Performance Evaluation of a 25 kW_e Biomass Power Generation System Prototype for Community in Thailand

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ABSTRACT

This paper describes a 25 kW_e biomass power generation system that was developed and operated at the School of Renewable Energy Technology. The purpose of this study is to evaluate system performance in the first 6 months. The system is comprised of two main parts namely, downdraft gasifier system and gas engine-generator system. In this study Eucalyptus wood chips were gasified with a downdraft gasifier, finally the producer gas was used to generate electricity by engine-generator system. The gasifier performance was evaluated in terms of fuel consumption rate, calorific value of producer gas and gasification efficiency. The gas engine-generator system was evaluated in terms of power generation efficiency. Results of this study shown that fuel consumption rate was about 50 kg h^{-1}, heating value of producer gas was 4.5 MJ m^{-3}, gasification efficiency was about 66% and efficiency of gas engine-generator system was about 15%. System performance, therefore, was 10%.

Keywords: *Biomass, Gasifier, Gasification, Gas Engine System, Power Generation System, Performance*

1. INTRODUCTION

The agricultural sector is the base of Thailand's economy and accounts for about 60% of labor forces. Biomass can be derived from the cultivation of dedicated energy crops and from biomass wastes. Major sources of biomass in Thailand are sugar cane, rice, oil palm and wood waste which yield a total potential of nearly 80 million tons per year [1]. The agricultural residuals in year 2002 can be estimated at about 48,294 million kg and can be converted to energy of about 721,936 TJ or 9,630 MW [2, 3]. Wood industry is also a major source which is mostly concentrated in the northern part of the country, whereas rubber wood and Eucalyptus plantations are found mostly in southern and northeastern regions, respectively. Among these potential biomass sources, waste products from wood and agro-industries apparently are the least expensive.

Nowadays, Thailand has unoccupied land of about 5.60×10^9 m^2 [4]. C_4 plants have the potential to produce over 120 tons wet weight per hectare per year, so in Thailand, unoccupied land can be developed for biomass sources of about 67 million tons per year wet weight of Eucalyptus wood, which can be utilized for energy generation of about 1,162,560 million MJ or 15,500 MW per year [5]. So biomass is the most common form of renewable energy sources and is expected to be used for power generation.

Biomass gasification technology is one of the most potential and suitable technologies for developing countries which have abundant biomass such as Thailand. Research into this technology has been ongoing for a long time and it has received increasing attention in the energy market but its optimization and further development for appreciation of the different conditions and kinds of biomass should be developed and researched continuously in each country. At present, gasification technology for electrical generation is not developed widely in Thailand. Using renewable energy sources will be encouraged by this technology for reduction of global warming, importing power and traditional community power in Thailand [6, 7, 8, 9].

Biomass power generation system prototype (BPGSP) in Fig. 1 was developed and tested by academic cooperation, namely School of Renewable Energy Technology (SERT), Wire & Wireless Co., Ltd., Thailand and Wind Ltd., Japan. This study aims to evaluate the system performance. The system is comprised of two main parts, namely, downdraft gasifier system that is combined with the cleaning system and gas engine-generator system. Eucalyptus residues shown in Fig 1 were used for fuel of gasification system.

Fig.1 The BPGSP at SERT (Left) and Eucalyptus residuals were used for fuel (Right)

2. MATERIALS AND METHODS

2.1 System description

The schematic diagram of BPGSP is shown in Fig. 2. The plant consists of components, which will be described in the following.

2.1.1 The downdraft gasifier system

The gasifier is of downdraft type with one air entrance opening. The throat is approximately 400 mm. Gasifier consists of a well-insulated cylindrical reactor, fixed type stainless- steel grate and an induced draft fan. The reactor is a cylindrical steel shell insulated from outside with fiberglass of 25 mm thickness and covered with stainless **s**teel. The air distribution unit that supplement the air taken through the electrical blower consists of an air tuyere of 65 mm diameter and 165 mm length. The tuyere consists of 20 holes (10 mm diameter of holes). This tuyere is placed at 350 mm above the grate in the middle of gasifier. The grate was fabricated from stainless-steel. The grate area (0.12 m^2) was designed from specific gasification rate (SGR) of 417 kg h^{-1} m^{-2} and a fuel input rate of 50 kg h^{-1}. The ash falls into the ash pit tank, which was fabricated from stainless steel sheets of 6 mm thickness. The volume of ash pit (0.12 m^3) was sufficient to allow operation without removal of ashes for many hours (around 30 h).

To start of the gasifier, not only an electronic air supply blower, capacity 0.5 kW, was used to supply air, but also an electric suction blower, capacity 0.7 kW, was used to suck a flame torch to ignite wood chips inside the gasifier. After the gasification was developed well and the engine operated by producer gases, the suction blower was switched off, but the main air supply blower was left on continuously.

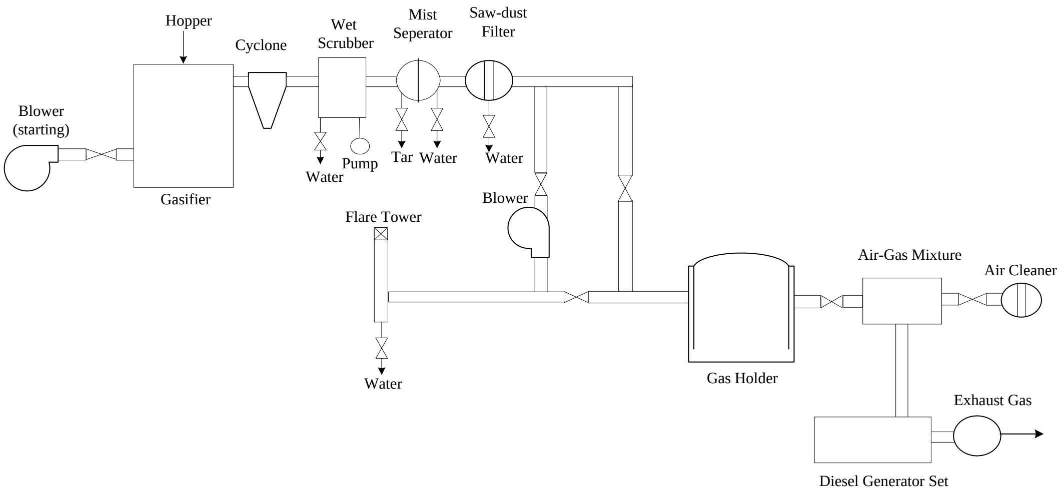


Fig. 2 Schematic block diagram of 25 kW_e BPGSP

The technical specifications of the gasifier system are given at the table 1 below.

Table 1 The technical specifications of the gasifier system

Gasifier system	**Technical specifications**
Type	Down draft, (closed top, throat-less)
Biomass	Eucalyptus wood chips
Biomass consumption rate	50 kg h-1
Capacity	607 MJ h-1
Ash removal unit	Manual rotating type.
Fuel feeding	Manual per batch
Gas discharge	Electric suction blower for starting up

Normally, gas cleaning/cooling system is integrated with gasifier. It is necessary for internal combustion engine. The main functions of gas cleaning/cooling system are removing tar and particulate and cooling gas for gas engine.

Gas cleaning/cooling system consists of the following.

Cyclone filter: when producer gas from gasifier is passed on to the cyclone filter, the coarse particulates are separated from the gas stream in a high efficiency cyclone separator by centrifugal force.

Wet scrubber: tar and some tiny particulates are cleaned and cooled by wet scrubber. The contact of the sprayed water from the upper scrubber and producer gas that flow from cyclone filter made the gas temperature cool down. Therefore, the volatile substances in producer gas are condensed and discharged with water. In this part the particulates in producer gas that were not cleaned by cyclone filter are captured by water again. Waste water from wet scrubber is treated before reused for closed system.

Mist separator: gases from wet scrubber have to be separated from the water vapor by mist separator before flowing to the internal combustion engine.

Saw-dust filter: for confidence of using producer gas in engine, there is no water vapor; gas will pass through sawdust and the water vapor will be absorbed by sawdust.

Gas holder: Producer gas was stored in the holder that could be flexible following the amount of producer gas. It is used to run the system continuously.

2.2.2 Gas engine-generator system

In this study the spark ignition engine was run on producer gas alone. Diesel engine was converted to full producer gas operation by lowering the compression ratio and installing a spark ignition system. Gas is introduced into the engine after being mixed with air. Engine speed is kept constant at 1,500 rpm.

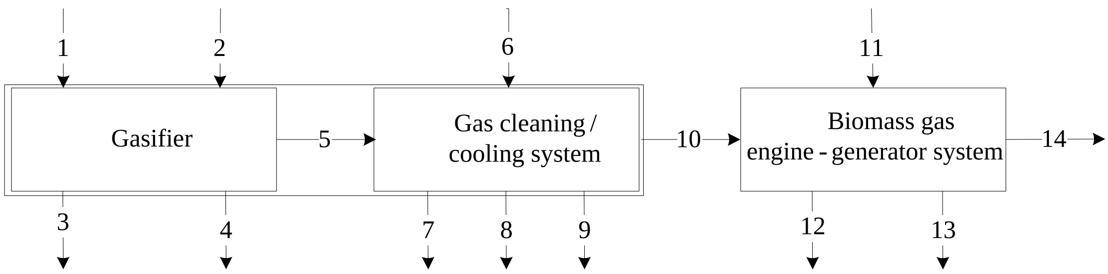
A modified diesel engine converts the engine's shaft power to electricity. The produced gas has proven to be excellent fuel for spark ignition engine. The 4-stroke engine is a natural aspirated six cylinder ($6 \times 1{,}000$ cc), spark ignition engine operating at full load. The engine is connected to producer gas and liquefied petroleum gas (LPG). LPG is used during start up and shut down for cleaning tar at the cylinders of engine. It is possible to operate the engine on producer gas, LPG or any mixture of the two.

This performance evaluation focuses on only producer gas to operate an engine. The produced electricity is supplied to dummy load. In future concept it will be supplied to an electric grid.

The alternator is a short-circuit proof, self-excited internal pole machine in synchronous construction with the following specifications: power output 62.5 kVA, power factor cos phi 0.8, voltage 380/220 V and frequency 50 Hz.

2.2 Theoretical considerations

Schematically, a gasifier system operating in conjunction with a spark ignited engine can be depicted as shown in Fig. 3. Three primary components are recognized: (1) the gasifier, (2) the gas cleaning or scrubbing system necessary to prove gas quality by removing tar, particulate matter, and water, and to cool the gas for the internal combustion engine, and (3) the engine-generator system. Each has material and energy flows as shown in the figure. Of interest for evaluating the first-law thermodynamic performance of the system is the thermal efficiency, which is defined as an overall system thermal efficiency, or taken at intermediate points depending on the application.



1, fuel; 2, air supply for gasification; 3, char; 4, heat transfer from the gasifier; 5, hot producer gas; 6, water into the gas scrubbing system; 7, water out of the gas scrubbing system; 8, particulate matter, tar and condensed water from the gas scrubbing system; 9, heat transfer from the gas cleaning system; 10, scrubbed producer gas; 11, engine combustion air; 12, engine exhaust; 13, heat transfer from the engine; 14, output power.

Fig. 3 Mass and energy flows in biomass gasifier-engine system.

An important factor determining the actual technical operation is the gasification efficiency. For the gasifier, a so called "hot gas" efficiency (evaluated at point 5 of Fig. 3) is normally defined which measures the ratio of the total gas power (sensible plus chemical) to the input power of the reactor (primarily in the form of fuel energy). A "cold-gas" efficiency (point 10) is recognized, which relates the gas power at the outlet of the gas scrubbing system to the input power of the reactor (primarily in the form of fuel energy).

An overall system efficiency (point 14) is defined as the ratio of total power (the engine brake power that was extended to generator) to the gasifier input power.

If the gasifier input power is taken (for approximation) as the fuel power, the overall system efficiency can be written as:

$$\eta_t = \frac{p_o}{P_i} \times 100\% \tag{1}$$

where η_t is the thermal efficiency (%), p_o is the total power of balance for three phase (W), p_i is the fuel power (W) [10].

The output power is the sum of all phase powers. For balance of three phase, the output power can be written as:

$$p_o = 3V_p \times I_p \times pf \tag{2}$$

where V_p is phase volts (V), I_p is phase current (A) and pf is power factor [11].

The input power, P_i can be written as:

$$P_i = H_s \times M_s \tag{3}$$

where H_s is lower heating value of gasifier fuel (kJ kg^{-1}), M_s is gasifier solid fuel consumption (kg h^{-1}).

A useful definition of the gasification efficiency if the gas is used for engine applications is:

$$\eta_m = \frac{H_g \times Q_g}{H_s \times M_s} \times 100\% \tag{4}$$

where η_m is gasification efficiency (%) (mechanical), H_g is heating value of the gas (kJ m^{-3}), Q_g is volume flow of gas (m^3 h^{-1}).

The heating value of such a stoichiometric mixture can be calculated from the following formula:

$$H_g = \frac{12{,}680\ V_{CO} + 10{,}800\ V_{H_2} + 35{,}900\ V_{CH_4}}{1 + 2.38\ V_{CO} + 2.38 V_{H_2} + 9.52\ V_{CH_4}} \tag{5}$$

where H_g is the heating value of a stoichiometric mixture of producer gas and air in kJ m^{-3}, V_{CO} is volume fraction of carbon monoxide in the gas (before mixing with air), V_{H_2} is volume fraction of hydrogen in the gas (before mixing with air), V_{CH_4} is volume fraction of methane in the gas (before mixing with air).

The maximum volume flow (m^3 h^{-1}) of gas can be calculated from the following formula:

$$Q_g = \frac{60 \times rpm \times D}{2 \times 1{,}000} \times stoichiometric\ air/gas\ ratio \tag{6}$$

where rpm is the number of combustion strokes in a given time (number of revolutions per minute: rpm), D is the displacement of cylinder, the stoichiometric air/gas ratio = 1:1 [12].

The specific gasification rate, ψ (kg m^{-2} h^{-1}), is defined as:

$$\psi = \frac{M_s}{A}, \quad (7)$$

where A is the reactor cross-sectional area (m^2).

2.3 System operation and analysis

Proximate and ultimate analysis of fuel was carried out before the test by the Department of Science Service, Ministry of Science and Technology, Bangkok, Thailand. Size of Eucalyptus wood chips ranges from $2 \times 2 \times 5$ to $4 \times 4 \times 7$ cm^3. Bulk density of Eucalyptus wood chips is about 284 kg m^{-3}. A bomb calorimeter was used to measure the lower heating values of biomass fuel.

Generally the system was operated 8 hours per day. At starting time, about 35 kg of wood chips were loaded up to the air nozzle level. At that time the electric air supply blower was started, drawing air for starting gasification for around 30 minutes, after that 15-20 kg fuel was loaded up on top of the gasifier.

At starting up, gas went to the flare tower and was ignited for burning gas. At that time, the gas engine was started by LPG for keeping warm and cleaning the engine. Then the producer gas became combustible gas, observed by ignition producer gas at the flare tower. After that the gas and air control valves were opened to air-gas mixture of 1:1 ratio before being passed to the engine and thereafter LPG valve and the suction blower were shut down. A stand with ladder was provided with the system for facilitating manual fuel feeding and other operations. Analysis of the feedstock is given in Table 2, and 3.

Table 2 Proximate analysis and calorific value data of Eucalyptus wood chips

Average proximate analysis data and energy content of Eucalyptus wood chips	
Moisture content (As received basis)	8.3
Volatile matter (% weight dry basis)	78.91
Ash (% weight dry basis)	0.37
Fixed carbon (% weight dry basis)	20.72
Total	100.00
Gross calorific value (kcal/kg)	4,653
Net calorific value (kcal/kg)	4,381

Table 3 Ultimate analysis data of Eucalyptus wood chips

Ultimate analysis	**% Weight dry basis**
Carbon	57.5
Hydrogen	5.3
Oxygen	36.7
Nitrogen	0.1
Sulfur	0.03
Total organic (C + H + O)	99.5

Performance measurements were taken after the stable operation of the system was observed, i.e., constant energy output as 25 kW of electricity. The feeding interval was about 25 minutes per 20 kg fuel batch.

Chromel-Alumel type K thermocouples and digital multi-channel temperature indicator were used to measure temperatures. Producer gas samples were collected by gas sampling bag (Tedlar® bags) and analyzed by using gas chromatography (GC-2014 SHIMADZU GAS CHROMATOGRAPH). The chromatograph consisted of two columns Molecular sieve and Porapack N as stationary media and Argon as carrier gas. Chromatography used Thermal conductivity Detector (TCD) as the detector. Total tar and particulate are measured by gravimetric method with polyvinyl chloride (PVC) filter pore size 5 µ.

3. Result and discussion

The average biomass consumption rate is about 50 kg h^{-1}, so the input power is 255 kW. The system was operated at an average gas flow of 135 Nm^3 h^{-1}. The average calorific value of producer gas was 4.5 MJ m^{-3} and cold gas efficiency was about 66%.

The engine was operated on producer gas. The engine was started up fuelled by LPG, and switched over to producer gas. The power was reduced compared to LPG operation by a power factor of 0.8. The output power was about 45 kW_e on LPG, while the maximum output power at full load was 25 kW_e on producer gas only. The oxygen and carbon-monoxide (CO) contents in the exhaust gas from the engine varied from 9% to 10% and 3% to 5%, respectively.

The efficiency of the system was about 10% from wood to electricity. The gas engine-generator efficiency was about 15%. The parameters of this study are shown in Table 4.

Table 4 The parameters for evaluating the performance of BPGSP

Parameters	Average
Output power (W)	25,392
Power factor	0.8
Phase current (A)	46
Phase volts (V)	230
Input power (W)	254,755
Lower heating value (kJ kg^{-1})	18,342
Biomass consumption rate (kg h^{-1})	50
Specific gasification rate (kg m^3 h^{-1})	417
Gas compositions	
CO (%)	21.21
CH_4 (%)	5.65
H_2 (%)	14.78
N_2 (%)	41.14
CO_2 (%)	17.15
O_2 (%)	0.07
Producer gas flow rate (Nm^3 h^{-1})	135
Tar and particulate (mg Nm^{-3})	161
The heating value of a stoichiometric mixture of producer gas and air(kJ/m^3)	4,496
Cold gas efficiency (%)	66
Biomass gas engine-generator efficiency (%)	15
Overall efficiency (%) (thermal)	10

The variations in the temperatures of different zones of the gasifier with respect to time were noted for Eucalyptus residue fuel. It was observed that temperatures at 50, 250 and 450 mm above the gate were irregular following the feeding interval and supplied air flow rate. The temperature started to decrease after biomass was refilled, but percent of CO content in producer gas would start to increase. After that the percent of CO content in producer gas would decrease while the temperature in oxidation zone and supplied air flow rate increased shown in Fig 4 Fig.5 and Fig.6.

The temperature at the 50 mm above the grate, reduction zone, is quite constant at 500 °C. The temperatures at the 250 mm above the grate, oxidation zone, and at 450 mm above the grate, pyrolysis zone, are 500 to 800 °C.

The percent of CO content in producer gas varied from 14% to 28% and the average CO content was 21%.

Temperatures in gasifier increased following the supplied air flow rate of gasifier shown in Fig 5. The supplied air flow rate varied from 40 $m^3\ h^{-1}$ to 75 $m^3\ h^{-1}$ and the average air flow rate is about 60 $m^3\ h^{-1}$.

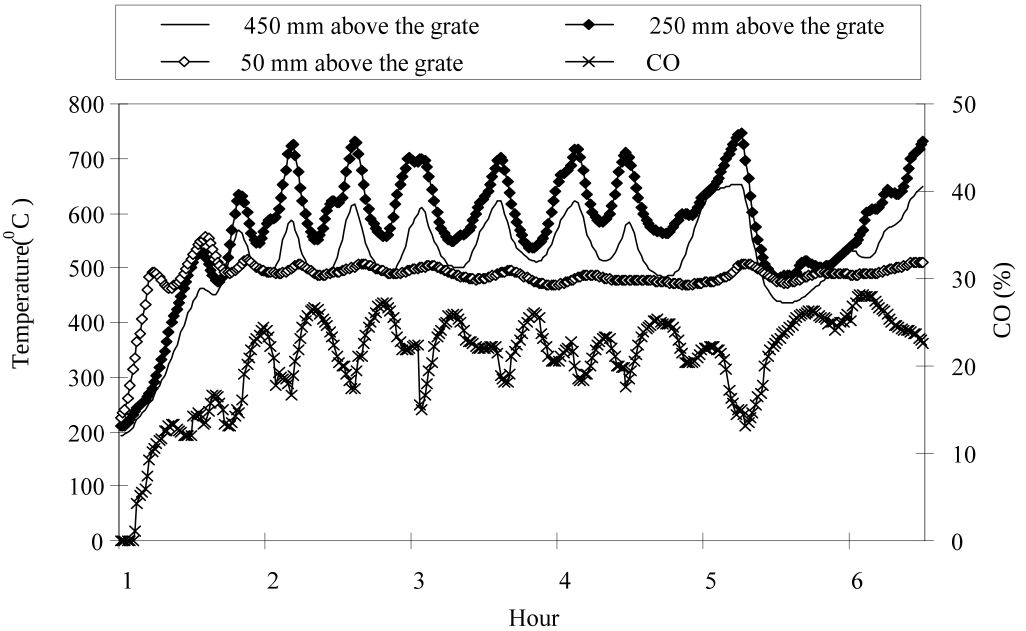


Fig. 4 Temperatures in gasifier and percent of CO in producer gas

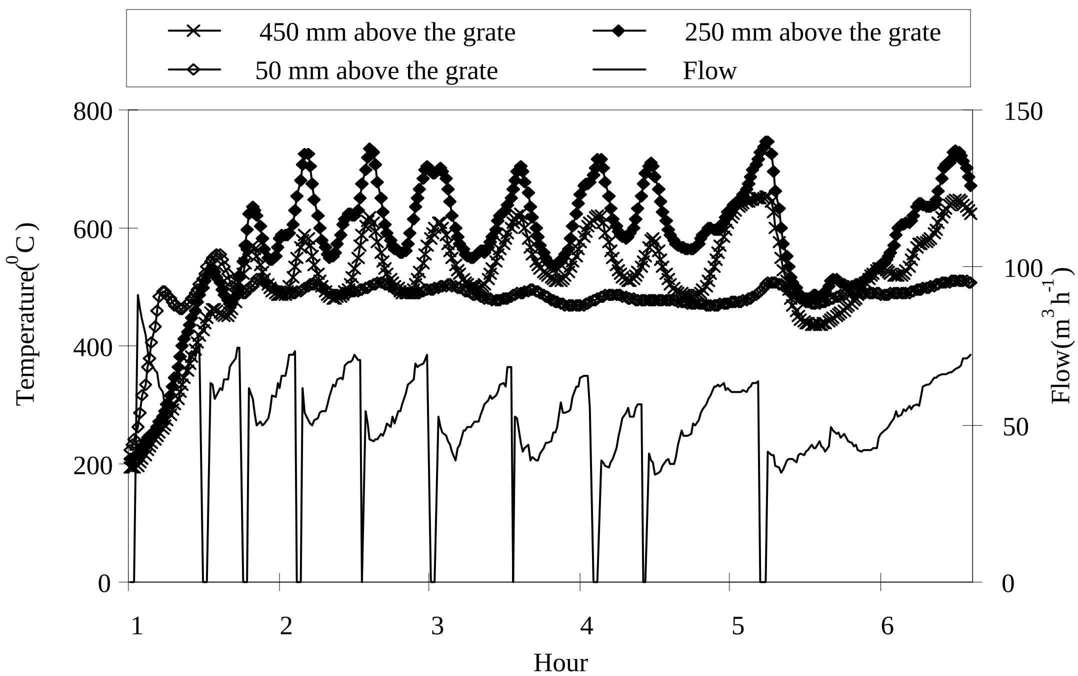


Fig. 5 Temperatures in gasifier and supplied air flow rate

Fig. 6 show the relation among supplied air flow rate and percent of CO content in producer gas. The supplied air flow rate was dropped when biomass was refilled. After that percent of CO content in producer gas would start to increase until carbon of biomass was not enough for partial oxidation the percent of CO content in producer gas would decrease while the supplied air flow rate increased.

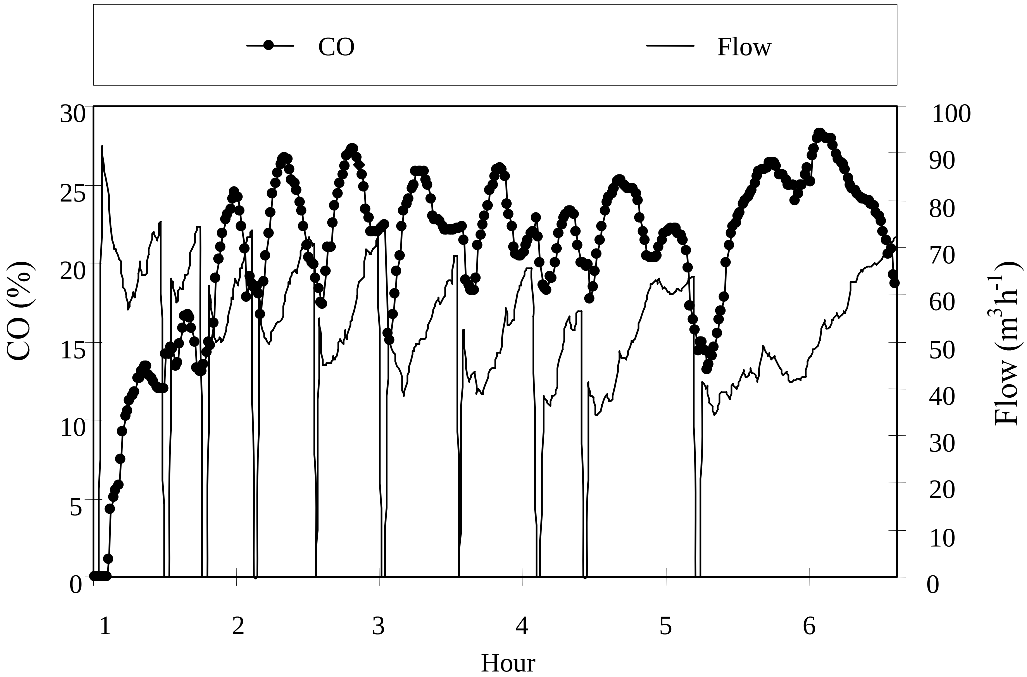


Fig. 6 The relation between percent of CO in producer gas and supplied air flow rate

4. CONCLUSION

Wood industry is a major source in the northern part of the country. Eucalyptus residuals were satisfactorily gasified in a 25 kW_e BPGSP. It was demonstrated that the system can be operated for several weeks. The operation was successful. The engine operated well on the producer gas, but some deposits were seen in the engine afterwards. The engine–generator system was reduced to about 44% compared to LPG operation by a power factor of 0.8. The power loss was higher than expected, about 35% as a result of the lower heating value of a producer gas/air mixture. Concerning the efficiency of system there are some problems that need to be proved such as the optimization of supplied air flow rate for high gasification efficiency and the concern about the efficiency of engine. Normally, cool gas efficiency of gasifier should not be less than 70% and the thermal conversion efficiency of modified diesel engine on producer should not be less than 25% and for overall efficiency should not less than 14% [13].

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