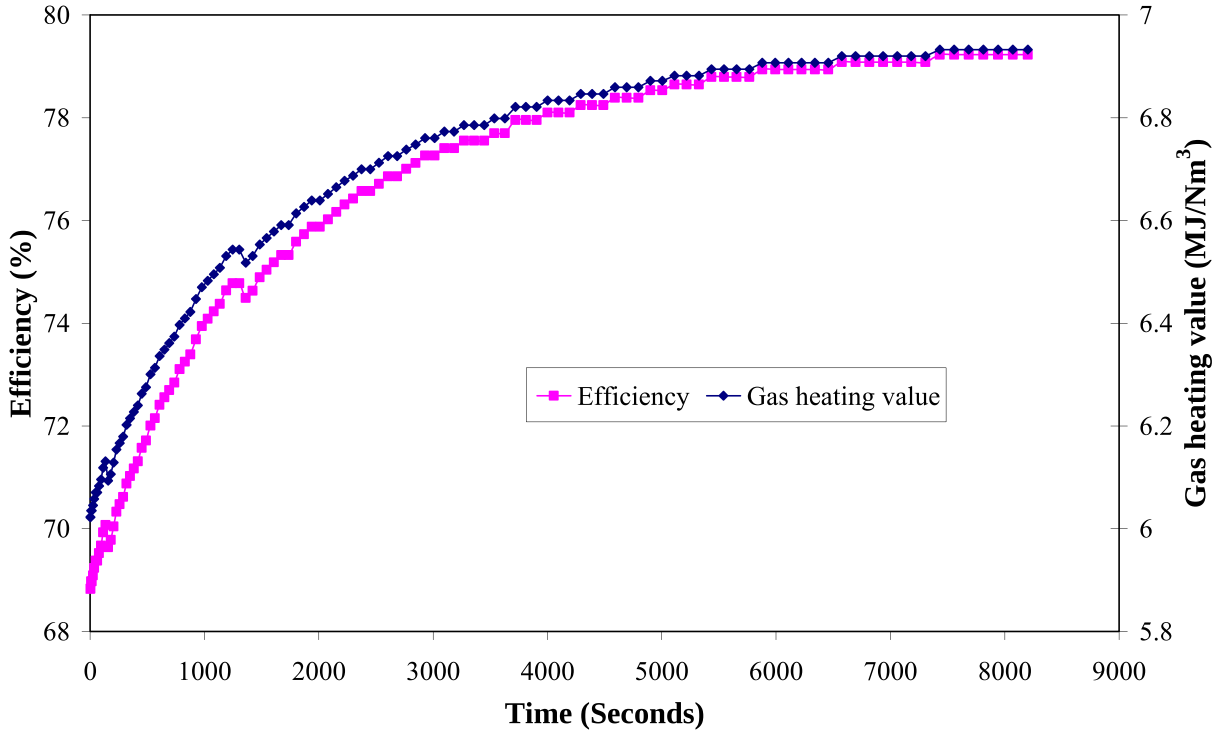


Figure 4. Gas heating value and gasifier conversion efficiency calculated using the percentage composition of combustible gases

*4.2 Measured results*

Figure 5 shows the major gas composition obtained using the gas and temperature measurement system. The measurements were taken when the gasifier operated for 20 minutes; at this time the gas production is already stable hence the data presented resembles uniform gas profiles. The uniformity of the gas profiles also implies that the gasifier operating conditions do not change drastically during operation, which is a good aspect. The variations in gas production represents inconsistent gasifier operating conditions, therefore the gasifier cannot be reliable. Variations are experienced with varying loads but they are not as drastic. The gas production follows the engine demand f the gasifier is coupled to an operating engine, however in this case the gasifier was not coupled to an engine but operated from the air blast.

An average of 30% hydrogen content was measured during experimentation, which was slightly higher than the simulated figure. The volume concentration of 25% was measured for carbon monoxide, which was not different from the simulation results. The volume of carbon dioxide was found to be an average of 15%, which was slightly higher than the simulation results, the average methane content was 1.4%, just 0.4% lower than the simulated results. The latter gas profiles did not have a huge impact on the conversion efficiency of the gasifier as evident in Figure 6.

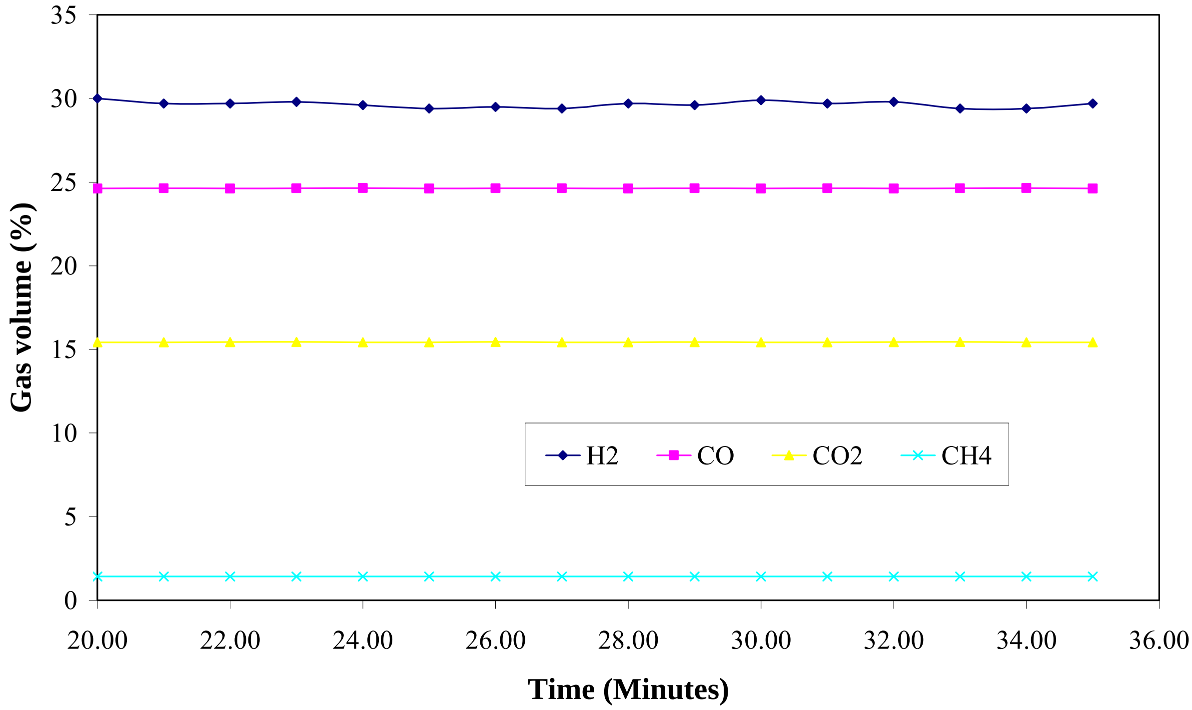


Figure 5. The measured gas compositions

Figure 6 shows the gas heating value and the gasifier conversion efficiency, the average gas heating value was found to be 6.64MJ/Nm$^3$. This was 0.4% higher than the simulated heating value which was 6.60. This had a slight impact on the conversion efficiency as the latter is directly proportional to the gas heating value. The measured data suggested a conversion efficiency of 76% as shown in figure 6, while the simulated data suggested an efficiency of 75%, however both values still lie within the known cold gas efficiencies of biomass gasifiers as reported previously in this paper, and the 1% difference is insignificant.

The conversion efficiency of biomass gasifiers is dependent on gasifier operating conditions and fuel properties. The experimental gasifier operating conditions were used during simulation of the gasifier performance. The gasifier operates at atmospheric pressure (1bar); the maximum temperature recorded in the gasifier was 1500°C at the igniter sleeve after 20 minutes from start-up. The air temperature before pre-heating was 25°C, this gets preheated to around 500°C before entering the combustion zone to maintain the temperature at a maximum of 1500°C in the combustion zone to enable tar conversion. Higher gasification efficiencies are achieved at higher temperatures [9]. The air inlet temperature was

kept at 500°C for simulation. The equivalence ratio of 0.26 was also assumed for simulations, which is the operating equivalence ratio for the Johansson biomass gasifier.
It has been established that maximum efficiency is achieved with an equivalence ratio of 0.26. As more air is supplied hydrogen and carbon monoxide gases yield reduces, this is because of the oxidation of the latter gases to water vapour and carbon dioxide respectively [10].The calorific value of gases decreases with an increase in equivalent ratio [11].

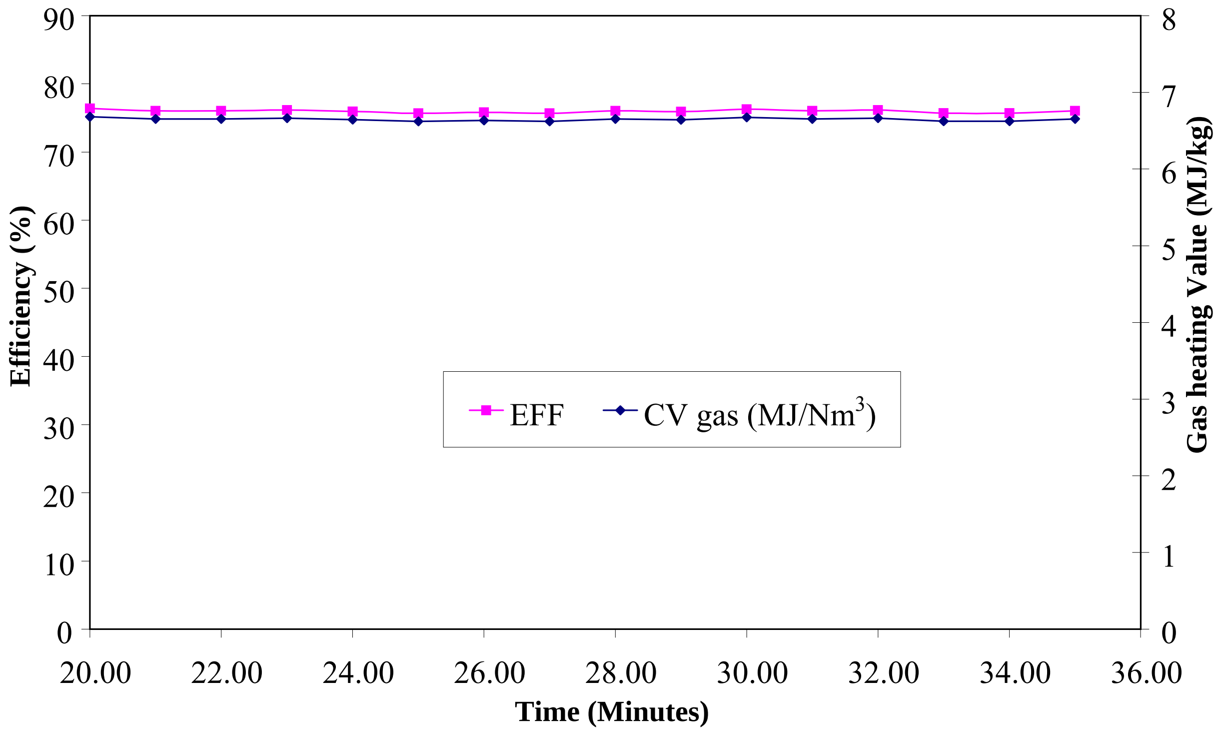


Figure 6. The gas heating value and gasifier conversion efficiency

## 5. Conclusion

This paper sought to establish the conversion efficiency of the 180Nm$^3$/h Johansson Biomass Gasifier System installed as a research and development prototype by Eskom. The main aim of this work was to establish the conversion efficiency of the gasifier before installation of a 300Nm$^3$/h gasifier system at a rural village for community economic empowerment. The conversion efficiency of biomass gasifiers is an important factor that determines the feasibility of using a biomass gasifier, hence the relevance of this work. The findings of this work assisted in decision making regarding the installation of the commercial plant, which has since been installed.

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