SECONDARY GASIFIER FOR IMPROVED VIPP SYSTEM PERFORMANCE

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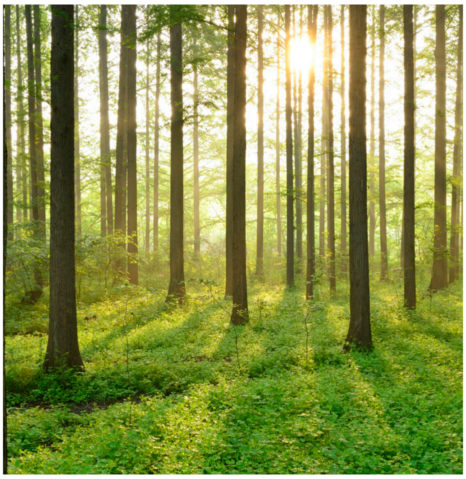

ENERGIGASTEKNIK

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Secondary Gasifier for Improved Vipp System Performance

Gasification of tar, char and wood

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Foreword

This project evaluated a secondary gasifier in order to improve cold gas efficiency of the Hortlax entrained flow gasifier. Saw dust was effectively gasified in the secondary gasifier, while gasification of wood char and tar was challenging due to high moisture content. The results can contribute to more efficient gasification of biomass.

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Sammanfattning

Meva Energy AB utvecklar förgasningsteknik baserad på pulverförgasning i en cyklonreaktor. Utvecklingen bedrivs huvudsakligen i den fullskaleanläggning som uppfördes 2010-2012 i Hortlax utanför Piteå. Anläggningen är dimensionerad för ett bränsleflöde på 1000 kg / h för produktion av 1,2 MW el samt 2,4 MW fjärrvärme. Anläggningen har nu nått en betydande teknisk mognad med avsevärt förbättrad tillgänglighet och stabilitet.

En återstående teknisk flaskhals är gasutbytet, dvs reaktorns förmåga att omvandla bränsleenergi till förbränningsenergi i syntesgasen. I förgasaren omvandlas bränslet till syntesgas men även till biprodukter som tjära och träkol. En betydande andel av ingående bränsleenergi återfinns i dessa biprodukter varför de bidrar till att reducera gasutbytet.

Syftet med projektet var att konstruera en 200 kW högtemperaturförgasare och optimera denna med avseende på tjärkrackning och förgasning av träkol. Direkt förgasning av sågspån studerades också. Reaktorn, tillverkades i Inconel 600, hade en diameter av 600 mm och en höjd av 3000 mm. Den övre delen av reaktorn konstruerades som en suspensionsförgasare och i botten som en fastbäddförgasare. Designtemperaturen var 1100 ° C. På torkat sågspån uppnåddes höga gasutbyten, cirka 80%, jämfört med målet på 70%. Högst gasutbyte uppnåddes vid måttlig temperatur, runt 850 ° C, lambda-värde 0.35 och gasuppehållstid på cirka 10 s. Tillförsel av ånga som förgasningsreaktant hade en positiv inverkan på gasutbytet och ökade vätehalten i syntesgasen.

Med trätjära och träkol uppnåddes inte de förväntade gasutbyten. Detta var ett resultat av alltför hög fukthalt, > 70%, som i sin tur sänkte förgasningstemperaturen under 700 ° C. För att uppnå högre reaktortemperaturer och högre utbyten måste dessa bränslen avvattnas mekaniskt eller torkas före förgasning. Fuktig tjära och träkol skulle dock kunna användas om primär- och sekundärförgasaren kombineras.

Summary

Meva Energy operates a full-scale gasification plant in Hortlax in northern Sweden. The plant, using grinded wood pellets as a fuel, is designed for a fuel flow rate of 1000 kg/h to generate 1.2 MW of power as well as 2.4 MW of district heat. The plant has now reached a significant level of technical maturity with improved availability and stability. One significant room for improvement to the gasifier is the cold gas efficiency e.g. the conversion efficiency from fuel-bound energy to combustion energy in the gas. In the gasifier, fuel is converted to syngas but unavoidably also to by-products such as tar and char. These by-products carry a significant amount of energy that represents a loss in potential cold-gas efficiency. The aim of the project was to construct and operate a 200 kW high temperature secondary gasifier that could improve the overall system efficiency by directly improving the conversion efficiency of wood or by cracking and gasifying the by-products char and tar into syngas. The reactor, constructed in Inconel 600, had a diameter of 600 mm and a height of 3000 mm. It was designed as a combination of an entrained flow gasifier and a fixed bed gasifier. The design temperature was 1100 °C. On dried saw dust the reactor performed very well with a cold gas efficiency of up to 80% which is higher than the target of 70%. On saw dust the highest CGE was achieved at moderate temperature, around 850 °C, lambda value 0.35 and gas residence time of 10 s. Injection of steam had a positive impact on the CGE and increased the hydrogen content in the syngas. With wood tar and wood char the CGE was lower, 35 and 15% respectively. These low conversion efficiencies were a result of the high water content in these fuels, >70%, which in turn lowered the reactor temperature below 700 °C. To achieve higher reactor temperatures and higher conversion efficiencies these fuels must be mechanically dewatered or dried prior to gasification. One appealing solution with the possibility to crack tar with high moisture content is to combine the primary and the secondary gasifier.

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1 Introduction

1.1 MEVA ENERGY AB

Meva Energy AB was founded in 2008 as a result of research on suspension gasification at Luleå University of Technology. Since then the company has developed a complete process including fuel preparation, gasification, gas cooling, gas cleaning and related auxiliary systems. The resulting gas (syngas) can be used for power generation in an internal combustion engine, or directly as a gaseous fuel in an existing industrial process. The company's business concept is to be a global player in this area and to offer technology in the form of turnkey facilities or long gas contracts for electricity and/or heat delivery.

Meva Energy has since a long period focused on research and development including lab trials, pilot tests and construction of a full-scale plant. This plant is commercially sold to Pite Energi AB, but has historically also served as a demonstration and development facility. The company has close ties to major research actors in Sweden such as RISE Energy Technology Center, KTH Royal Institute of Technology, Luleå University of Technology. Meva Energy is a member of the Swedish Gasification Centre, Svenskt Förgasningscenter (SFC), and is a portfolio company at the Swedish Energy Agency.

1.2 GASIFICATION

Gasification is the process in which a carbon containing, liquid or solid, substance is converted into an energy rich gas. For gasification to take place, high temperature and an oxidizing agent is necessary. The oxidizing agent can be either air, oxygen, steam, carbon dioxide or a mixture of these. The gasification process occurs according to the following stages: drying, pyrolysis, oxidation and finally reduction. The reactions occurring during gasification are endothermal, except for oxidation, and because of that, heat needs to be supplied to the reactor. The heat can be supplied externally or internally. If the heat is supplied externally, the gasification is normally referred to as indirect or allothermal gasification.

There are a few different types of gasifiers and most of them have traditionally been used to gasify coal or heavy oils, but most of them can also, and have been, used to gasify biomass either in full scale or pilot scale.

1.2.1 Fixed bed gasifiers

In fixed bed (sometimes denoted moving bed) gasifiers, the fuel (which in this case must be a solid) slowly moves through the bed as it is converted into gas. Fixed bed gasifiers are either of downdraft, updraft or crossdraft configuration depending on how the gas moves relative to the bed. Fixed bed gasifiers are the most commonly used type of gasifier due to simplicity of design, cost and operational experience. Crossdraft gasifiers are not used to any greater extent due to lower thermal efficiency and higher tar outputs compared to the other two designs.

In downdraft gasifiers, fuel is fed at the top of the gasifier and the oxidizing agent is injected typically in the middle along the length of the reactor. At the top of the gasifier, the fuel is dried as it moves downwards. The drying gases contain mostly water vapor which helps the reduction reactions further down. As the dry fuel moves down and approaches the zone where the oxidizing agent is supplied, the fuel starts to undergo pyrolysis. Pyrolysis is a breakdown of the molecules in the fuel to produce gaseous components. At low temperature, the gas typically contains CO, CO_2, H_2 and lower hydrocarbons such as methane, ethylene, alcohols and organic acids. Higher temperature pyrolysis produces more gas and more hydrocarbons. At higher temperature, more aromatic hydrocarbons are formed than at lower temperature and this is where most of the gasification tars originate from.

Following the pyrolysis zone, a part of the gases formed during pyrolysis are oxidized in the oxidation zone to produce the necessary heat to maintain operating temperature in the reactor. The oxidizing agent must be an oxygen containing gas as the reactions must be exothermic in the oxidizing zone.

The final stage in gasification is the reduction zone in which the formed gases and remaining fuel particles undergo reduction to produce more gas with higher heating value. Any solid fuel remaining after pyrolysis is converted in the oxidizing and reduction zones. For biomass applications, tars formed during pyrolysis are readily converted in the reduction zone during reaction with the remaining char which constitutes the bed at the bottom of the downdraft gasifier. Of the fixed bed gasifiers, the downdraft typically produces the cleanest gas in terms of tars, typically less than 1 wt-% of the dry wood feed [1].

In updraft gasifiers, the oxidizing agent is injected in the bottom of the reactor where the oxidation zone forms. Fuel is still fed at the top of the reactor where drying still occurs. In the updraft gasifier, the reduction zone is above the oxidizing zone followed by the pyrolysis zone. This design results in much more tar in the outlet of the gasifier as the tars do not pass through the reduction zone. The advantage of the updraft gasifier is the higher thermal efficiency of the design as it is, in effect, a counter current heat exchanger. The updraft gasifier also allows fuels with higher moisture content (< 50 wt-% moisture) compared to downdraft gasifiers (around 20 wt-%) [2]. For biomass, fixed bed gasifiers are typically limited to smaller scale, with practical limits around 1 MW thermal (MW_{th}) capacity.

1.2.2 Fluidized bed gasifiers

In fluidized bed gasifiers, the fuel is mixed with a bed material and the oxidizing agent is injected in the bottom of the reactor at high velocity which causes the bed to lift and start to fluidize. The degree of fluidization determines if the bed is bubbling or circulating type. In circulating fluidized bed type gasifiers, the bed particles are allowed to leave the reactor vessel and then separated from the gas. The particles are then injected at the bottom of the reactor. Most allothermal type gasifiers use this type of gasifier to externally heat up the bed material before injection into the gasifier. The oxidizing agent used in allothermal gasification is typically pure steam.

Fluidized bed gasifiers have a more uniform temperature distribution in the reactor than fixed bed gasifiers and because of that there are no clear defined zones in the reactor. The same reactions still take place, but they occur individually on each fuel particle. The advantages of the fluidized bed gasifiers are large scale operation, ability to use catalytically active materials in the bed, allothermal operation, and others.

1.2.3 Entrained flow gasifiers

Meva Energy focuses on entrained flow gasification. Entrained flow gasifiers are the most robust type of gasifier in terms of flexibility. In entrained flow gasifiers, the fuel particles are small (typically < 1 mm) and the residence time very short (seconds compared to minutes in fixed bed). Temperature in entrained flow gasifiers are typically in the range of 1200-1600 °C (compared to around 850 °C for fluidized and fixed bed gasifier). The strength of the high temperature entrained flow gasifier is the pure gas that is produced. The high temperature allows for almost complete conversion of impurities, such as tars and lower hydrocarbons, into synthesis gas ($CO + H_2$). The flexibility of the entrained flow gasifiers comes from the ability to handle any kind of fuel, as long as the particles are small enough. Furthermore, high-ash fuels are also possible in special slagging-type entrained flow gasifiers. Ash melting points are problematic, especially for biomass and particularly for non-woody biomasses such as straw.

1.3 TARS

All gasifiers that have insufficient residence time and/or temperature will produce gas containing tars. Tar is the term used to describe hydrocarbons, in gasification gas, with a molecular weight greater than that of benzene [3]. For most biomass gasification plants, tars typically consist of polyaromatic hydrocarbons (PAH) such as naphthalene and anthracene. These components derive from the polymers in the biomass, especially the lignin. The tars can be converted into synthesis gas if sufficient time, heat and oxidizing agents are available. In recent years, most research efforts have been spent on catalytic conversion of the tars and in particular nickel-based reforming catalysts. The problem with using nickel-based catalysts in gasification plants is the need to desulfurize prior to reforming as the nickel-based catalysts are prone to sulfur-poisoning [4, 5]. Furthermore, reforming catalysts are also readily deactivated by physical blockage from, for example, fly ash and soot. Fly ash and soot are readily available in the gas produced by biomass gasifiers.

The non-catalytic conversion of tars into synthesis gas requires higher temperatures than catalytic conversion (>1100 °C compared to 800-900 °C) and as a result, more energy is required for non-catalytic conversion. Furthermore, increased temperatures increase the formation of soot. Soot is solid particles consisting of mostly carbon arranged as graphite. At elevated temperatures, the polyaromatic hydrocarbons such as naphthalene will agglomerate and form larger molecules that eventually form soot. Conversion of soot into gas is possible, but the process is slower than conversion of tars or char in biomass.

2 The Hortlax plant and project outline

Meva Energy´s Hortlax plant (Figure 1) is a full-scale gasification plant designed to produce 1.2 MW of electricity and 2.4 MW of heat from 4.8 MW of fuel. The fuel is locally produced wood pellets.

2.1 PROCESS DESCRIPTION

The fuel is delivered to the plant by truck and blown into a storage silo. From the silo the fuel is screw conveyed to the disc mill where it is grinded to about 0.5-1.0 mm wood powder. From the mill the powder is transported pneumatically, using the gasification air as carrier, to the cyclonic gasifier. The produced syngas along with tar and particulate matter, leaves the reactor at the top whereas charcoal falls to the bottom and leaves the reactor by means of a wet ash handling system. The syngas is cooled from about 950 °C to 80 °C in a water quench. During cooling, tar is condensed and flows with the water to the tar/water separator. The gas is then further cleaned and cooled in a venturi scrubber, a random packed scrubber, and finally in a wet electrostatic precipitator. Purified syngas is fed to a 91 L internal combustion engine for both power and heat production. The foul process water is purified in a tar/water separator, cooled in a number of heat exchangers and then recirculated.

Figure 1: The Meva Hortlax plant.

Figure 2: The primary gasifier in Hortlax with its two fuel inlets.

2.2 THE CYCLONE GASIFIER

The cyclone gasifier (Figure 2) is classified as an entrained flow reactor, see chapter 1.2.3. However, it operates at much lower temperatures than the typical entrained flow, around 900-950 °C.

The fuel/air mixture enters the cyclone tangentially. The air and the produced gas flow in a helical pattern, beginning at the top of the cyclone and ending at the bottom end before exiting the cyclone in a straight stream through the center of the cyclone and out the top. Wood powder and ash in the rotating stream have too much inertia to follow the tight curve of the stream, and strike the outside wall, then falling to the bottom of the cyclone. The principle of the cyclone gasifier is shown in Figure 3.

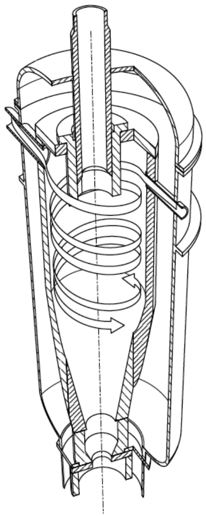

Figure 3: Principle of the Meva cyclone gasifier.

In the reactor, the fuel undergoes four basic processes, e.g. drying, pyrolysis, oxidation and reduction. When the wood particle is heated any bound water is evaporated. Further heating results in a pyrolysis process where volatile matters in the wood is released and converted to permanent gases, pyrolysis oil and tar. Combustion processes occurs simultaneously providing heat necessary to maintain the temperature. Drying, pyrolysis and combustion are all very fast and occur in the top section of the reactor.

As mentioned above, gasification takes place at relatively low temperatures (about 900-950 °C) and for a very short residence time of a few seconds. These conditions enable good conversion of the bulk of fuel fed into the reactor. However, biomass is rather recalcitrant and it is not possible to completely convert all fuel under these conditions. In particular, the temperature and residence time are insufficient to break (crack) all the tar formed during the pyrolysis and to gasify formed charcoal into gas. The energy available in these by-product streams is shown in Figure 4 below. It would be technically possible to achieve a more complete tar or charcoal conversion by having a larger gasifier volume (longer residence time) and higher temperature, but such a process is likely to have a reduced cost effectiveness since the reactor needs to be larger in volume (more expensive) and because the higher gasification temperature leads to greater fuel consumption and a lower heat value on the syngas.

An alternative, and Meva Energy's preferred approach, is therefore to accept that the (primary) gasifier does not crack / convert all fuel and instead introduce a significantly smaller secondary gasifier whose purpose is to gasify remaining tar / coal. The tar from the primary reactor condenses during the gas cleaning and is fed to the secondary gasifier. Residual carbon is collected in the bottom of the primary gasifier and fed to the same secondary gasifier. This approach will not only increase the gas production but also reduce the disposal costs of the by-product streams.

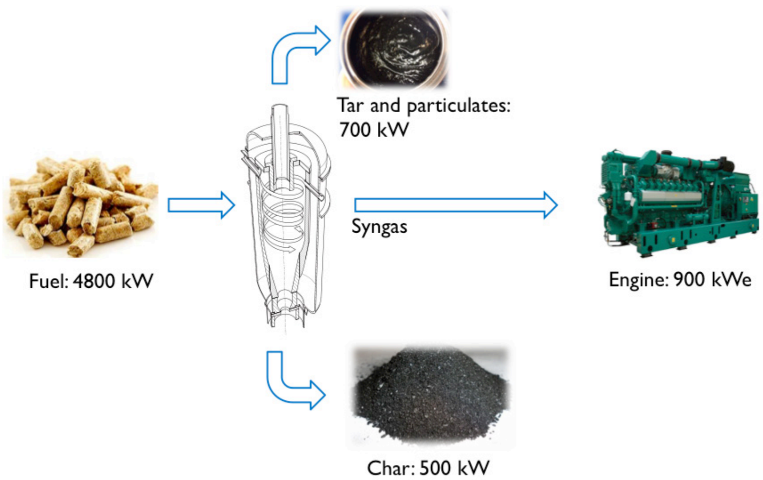

Figure 4: Production of tar and char during cyclone gasification.

2.3 AIM OF THE PROJECT

The aim of the project was to construct and operate a high temperature secondary gasifier for conversion of tar and char to syngas. In addition, its ability to convert biomass directly to syngas at a high efficiency was to be determined and compared with the performance of the primary gasifier. The goal was to demonstrate a performance of the combined cyclone gasifier and the secondary gasifier corresponding to a CGE of 70%.

3 Secondary gasifier

3.1 DESIGN CRITERA

The reactor design criteria are summarized in Table 1 Secondary reactor design criteria .

Table 1 Secondary reactor design criteria

Parameter	Value
Fuel	Tar, char and wood powder
Fuel flow rate (kW)	200
Lambda value	0.4
Maximum temperature (°C)	1100
Pressure (barg)	1,0
Gas maximum vertical velocity (m/s)	0.5
Gas residence time (s)	5

3.2 CONSTRUCTION

Based on the design criteria’s the reactor was built in high temperature resistant Inconel 600 (Figure 5). The reactor is circular with a diameter of 600 mm and effective height of 2000 mm. The reactor, designed to be operated under atmospheric pressure, is heated by two electrical ceramic heaters mounted on the outside of the reactor. Total power output is 15 kW. Inside there is a thin ceramic coating that protects the metal from the hot gases inside the reactor. The reactor is suspended in two flanges. The bottom of these is on a tripod, the upper is spring-mounted to work with the reactor's vertical temperature expansion. Both flanges are cooled by compressed air circulating in channels inside the flanges.

For fuel injection, two DN50 flanges were installed at a height of about 1000 mm.

The bottom of the reactor consists of a circular, slightly concave perforated ceramic disc. The purpose of the ceramic disc is to allow the residual char to form a fixed or semi-fluidizing bed through which the gasification air is blown from below. Gasification air is supplied beneath the perforated plate and reaches the bed through 7 mm air holes in the ceramic disc. Below the ceramic plate there is an ash cooling tank in which any molten ash or any hot residual char is collected and cooled.

Figure 5: The secondary gasifier in Hortlax.

3.3 EVALUATION PRINCIPLES

During the project, a number of campaigns have been carried out. The general evaluation procedure is described below and deviation from this procedure is commented under the respective section for each campaign.

1. Calibration of fuel feeding device e.g. determine fuel flow rate as a function of the frequency of the feeding device
2. Analysis of fuel properties i.e. heating value, moisture content (RISE-Borås, RISE-ETC Piteå)
3. Preheating of reactor using the electrical heating elements to the desired temperature.
4. Starting feeding of fuel and air
5. Feeding helium to reactor.
6. Reaching stable reactor conditions
7. Gas sampling
   a. Gas composition was determined by Micro-GC (ETC-Piteå)
   b. Tar analysis was determined by the SPA method (KTH)

The syngas heating value was calculated from the gas composition including benzene. From the helium concentration in the gas and the helium flow rate, the gas flow rate could be calculated. Given the fuel flow rate (FMF), fuel heating value (FLHV), the gas flow rate (GVF) and the gas heating value (GLHV), the reactor cold-gas-efficiency (CGE) was calculated:

$$CGE = \frac{GVF * GLHV}{FMF * FLHV} * 100$$

Generally, reported CGE values do not include heat provided by the electrical heaters nor heat with preheated air or steam. On the other hand, heat losses from the reactor have also been excluded. Comments are added where required.

4 Results

4.1 OPERATION ON TAR

4.1.1 Coal tar

During the design phase of the reactor, the physical properties of the tar was expected to be similar to that of coal tar. Such tar has a rather low concentration of particular matter and a viscosity that is highly temperature dependent. Such tar can easily be pumped by a centrifugal pump or by an excentre screw pump at elevated temperatures of 50 °C. The latter type was used for feeding the coal tar to the gasifier. Coal tar was used since the Hortlax gasifier was not operational while being rebuilt. The tar was provided by SSAB coking plant in Luleå. For tar-injection a taylor made air-atomized tar nozzle was constructed. The tar was fed through an inner tube whereas the air flowed through twisted channels thereby creating a swirl that atomized the tar. Small droplets improve the contact between the fuel and the gas and should therefore improve the performance of the system. Figure 6 shows the nozzle and its spray pattern.

Figure 6: Tar injection nozzles and the spray pattern.

During the trials with coal tar all gasification air, preheated to about 400 °C, was supplied through the nozzle. During the test, both reactor temperature and residence time was varied, see Table 2 below. As can be seen, the highest temperature was 970 °C and unfortunately during this campaign it was not possible to increase the temperature further due to severe heat losses from the reactor. Therefore, the reactor was insulated further, both from the outside but also from inside with ceramics.

The highest CGE was achieved at the lower temperatures, 848 °C (see Table 2). The CO content was reasonably high but hydrogen content was lower than expected (Table 2). The calculated gas heating value was lower than that from the primary cyclone reactor, peaking at 3.5 MJ/Nm^3 (Table 3).

Figure 8 shows the CGE as a function of the gasification temperature. In the temperature range of 840 °C to 980 °C a higher temperature results in lower CGE.

In general terms, the results indicate that none or a highly marginal thermal tar cracking occurs at temperatures below 1000 °C. Probably only oxidation and partial oxidation (which generate CO and CO_2) occur with the oxygen available from the air. The water-gas shift reaction also occurs which produce hydrogen gas from CO.

Table 2 Operating conditions and CGE while operating the secondary gasifier on coal tar

Sample	Average temperature	Residence time	Fuel flow r.	Lambda	CGE
	°C	s	kg/h	--	%
1	877	14.3	10.8	0.31	29
2	880	13.9	10.8	0.31	30
3	848	14.4	10.8	0.31	31
4	867	14.1	10.8	0.31	31
5	855	29.4	5.2	0.33	27
6	855	34.7	5.2	0.33	14
7	960	27.0	5.2	0.32	27
8	970	26.8	5.2	0.31	26
9	964	26.9	6.8	0.24	22
10	964	26.7	6.8	0.24	23

Table 3 Gas composition and calculated gas heating value while operating the secondary gasifier on coal tar.

Sample	H_2	CO	CO_2	N_2	CH_4	$C6H_6$	Other	LHV
	%	%	%	%	%	%	%	MJ/Nm^3
1	4.1	18.0	5.5	69.5	1.2	0.1	1.4	3.23
2	4.7	18.3	6.3	67.9	1.1	0.1	1.4	3.32
3	4.3	19.5	5.3	68.0	1.2	0.1	1.4	3.44
4	4.6	19.3	5.5	67.8	1.2	0.1	1.4	3.45
5	3.4	16.5	6.7	70.9	0.9	0.1	1.0	2.90
6	2.3	8.8	2.8	83.5	0.8	0.1	0.9	1.76
7	6.3	15.5	6.6	69.2	0.7	0.1	0.7	2.91
8	6.6	15.8	7.0	67.9	0.5	0.0	0.5	2.87
9	6.1	17.1	5.7	68.7	0.7	0.1	0.8	3.10
10	6.6	17.2	5.5	68.3	0.7	0.1	0.8	3.19

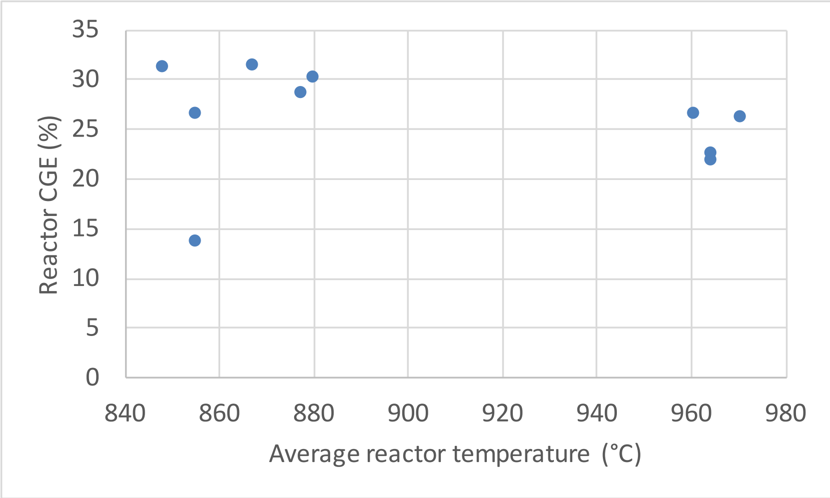

Figure 7: CGE as a function of average gasification temperature.

4.1.2 Wood tar

The Hortlax plant was operated at typical operating conditions when the wood tar was sampled and stored in a 1 m^3 IBC container.

A non-compacting screw fed from a vessel with a bottom scraper was designed and turned out to work well during bench scale tests, see Figure 8.

Figure 8: Wood tar feeder outlet.

The properties of the tar were analysed at three separate occasions and the results are summarized in Table 4.

Table 4 Properties of wood tar

	1	2	3
Total moisture (w%)	60	74	74
Ash (w%)	0.5	0.4	0.9
Chlorine (w%)	<0.01	<0.01	n.d.
Sulphur (w%)	0.04	<0.02	<0.02
Carbon (w%)	38	28	26
Hydrogen (w%)*	7.6	7.9	8.0
Nitrogen (w%)	0.06	0.05	<0.05
Lower heating value (MJ/kg)	17.0	9.96	7.99

*Includes hydrogen bound to water

As can be seen the tar is characterized by a very high moisture content, 60-74%. The lower moisture content of sample nr 1 can be explained by the fact that that sample has been stored in a closed container for about 2 months before analysis, whereas sample 2 and 3 were fresh tar analysed within a week after sampling. Thus, during storage the hydrophobic tar exudes moisture that forms a separate phase.

Moisture in this case consists of not only water but also low boiling tar components e.g. benzene, styrene and naphthalene. This can clearly be seen in Figure 9 below showing the thermogravimetric behavior of tar. The onset of mass loss is at 72 °C while the major mass loss is complete at 130 °C. This implies that light volatiles and water are the main compounds. ~22wt% of the material did not decompose/evaporate indicating the presence of solid char and/or ash as well. The final observation can probably explain the high moisture content despite the hydrophobic properties of the tar. Most likely the water is bound to the solid particles in the tar.

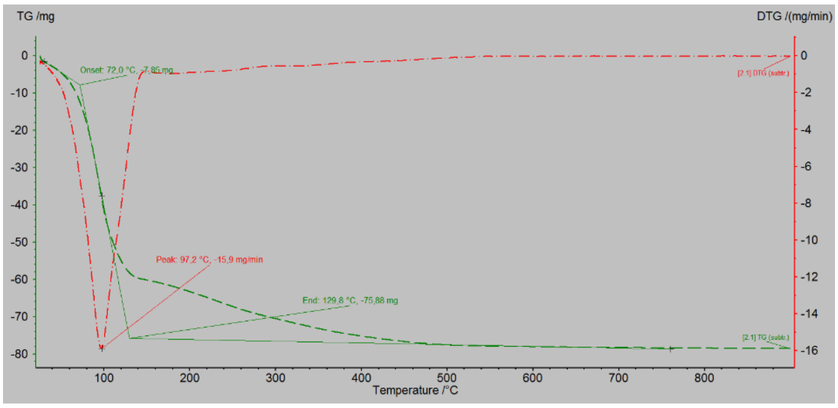

Figure 9: Thermogravimetric analysis of the tar with steam atmosphere.

The developed tar feeder described above was mounted on the reactor.

The high moisture content made it difficult to reach high temperatures in the secondary gasifier. Even at high lambda values of 0.49-0.74 the temperature was below 600 °C which is too low to achieve thermal cracking of the tar (Table 5). The produced gas is probably the result of partial oxidation of tar or gasification of char forming a bed at the bottom of the gasifier.

The highest concentration of CO and H_2 was 15 and 5% respectively whereas the highest heating value of the gas was 2.4 MJ/Nm^3 (Table 6). The CGE increased with time which could be explained by accumulation of fuel inside the reactor during the campaign. This accumulation could contribute to the gas production later in the campaign.

Table 5 Operating conditions and CGE during the campaign in wood tar

Sample	Average temperature	Residence time	Fuel flow	Lambda	CGE
	°C	s	kg/h	--	--
1	618	24.0	13.1	0.49	13.8
2	566	25,4	13,1	0.49	18,6
3	566	26,3	13,1	0.49	22,4
4	566	25,1	13,1	0.49	23,1
5	560	29,7	8,7	0.74	39,5
6	537	32,5	8,7	0.74	37,9

Table 6 Gas composition during the campaign on wood tar

Sample	CO	H_2	CO_2	N_2	CH_4	$C6H_6$	LHV (MJ/Nm^3)
1	7.4	2.0	12.1	75.7	0.0	0.02	1.23
2	10.0	3.3	11.5	72.6	0.0	0.01	1.64
3	13.0	4.0	11.6	68.5	0.1	0.02	2.11
4	12.3	3.8	10.6	70.6	0.0	0.01	1.99
5	14.3	4.1	9.6	69.3	0.0	0.01	2.27
6	14.6	4.5	10.7	67.2	0.0	0.06	2.41

4.2 CHAR

During operation of the Hortlax plant, wet char from the reactor was separated from the water and collected in a wet ash container. The char was analysed with respect to moisture content, heating value and composition. The results are presented in Table 7. The main component of the char was carbon representing about 90% on a dry basis. The ash content was around 7%.

Table 7 Char physical properties and composition

Total moisture (w%)	74
Ash (w% dry basis)	6.9
Chlorine (w% dry basis)	<0.01
Sulphur (w% dry basis)	0.01
Carbon (w% dry basis)	90.7
Hydrogen (w% dry basis)	0.5
Nitrogen (w% dry basis)	0.5
Oxygen (w% dry basis)	1.0
Lower heating value on dry basis (MJ/kg)	31.0

The trials with char are summarized in Table 8 and Table 9.

Table 8 Composition of syngas while operating the reactor on char

Sample	CO	H_2	CO_2	N_2	CH_4	C_6H_6	LHV (MJ/Nm^3)
1	7.2	3.4	14.2	71.4	0,0	0,01	1.31
2	8.7	3.8	13.7	70.1	0,0	0,01	1.52
3	11.7	6.3	12.5	65.6	0,1	0,00	2.19

Table 9 Operating conditions and CGE with char

Sample	**Average temperature** °C	**Residence time** s	**Fuel flow r.** kg/h	**Lambda**	**CGE**
1	570	4.6	15	0.52	8.9
2	523	4.9	15	0.52	9.6
3	566	4.9	15	0.52	13.8

Due to the very high moisture content of the char, the reactor temperature was well below that required for gasification to take place. The CGE was estimated to 14% and the highest heating value of the gas 2.2 MJ/Nm^3.

4.3 BIOMASS

The secondary gasifier has been operated on wood powder on a number of occasions. On two occasions (campaign 1 and 2), a long-term stored wood powder was used. During campaign 3 and 4 fresh and dried wood powder, kindly provided by a local pellet producer, was used.

Wood powder was fed to the reactor by a frequency controlled screw.

Higher gasification temperature lowered the CGE (Figure 10). Addition of steam has positive effect on the gasification with higher CGE. The highest CGE, around 80%, was achieved at a rather low temperature, 850 °C.

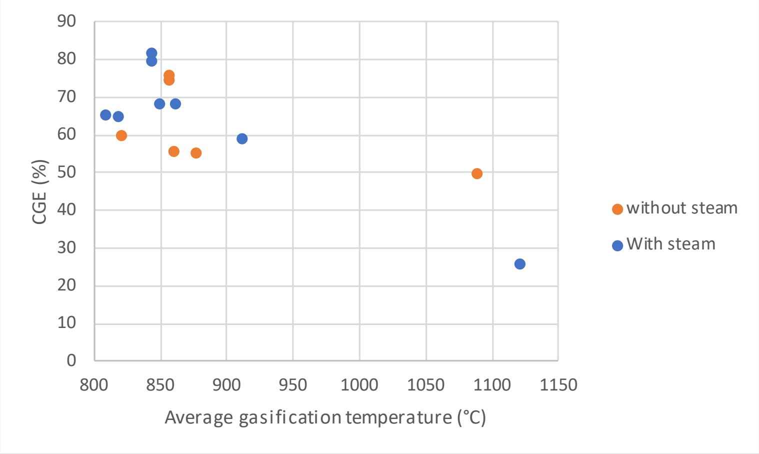

Figure 10: Cold gas efficiency as a function of gasification temperate while operating on fresh wood powder.

The gas heating value, on the other hand, was lower when steam was added to the reactor (Figure 11). Addition of steam seemed to lower the gas heating value and this was probably due to the fact that more air, containing inert nitrogen, had to be added to maintain the reactor temperature. However, the heating value of the gas from the secondary gasifier is not critical since it will be mixed with gas from the primary gasifier. The engine requires a heating value above 5 MJ/Nm^3 and this will be met even if the gas from the secondary gasifier is highly diluted.

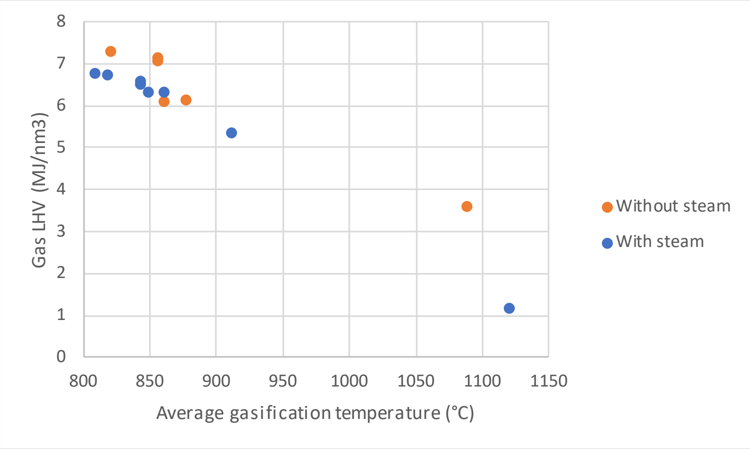

Figure 11 Gas LHV as a function of gasification temperate while operating on fresh wood powder.

The same trend was observed while operating the gasifier on long-term stored saw dust. The highest CGE was achieved at low gasification temperatures (>900 °C).

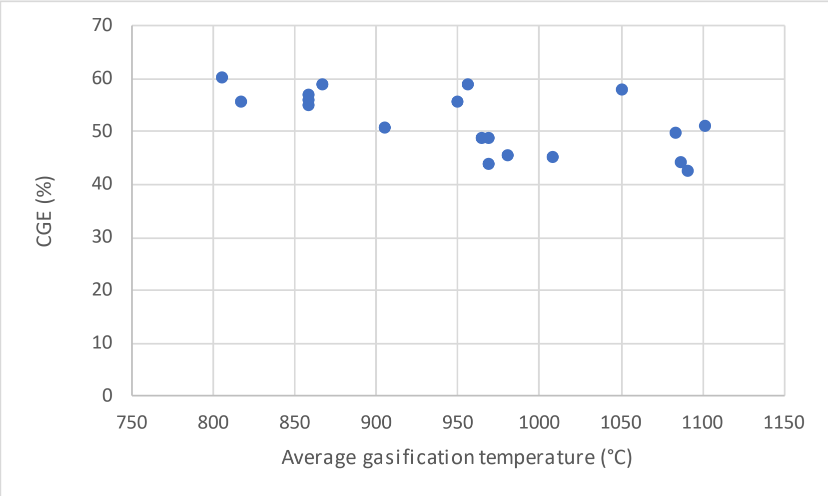

Figure 12 Cold gas efficiency function of gasification temperate while operating on stored wood powder.

5 Discussion and conclusions

The goal of the project was to construct, operate and evaluate a new reactor type for cracking of biomass tars and conversion of residual char to increase the cold gas efficiency of the primary gasification reactor. Target CGE for the system (primary + secondary gasifiers) is 70%. The primary system reaches a CGE of 53% today. To reach 70% CGE in total, the secondary gasifier needs to have a CGE of at least 66% while operating on both char and tar.

Results from the experiments with coal derived tars showed a rather low conversion of the tars. Assuming that all tars are naphthalene, experiments with sample 1 in Table 2 show a conversion of roughly 19% on a molar basis, or 19% of the carbon in the tars are converted into gaseous components. Some of the lower aromatic compounds are most likely only evaporated from the fuel without any conversion. For a more complete conversion, it is likely that more oxidant needs to be present, be that steam, CO_2 or oxygen. The calculated residence time should be sufficient to allow very high conversions of the hydrocarbons, but without something to react with (the oxidant), soot and coke are the only likely products [6]. The formation of soot and coke is inevitable when operating a gasifier on highly aromatic feedstocks, such as tar.

When the secondary gasifier is operated on wood tars it manages a CGE of almost 40% (sample 5 in Table 5 and Table 6). Some additional improvements are required to reach the target of 66%, but several factors influence the conversion. First and foremost, the tars have a very high moisture content. The high moisture content requires significant amounts of energy to vaporize all the water which results in too low temperatures (< 600 °C for most experiments with one at 618 °C). The temperature is not the peak temperature in the reactor, but rather the outlet temperature. On the other hand, the formed steam will increase the conversion of tars and char, but in order to achieve acceptable conversions (> 65% in this case), the temperature in the reactor should be significantly higher. Carbon conversion was almost 40% for sample 5. Furthermore as was discussed above, the reactor was not operating at steady state. Due to this, accumulation of carbon is possible. Tar that is not cracked, or tars that have a boiling point that is higher than the thermal degradation point for the hydrocarbon, will condense and start to form coke and soot. Comparing the experiments with wood tar with those with coal tars, it looks promising. CGE when operating on coal tars were in the range 25-30% and for wood tars 20-40% despite the high moisture content of the wood tars. The higher conversions of wood tars, compared to coal tars, was at a significantly lower temperature which indicates that the wood tars are much more reactive than the coal tars.

Char gasification requires high temperature, oxidant and sufficient residence time to reach high conversions. As was the case with the wood tar, the char has a very high moisture content. The high moisture content is a consequence of the wet ash handling in the plant. Overall the efficiency of the reactor is severely hampered by the high moisture content in the char. Because of this, it is hard to draw an accurate conclusion on how well the reactor will handle a fuel with a more realistic moisture content.

Finally, when the reactor was operated on stored wood powder, CGE was as expected around 55%. This is similar to the performance of the primary gasifier. Higher efficiencies require either catalytic conversion of the formed tars or significantly higher temperature and residence time. When the gasifier was operated on fresh and dried wood, CGE reached on average 70% on fresh wood and averaged 60% on stored wood. Operating with the fresh wood powder not only yielded a CGE that is higher than for the primary gasifier, the heating value of the gas was also higher. At a heating value above 7 MJ/Nm^3, compared to around 6 MJ/Nm^3 for the primary gasifier, the secondary gasifier produces a richer gas. CGE and heating value are connected, but it is possible to achieve low CGE and high LHV and vice versa. Ideal would be to target 5 MJ/Nm^3, which is the lowest acceptable heating value for the gas, and try to reach the highest possible CGE. Comparing the CGE for wood, tar and char for the secondary gasifier, it indicates that higher CGEs for tar and char should be possible.

The reactor was developed to gasify the char and crack the tars formed in the primary gasifier to reach a system CGE of 70%. The high moisture content of both the tar and char samples makes it very difficult for the secondary gasifier to reach the target CGE. Too much air needs to be supplied to maintain a sufficient temperature for gasification and tar cracking. During operation, the air-to-fuel ratio (lambda) was fixed, meaning the actual temperature was not sufficient as can be seen from the tables (Table 5 and Table 9). This was the case for both tar and char. For char, the highest CGE was 15% and two of the samples were < 10%, which is very low. For these experiments, the highest CGE for the secondary gasifier was calculated to 40% while operating on wood tars. If the same CGE can be maintained when operating on both tars and char, the system CGE will be 63%. For full scale operation this will not be the case as this reactor will not be operated on fuel with that much moisture. It is perfectly reasonable, given the high performance when running on wood powder, to expect that the secondary gasifier can reach the target CGE and for the system CGE to surpass the target CGE.

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SECONDARY GASIFIER FOR IMPROVED VIPP SYSTEM PERFORMANCE

This report details a series of gasification tests of biomass, biochar and tar in a so-called secondary gasifier designed to provide longer residence time and higher temperature than during primary gasification. Providing such conditions in a secondary gasifier is a key feature in order to reach high efficiency levels. As various tar compounds exhibit different chemical properties in terms of cracking the tar-cracking ability of the gasifier needs to have a corresponding versatility.

A particular aspect of the study is that the tests involved the design of a new gasifier type utilizing a combination of entrained flow and bed gasification principle. This corresponds to the need to gasify feedstock of fine fraction type or liquid type.

The findings indicate ability to reach high levels of cold gas efficiency in a combined entrained flow and bed gasifier. The gasifier type also confirmed ability to convert tar to syngas by means of cracking. These learnings are important as tar cracking is necessary to reach high levels of efficiency in biomass gasification.

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