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Design and development of a 20 kW cleaning and cooling system for a wood-chip gasifier

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Abstract
The present study was undertaken with the objectives to develop a filter system for a 20 kW engine application and to test the filter. It was observed that tar content in the gas ranged from 12.4 to 85 mg/m^3, which was considered on the higher side, in some cases, compared from an accepted limit of 50 mg/m^3. The 20 kW cleaning and cooling system for cleaning of producer gas was developed by calculating the gas flow and maximum retention time in the filter. The diameter of these three filters, viz., water scrubber, wet filter and dry filter was calculated from retention time and velocity in the filter, which was found to be 0.20, 0.40 and 0.50 m respectively, with filter height of 0.80 m. The developed filter was evaluated for reduction of tar in the producer gas after cleaning. The tar content in the producer gas after filtration by using the system varies from 24 to 53.52 mg/m^3. The tar absorption using this filter system was 99.35%, while the pressure drop varied between 10 to 25 mm of the water column. The system was also operated by coupling with a small capacity IC engine. The diesel replacement was found to be in the range of 65.66 %.

Keywords: cleaning and cooling system, wood-chip gasifier, biomass, gasification

Introduction

Energy is necessary for the existence of human beings, which helps for the modernization of society. Biomass has been one of the main energy sources of mankind ever since the dawn of civilization, although its importance dwindled after the 19th century. Worldwide, about 14 per cent of the energy supply is from biomass although some of the developing countries depend on biomass for more than 70 per cent of their energy requirements (Anon 1988). As conventional biomass utilization processes are crude and highly inefficient, they are having the capability of substituting conventional energy sources, when renewable energy sources are used in hybrid mode for future requirements. Open air burning of biomass results in inefficient energy utilization, liberation and process environmental hazards, therefore, a good solution for technical application of biomass energy is conversion of biomass by a gasification process. Gasification technology development is on the rising side of the knowledge curve, thus in future; gasification systems many turn out to be more attractive even at higher capacity levels for safe power application. Thus, the technologies are being promoted by the ministry for conversion of biomass to electricity via biomass gasification.

Biomass gasification is the process by which solid biomass materials are converted by a series of thermochemical reactions, to a combustible gas called producer gas, liquids (tar and oils) and solids (char and ash). The reactions are carried out in the reactor called a gasifier. Slow heating rate and low temperature favour the formation of chars whereas; rapid heating promotes the formation of liquids. This tar yields may be as much as one third of mass feed and energy. The combustible gas comprises mainly of carbon monoxide (18-22%); hydrogen

(15-20%); methane (1-5%); carbon dioxide (8-12%) and nitrogen (45-55%). The calorific value of producer gas is 1000-1200 kcal/Nm^3 (Globosky and Bain 1981) whereas; the conversion efficiency was 80 per cent. Reliable gasification systems related to the quality of the gas in terms of energy and the tar content and particulates in the gas. Though the poor energy conversion of solid fuel to the gas was acceptable, the higher particulate and tar content caused difficulties in using the gas for engine applications (Chaplin and Joseph 1989).

Biomass is an important energy resource for enhancing power generation capacity of the country. Tar behaviour in the gas varies much from one process to another, types of fuel, the oxidizing agent, reactor type, fuel type and forms, from about 1-180 g/Nm^3 (Nair et al 2003). Tar causes fouling and corrosion of engine parts, equipment, down stream catalyst deactivation of fuel cell electrodes, environmental pollution and serious health damage. It has thus to be eliminated from the raw producer gas. Therefore, it is essential to carry out cleaning over dust particles and condensate of tar from the gas before it is used in the engine. Although biomass is getting increased attention as a renewable energy source, one of the remaining problems still to be solved is the reduction of the high level of tar present in the product gas from gasification of biomass. Gas cleaning remains the paramount obstacle in the use of biomass gasifier for engine operation, gas turbines and fuel cell applications. Removal of tar content and dust particulate from the gas is critical for maintaining engine life with acceptable performance. Gas cleaning and waste handling remain the critical engineering challenges for the adoption of the technology at small-scale power generation. Thus, the study was carried out with objectives to develop a filter system for a 20 kW engine application and to test the filter.

Materials and methods

Experimental technologies are used for development of an efficient cleaning and cooling system for 20 kW gasifier engine systems to quality produce gas for engine applications. Various parameters were taken into consideration: the biomass consumption rate and gas generation rate of gasifier, level of tar content at the inlet and outlet, gas velocity in the filter and gas temperature at exit of cleaning system and pressure drop across the filter. The designed 20 kW capacity cleaning and cooling system was developed and evaluated. These filters evaluate to measure the tar gas outlet temperature, retention time of gas in the filter bed etc.

Biomass used for gasification

Biomass used for gasification during the study was rectangular teak wood chips, fairly uniform in shape and size. The length and width varies from 2.0 to 2.7cm and thickness 1.5 to 2.5 cm. The fuel wood chips were prepared by cutting the wood into pieces using an electrically operated circular saw into a desired size.

Experimental details

The 10 kW downdraft '*Kalyan*' gasifier developed by PAU Ludhiana was used for generation of producer gas for evaluation of a matching cooling and cleaning system. A hot wire anemometer was used to measure the gas velocity in the filter. The sensor of the hot wire anemometer oriented into the gas flow. The sensor senses the temperature of gas and shows the velocity. The clean gas collection system consists of an airtight plastic container / tank of 100 *l* capacity. The gas collection tank has the provision to fill water from the top and drain the water from bottom. The provision for supply of gas at the top of the tank was also available. As the water was drained from the bottom, the gas gets filled coming from the tar condenser. As the gas flows, due to suction mode, water drained out.

The collected water volume was considered as the volume of gas flows through the condenser. This gas flow was used to estimate the amount of tar present in the gas. The gas flows through the copper coil used for the measurement of tar. The velocity of gas flow through a 5 cm pipe was measured by an anemometer, and gas flow is measured by using the following formula.

$$Q = V \times A$$

Where, Q = Gas flow rate, m^3/h
V = Velocity of gas, m/h and
A = Area of pipe, m^2

To assess the tar content of producer gas, the developed filter unit was connected to the '*Kalyan*' downdraft gasifier. The tar condenser, gas flow measuring instrument (Anemometer) was connected to measure the gas flow to the filter. The U tube (graduated) manometer filled with water was used to measure the pressure drop across the filter. The pressure in the system during filtration at outlet and inlet of the filter was measured. The pressure drop was calculated by subtracting the outlet pressure from the inlet pressure of gas flowing through the filter.

The temperature of gas at the inlet and outlet of the filter system was measured by using a K-type (Chromel-Alumel) thermocouple and a digital temperature indicator. A copper helical shaped, tar condenser was used of the following dimensions: Inner Diameter: 8 mm and length: 6 m. The gas was passed through the condenser and it submersed in the chilled water. The condenser cooling temperature was kept between 4 and 6 degrees. The condenser system was efficient if temperature of water was maintained well around 4°C.

Tar and dust particulates collected in the copper condenser were collected by dissolving them in acetone and then draining from the condenser tube. Tar dissolved easily in acetone and the tube gets cleaned. The dissolved tar was dried at 50°C in the oven, and the acetone gets evaporated and tar with dust particulates remain in the petridish. Tar in milligrams is present in one cubic meter gas, and was calculated by using the gas flow and the tar content. The tar obtained at the outlet of filter was very negligible in amount.

Cooling and cleaning system parameter

The laboratory scale filter unit having a diameter 10.5 cm and height 80 cm was used for optimisation of filter parameters like bed height, filtering material, gas flow with respect to tar absorption and tar content. Retention time of gas in the filter material was calculated in seconds. It is a time requirement to pass the gas from filter materials filled in the filter. This factor was very important in designing the filter system to calculate the dimension of filter. This was calculated by using the following formula:

$$R\,T = \frac{BH}{Vg}$$

Where, R T = Retention time, s
B H = Bed height, m
V_g = Velocity of gas, m/s

The tar absorption was estimated by measuring the quantity of tar in the raw producer gas entering the cooling and cleaning system and tar in the gas from the outlet of the filter. The following formula was used to estimate the tar absorption:

$$\text{Tar absorption} = \frac{T_i - T_o}{Ti} \times 100\ \%$$

Where, T_i = Quantity of tar in raw producer gas at inlet of filter, mg/m^3
T_o = Quantity of tar in cleaned producer gas at outlet of filter, mg/m^3

Results and discussions

The data obtained from the experimentation on the laboratory scale filter unit with three different filtering materials at three different bed heights and three gas flow rates on tar content, tar absorption and retention time on the gas cleaning, were evaluated for the design. The best filter material and optimised thickness for achieving a low tar level in the gas was selected for the development of gas cleaning and cooling system for the three stage producer gas cleaning and cooling system. Considering the requirements of the quality of gas for the IC engine application i.e. level of tar content and dust particulates, moisture content and temperature of gases, the three-stage producer gas cooling and cleaning system was adopted. The three different stages for cleaning and cooling of gas are water scrubber, which will cool the gas and remove most of the dust particulates flowing through the gas due to high velocity. Some quantity of tar was also removed by having contact with water flowing counter current. The second stage of cooling and cleaning system was a wet filter, in which gas is expanded and velocity is reduced to cool the gas. Due to flow of cold water and selected filter bed material, tar was removed from the gas across the filter bed. The third stage of cleaning of producer gas was through a dry filter, in which final cleaning of tar and dust particulates was carried out while flowing the gas across the filter material filled in the filter. The other important function of dry filter material is to trap / condense the moisture content available in the gas before entering in to the IC engine.

The dimension of the developed filter was calculated on the basis of retention time observed in the experimentation and gas flows in the filter. Design procedure for a 20 kW cleaning and cooling system (see Figure 1) consists of some basic consideration and the experimental data support. The dimension of three stage filters was calculated by using the findings of a laboratory scale filter in case of the water scrubber and wet filter. The dimension of the dry filter was calculated on the basis of experimental data published by PAU Ludhiana during their filtration study (Anon 2002). While designing the system, major attention was given to achieving the low tar content in the producer gas. Bed height and bed materials in the developed filter were selected as charcoal and coconut coir for the wet and dry filters respectively, to achieve the tar content of 30 to 50 mg/m^3 in producer gas.

Filter systems design parameters

Estimation of gas flow through filters:

1. Biomass consumption for supply gas to engine = 1 kg / kWh
2. The gas production rate / kg of biomass = 1.8 to 2.0 Nam^3/kg
3. Biomass consumption for 20 kW gasifier = 20 x 1 = 20 kg / h
4. Gas produced by 20 kW gasifier systems = 20 x 1.9 = 38 m^3/h

The total gas flow of 38 m^3/h was considered to design the cooling and cleaning system.

Design of water scrubber

From the observation taken on the experimental filter, the retention time to remove the tar and dust particulates found was 3.5 seconds, which is average time, as the filter height was 80 cm, and the velocity was:

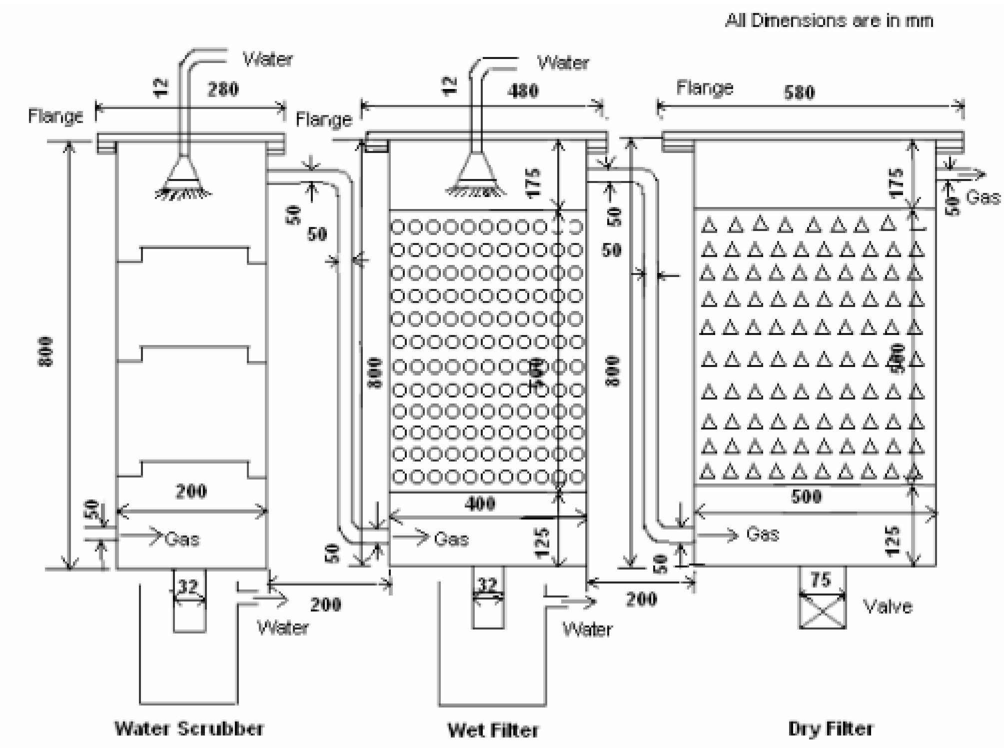

Figure 1: Line diagram of a developed 20 kW gas cleaning and cooling system

$$\text{Retention time} = \frac{\text{Bed height}}{\text{Velocity}}$$

$$3.0 = \frac{0.83}{V} = 0.276 \text{ m/sec}$$

The diameter of the water scrubber with velocity was 0.276 m/sec and gas flow of 38 m^3/h.

Discharge = Area × Velocity

$$Q = \Pi / 4 \times D^2 \times V$$

$$D^2 = \frac{38}{0.276 \times \Pi/4 \times 3600}$$

Therefore, D = 0.21 cm ≈ 20 cm

Where, Q = Gas flow rate, m^3/h

D = Diameter of pipe, meter

V = Velocity of gas, m/h

Design of wet filter

The wet filter was designed considering the results of experiments carried out for optimisation of bed heights with different materials. The study revealed the optimum retention time in a wet filter was found to be 6 to 8 s. Considering the retention time as 6 s in a charcoal filter material with 40 cm bed height, the diameter of the wet filter was calculated for 38 m^3/h gas flow rate required for 20 kW gasifier engine systems.

$$V = \frac{0.5}{6} = 0.083 \text{ m/s}$$

The diameter of wet scrubber was estimated as given below:

$$D^2 = \frac{38}{0.083 \times \Pi/4 \times 3600} = 0.168 \text{ m}^2$$

D = 40.5 cm ≈ 40 cm

The diameter of the wet filter was selected as 40 cm for gas cleaning.

Design of dry filter

The experiment carried out for a dry filter by PAU Ludhiana has concluded that the tar content in the producer gas after filtration was less than 80 mg/m^3. The retention period of gas in the filter bed height of 50 cm was found to be 10 seconds. The optimum retention period was considered 10 to 12 seconds. The velocity in the filter was estimated to be:

$$V = \frac{0.5}{10} = 0.05 \text{ m/s}$$

The diameter of the filter with 0.05 m/s velocity was estimated as:

$$D^2 = \frac{38}{0.05 \times \pi/4 \times 3600} = 0.262$$

D = ≈ 50 cm

Evaluation of the cooling and cleaning system

The developed system was evaluated by supplying the producer gas generated from a 10 kW downdraft gasifier. The system was coupled with a small capacity 5 hp IC engine to evaluate its performance. The performance results of the newly designed and developed producer gas cooling and cleaning system matching to 20 kW gasifier engine systems was discussed.

The feed material used for the experiment was wood chips. The gas generated from the down draft gasifier and updraft gasifier was supplied to the ‘developed cooling and cleaning system’. The newly developed producer gas cooling and cleaning system was evaluated to measure the tar content at the outlet of system. Details of parameters are shown in Table 1. During the experiment the velocity of producer gas was observed in the range of 10 to 23 m/s in the filter. Gas flow in the filter varied from 20.5 to 30.1 m^3/h. The tar content in the producer gas at filter outlet was 24 to 41 mg/m^3. The tar content obtained at the exit of the filter unit was varied from the range of requirements of producer gas suitable for IC engine (50 mg/m^3). The developed filter system was operating to be effective for cleaning the gas suitable for engine application. The cooling and cleaning system was attached and operated with water pumping load on a 3.7 kW engine system. The diesel replacement was found to be 65 per cent. The filter was efficient to absorb tar from 98.49 to 99.14 per cent. The pressure drop across the filter was found to vary from 0.13 to 23 mm of water column. The dust particulates occurred in the producer gas and ranged from 11 to 18 mg/m^3.

Estimation of tar

The tar estimation was carried out by assessing the tar absorption from the water scrubber followed by tar absorption in a wet filter and finally tar reduction in a dry filter. The output of tar from the gasifier was input to the water scrubber. The output of tar from the scrubber was input to the wet scrubber. Similarly the output of tar amount from the wet scrubber was input to the dry filter. The output of the dry filter was finally input to the engine system. The details of tar estimation at the outlet of the design system, is given in Table 2.

Conclusions

From this result, the following conclusions could drawn:

1. The tar content in the raw producer gas generated from wood chips varied from 2.71 to 6.25 gm/m^3.
2. A designed, developed and evaluated 20 kW capacity cooling and cleaning system has shown that the tar content is in the range of 24 to 53.52 mg/m^3.
3. The developed cooling and cleaning system is found to be suitable for cleaning the producer gas suitable for an engine application.

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Table 1: Testing of a developed 20 kW cooling and cleaning system

S. N.	*Gas flow (m^3/h)*	*Tar (g/m^3)*	*Tar + dust (g/m^3)*	*Initial tar (g/m^3)*	*Final tar (mg/m^3)*	*Tar absorption (%)*	*Pressure drop (mm H_2O)*	*Gas temp. (°C) Inlet*	*Outlet*
1	29.8	0.04	0.18	2.78	41.9	98.5	13	230	46
2	25.3	0.02	0.13	2.78	30.7	98.9	21	280	42
3	21.5	0.01	0.11	2.78	24.0	99.1	23	310	48
4	30.1	0.05	0.20	2.78	53.5	98.1	10	260	38
5	28.3	0.02	0.16	2.78	30.6	98.9	16	290	49
6	20.5	0.01	0.15	2.78	18.0	99.4	25	240	45

Table 2: Estimation of tar content at the outlet of a developed 20 kW cooling and cleaning system

	Initial tar content (g/m^3)	*Final tar content in gas (g/m^3)*	*Tar removed (g/m^3)*	*Retention time (s)*	*Tar absorption (%)*
Water scrubber	3.0	1.2	1.8	3.1	60
Wet filter	1.2	0.24	0.96	6	80
Dry filter	0.24	0.025	0.215	10	70