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The Pinch-method Applied on a Biomass Gasifier System

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Abstract

The scope of this study is to optimise the heat exchanger system in two down draft gasification systems and to compare them in terms of energy conversion efficiency and economy. In both cases the system consists of a thermal biomass gasifier followed by a gas cleaning unit and an IC engine with a power generator. A computer model of the system has been developed. Application of the model in combination with the Pinch method has been used in optimising the internal heat exchanging system in each of the two gasification systems. Following an optimisation of a two-stage gasifier and an open core gasifier respectively, the study shows that the two-stage gasifier has the highest power conversion efficiency, and the open core gasifier has the highest heat conversion efficiency. The economical comparison of the two gasification systems indicates that the two-stage gasifier is slightly more profitable.

Introduction

Thermal conversion of biomass is a sustainable substitute for burning fossil fuels in the production of electricity and heat. Contrary to most other sustainable energy sources, it is possible to store biomass and thereby relate the production to the demand. The utilisation of biomass in Europe is predominantly turned on straw and wood chips.

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Thermal conversion of biomass

Thermal conversion of biomass in a gasification system can be split into two main processes: pyrolysis and gasification. Pyrolysis is thermal conversion of organic material in an oxygen free atmosphere. This process requires a temperature of 200-600 °C. The pyrolysis products are char and volatile components, where the latter is made up of tar, pyrolysis gas and steam. The main components in the pyrolysis gas are carbon dioxide, carbon monoxide, methane and hydrogen.

In the gasification process a gasification agent is added to the char. This could be air, oxygen, steam, carbon dioxide or a mixture of these. The char is converted into producer gas and ashes. The main constituents in the producer gas correspond to those in the pyrolysis gas, but the concentrations are different. To obtain a reasonable conversion rate for the gasification process a temperature of at least 750 °C is required.

The pyrolysis and the gasification processes can take place in various types of gasifiers. The producer gas can be used as engine fuel, but due to the content of tar and particles in the gas, it must be cleaned before it is fed to the engine. Apart from the power production from the engine, the system produces high temperature heat by means of excess heat in the producer gas from the gasification chamber and the exhaust gas from the engine. Low temperature heat for district heating is produced by cooling of the engine, condensation of steam from drying of the biomass and end cooling of the producer gas and the exhaust gas. Both high and low temperature heat flows are included in the calculation of the heat conversion efficiency.

Types of gasifiers

This study is confined to down draft gasifiers. Two gasification systems have been examined: A two-stage gasifier and an open core gasifier. The two-stage gasifier has been designed at the Department of Energy Engineering at the Technical University of Denmark. In this type of gasifier the pyrolysis process and the char gasification process are separated into two individual units. The gasification agents are preheated air and superheated steam. In the upper part of the gasification chamber a part of the flammable constituents in the pyrolysis gas are burned. This causes the temperature to rise and it results in a thermal decomposition of the volatile tar. For a detailed description of the process see [1]. Figure 1 shows an outline of the two-stage gasifier.

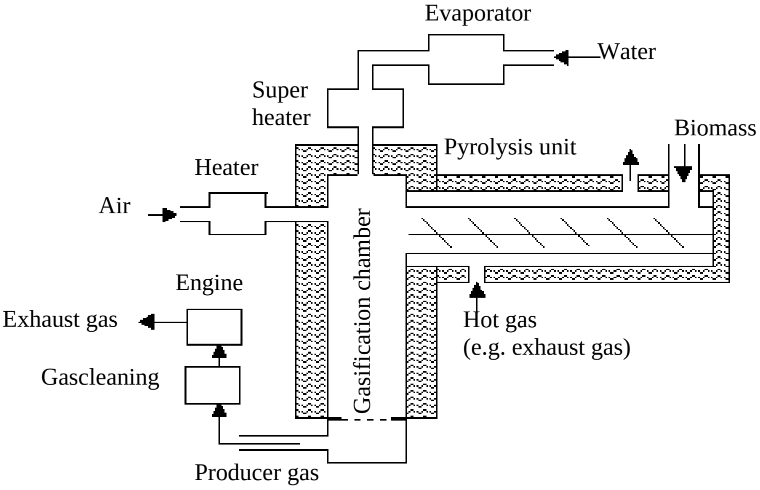

Figure 1 Outline of the two-stage gasifier.

In the open core gasifier both pyrolysis and gasification take place in the same chamber thus in different zones. The gasification agent is preheated air, which is added at the top of the chamber. The open core gasifier requires biomass with a limited moisture content, therefore the biomass must be dried before use. The tar production in an open core gasifier is usually higher than in a two-stage gasifier. This imposes stricter requirements upon the gas cleaning system. For a detailed description of the process, see [2]. Figure 2 shows an outline of the open core gasifier.

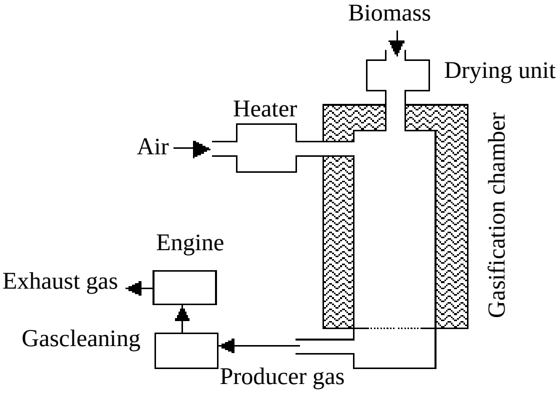

Figure 2 Outline of the open core gasifier.

Computer model of a down draft gasification system

A computer model of the over all gasification system including an engine and a power generator has been developed. The size of the gasification system is of the order of 2 $MW_{thermal}$. The model can simulate many types of fixed bed down draft gasifiers and can for instance be used for calculating the heat and the power conversion efficiencies for the total systems. The fundamental equations in the model are conservation of mass and energy. In modelling the pyrolysis unit the energy demand for this unit is calculated as the difference in the energy contents of the incoming and out going flows. The composition of pyrolysis products in the out going flows is determined by means of experimental results. The quantities of hydrogen, carbon dioxide, carbon monoxide and steam in the producer gas from the gasification process are determined by the water gas shift equilibrium equation, which is a temperature dependent function.

Parametric studies on the temperatures of the incoming flows to the gasification chamber have been carried out by means of the model. Figure 3 shows the heat, the power and the energy conversion efficiencies for the total system against the temperature of the incoming flows (pyrolysis products, air and steam) to the gasification chamber in the two-stage gasifier. All the flows to the gasification chamber are set at the same temperature. The study shows that the power conversion efficiency increases with increasing temperature of incoming flows to the gasification chamber, while the heat conversion efficiency decreases. The energy conversion efficiency is almost constant, but decreasing slightly due to an increase in the heat loss with increasing temperature. As the electricity price usually is higher than the price on heat, the temperature of the incoming flows should be raised as much as possible by means of internal heat exchanging, since this will only reduce the energy conversion efficiency slightly.

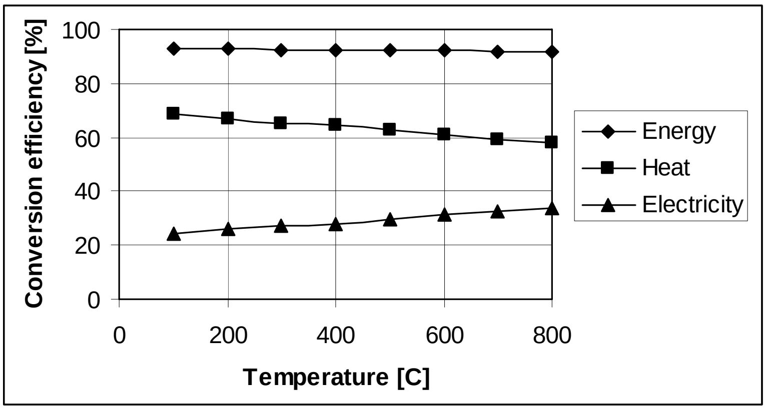

Figure 3 Heat, power and energy conversion efficiencies for the total system against the temperature of the incoming flows to the gasification chamber.

Energy analysis

The two gasification systems described above, have been compared and evaluated in terms of energy and economy. To examine whether it is possible to reach the desired temperature levels by means of internal heat exchanging the Pinch method has been applied on the open core gasifier and the two-stage gasifier. The temperature of the producer gas from the gasification chamber is 790 °C after a cyclone. In order to avoid large heat exchangers, the minimum temperature difference in the heat exchangers is set at 30 °C. Therefore the desired temperature of steam and air to the gasification chamber has been set at 760 °C. The pyrolysis unit is heated by the exhaust gas. This gas is preheated by the producer gas. (The reason for this is given later). The minimum temperature difference in the heat exchanger between the exhaust gas and the producer gas is also set at 30 °C. The minimum temperature difference in the pyrolysis unit is set at 100 °C, which is based on experimental results. Therefore the desired temperature of the pyrolysis products is set at 660 °C. The Pinch analysis shows that there is sufficient excess heat available in the system to reach the desired temperature levels of the incoming flows in the open core gasifier. In the two-stage gasifier the temperature levels can only be reached if the producer gas stream is split. By means of the Pinch method composite curves for the two gasification systems have been created. The composite curves for the two-stage gasifier and the open core gasifier (figure 4 and figure 5) shows that there is no external heat demand, since the cold and the hot composite curves ends at the same Q-value.

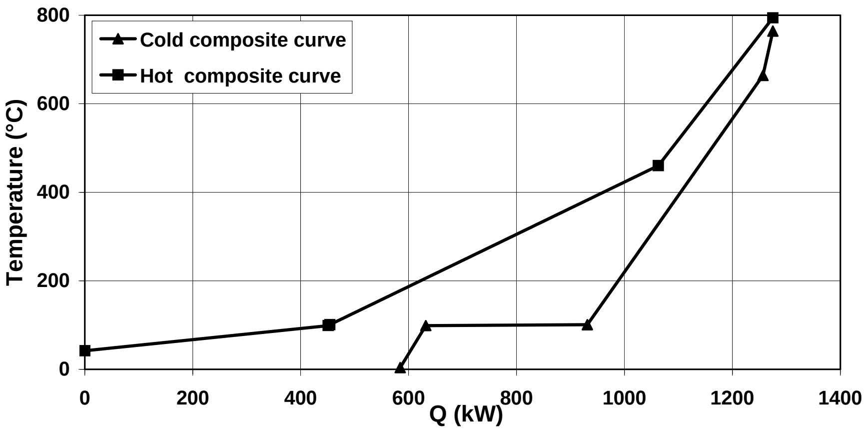

Figure 4 The composite curve for the two-stage gasifier.

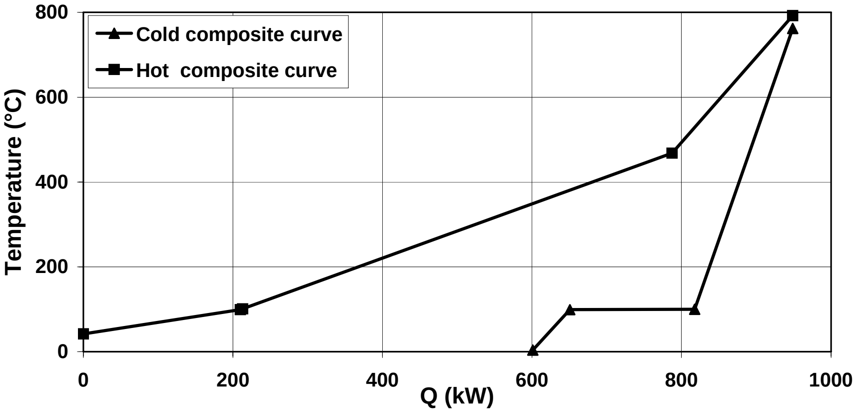

Figure 5 The composite curve for the open core gasifier.

If the producer gas stream in the two-stage gasification system is not split, the temperature of the flows to the gasification chamber has to be reduced. This is if the heat demand must be covered only through internal heat exchanging. The temperature of the air has to be lowered to 716 °C and the temperature of the pyrolysis products has to be lowered to 450 °C. This results in a power conversion efficiency of 30,0 %, which gives a corresponding heat conversion efficiency of 62,1 %.

If, on the other hand, the producer gas stream in the two-stage gasification system can be split the desired temperature levels can be reached. In this case the power conversion efficiency is increased to 32,5 %, which gives a corresponding heat conversion efficiency of 59,4 %.

In the open core gasification system the power conversion efficiency is 28,8 % and the corresponding heat conversion efficiency is 63,5 %.

Heat exchanger system

There are various possibilities for arranging the heat exchanger systems in the two gasification systems mentioned above. In the evaluation of the different heat exchanger systems, constraints within the system must be taken into account. Corrosion and fouling caused by the producer gas makes heat exchanging with the pyrolysis unit complicated because of its complex geometry. As the producer gas is at a higher temperature level than the exhaust gas, it is advantageous to exchange heat between the two gases before the exhaust gas is used in the heat exchanging with the pyrolysis unit. Since the heat capacity rate of the exhaust gas is almost the double of the producer gas, the exhaust gas should be split in order to reach the highest possible temperature. Using a counter flow heat exchanger the study shows that the temperature of the exhaust gas will rise sufficiently to raise the temperature of all the incoming flows to the levels found by the Pinch analysis.

On the basis of the constraints imposed on the system, there are only a limited number of possible heat exchanging systems. The best heat exchanger system is subsequently chosen as the one with the smallest heat transfer area. Figure 6 and figure 7 show the heat exchanging system with the smallest area for the two-stage gasification system when the producer gas stream is split and when it is not split.

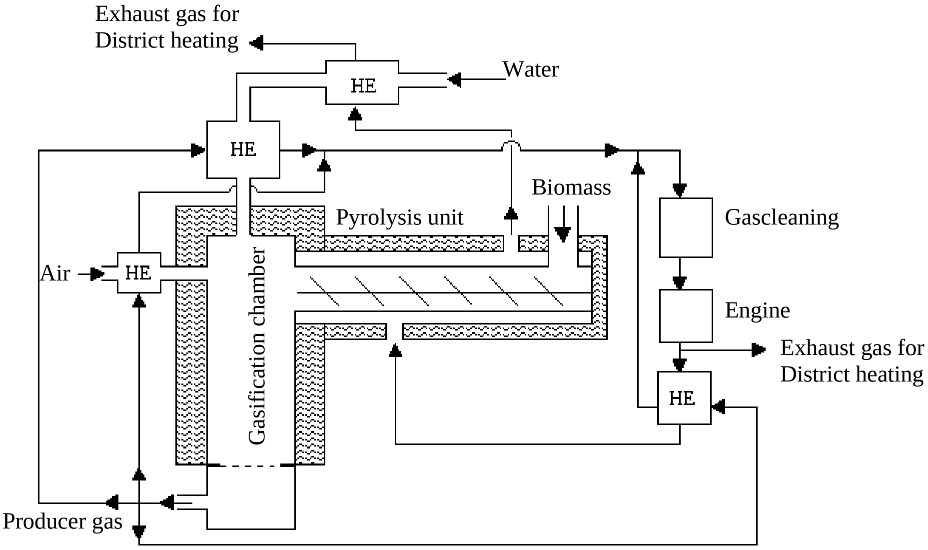

Figure 6 The heat exchanger system for the two-stage gasification system, when the producer gas stream can be split. HE indicates a heat exchanger.

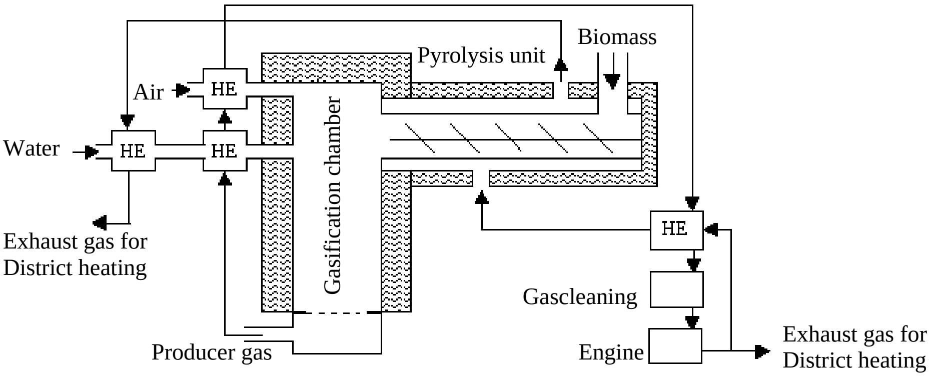

Figure 7 The heat exchanger system for the two-stage gasification system, when the producer gas stream is not split. HE indicates a heat exchanger.

The heat exchanging system with the smallest area for the open core gasification system is shown in figure 8.

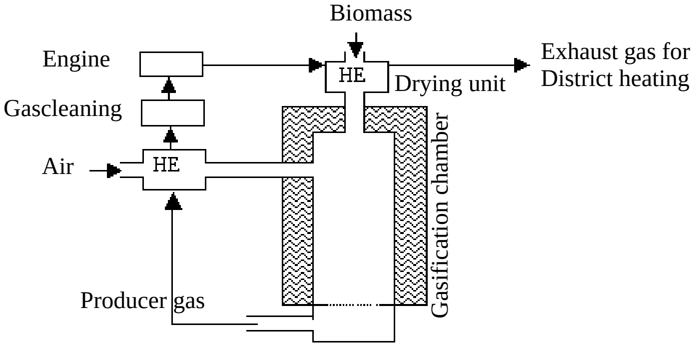

Figure 8 The heat exchanger system for the open core gasification system. HE indicates a heat exchanger.

Economical analysis

The economical analysis is made on the assumption that the gasification systems are connected to smaller district heating systems with a heat demand of 8400 MWh/year. An oil burner covers peak demands of 700 MWh/year, which leaves a heat production on biomass of 7700 MWh/year. To make the production comply with the annual variations in demand, the plant should be able to deliver a heat output of 1,3 MW. Since the heat conversion efficiencies for the gasification systems are not the same, the total energy input and electricity generation are not identical for the systems. The total energy input to the systems differs with only approximately 7 %. Therefore it is assumed that the investment for most of the components in the gasification systems are of the same order of magnitude. The components that differ in the systems are the evaporator, the super heater and the pyrolysis unit in the two-stage gasification system and the drying unit in connection with the open core gasifier. As there has not been build many commercial plants, it is difficult to estimate the costs of the single components. Studies show that the cost for the two-stage gasification system and the open core system are of the same order and in the area of 1 mill Euro / $MW_{Thermal}$ [3].

The operating costs are assumed to be alike for the two gasification systems apart from the fuel expenses. The operating revenues are made up of the selling of heat and power. The revenue is calculated on the basis of the electricity and heat price in Denmark, which on average for biomass CHP plants are 38 Euro per MWh of power and 36 Euro per MWh of heat. In Denmark there is a subsidy of 36 Euro per MWh of produced power on a biomass CHP plant. This increases the price for electricity to 74 Euro per MWh. The net operating revenues are calculated for the three cases (shown in figure 6-8) with and without subsidies. The results are presented in table 1.

Table 1 The power conversion efficiencies and the net operating revenues with and without subsidies for the two-stage gasifier and the open core gasifier.

		Two-stage		Open core
Producer gas flow		split	not split	not split
Power conversion efficiency	%	32,5	30,0	28,8
With subsidy	Euro/year	345.000	325.000	310.000
Without subsidy	Euro/year	195.000	190.000	185.000

Since the net operating revenues for the open core gasification system and for the two-stage gasification system with splitting of the producer gas differs the most, these will be compared. The simple proceeds for the gasification systems are defined as the net operating revenues over a period of 10 years minus the investment costs. Assuming that the simple proceeds are to be the same for the two systems, the ratio between the investment costs for the two systems can be calculated. This study shows that the proceeds for the two-stage gasification system with splitting of the producer gas stream is higher than for the open core gasification system as long as the investment in the two-stage gasification system is less than 1,2 times the investment in the open core gasification system. This is under the assumption that subsidies are given. Assuming no subsidies, the investment has to be less than 1,05 times the investment in the open core gasification system. In the above calculations it is assumed, that the investment for the plants are in the order of 1 mill EURO / $MW_{Thermal}$.

The calculations indicate that the two-stage gasifier is more efficient in terms of power conversion efficiency and likely to be more profitable than the open core gasification system. Therefore a bigger investment cost can be accepted.

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