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HELGA fluidised bed cooler

A. van der Drift

C.M. van der Meijden

H. Bodenstaff

H.P. Slump

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Colophon

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SenterNovem
P.O. Box 8242
NL-3503 RE UTRECHT
the Netherlands
Phone: (+31) 30 239 34 88
Contact person: K. Kwant
E-mail: k.kwant@novem.nl

The study is performed by:

ECN (contractor)
P.O. Box 1
NL-1755 ZG Petten
Phone: (+31) 224 564515
A. van der Drift
vanderdrift@ecn.nl

Geurts International BV
P.O. Box 2039
NL-2240 CA Wassenaar
Phone: (+31) 70 5123300
H.P. Slump
geurtshps@hetnet.nl

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Keywords

Gasification, gas cooler, fluidised bed, fouling, deposition.

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Summary

Biomass gasification attracts a lot of attention. It not only can offer a way to produce electricity efficiently, also gaseous and liquid energy carriers as well as chemicals can be synthesised from the gas produced by a gasifier. Large hydrocarbon molecules in the product gas however, are considered to be a major problem. It easily causes fouling by condensation on cold surfaces. The gas cooler therefore is prone to tar fouling.

From earlier work, it has become clear that the presence of a minimum amount of large particles can prevent the formation of an insulating fouling layer. This observation has been the basis for the development of the HELGA cooler concept. HELGA is a fluidised bed cooler that uses the abrasive forces of the fluidising bed material to constantly clean the cooler surfaces.

Within the present project, a lab-scale HELGA cooler has been designed, constructed and tested downstream a 7 m_n^3/h fluidised bed gasifier. It is concluded that a very high steady state heat transfer can be maintained of approximately 250 W/m^2K (bed-side) despite the fact that a thin tar coating appears on the cooler surfaces. The presence of the coating proves that erosion of the cooler tubes is not an issue. Moreover, the coating serves as chemical and physical barrier for corrosion.

During each test, the bed material in the fluidised bed cooler was coated with a thin layer of solidified tar. Furthermore, fouling and blocking of the gas distributor of the HELGA fluidised bed heat exchanger appeared to be a serious problem. This was solved by allowing enough particles hitting the gas distributor. This could be realised by allowing entrainment of bed material from gasifier to heat exchanger. The required addition of particles upstream the HELGA cooler nicely coincides with the necessity to refresh the HELGA bed regularly because of the tar coating formation on the bed particles. If particle entrainment is not an option (which is the case for certain gasification technologies), sand can be added from an external source.

A first design has been made of a HELGA-cooler downstream the existing 0.5 MW_{th} CFB-gasifier at ECN. A compact reactor of only 0.3 m diameter and 0.5 m bed height seems to be sufficient to cool the gas to 400°C with 200°C oil (or steam).

1. Introduction

A gasifier produces a combustible gas that can be used to efficiently generate electricity[1], produce gaseous or liquid energy carriers[2], chemicals, and/or heat. Gasification therefore is a versatile process that has been recognized as key process for future renewable energy generation from biomass.

Contrary to coal, biomass can be gasified efficiently at temperatures as low as 800-900°C due to the relatively high reactivity of biomass. At these temperatures, the product gas generally contains considerable amounts of hydrocarbon molecules. This mainly concerns methane, but also small amounts of higher hydrocarbons appear in the gas. Hydrocarbons larger than benzene are called tar [1]. Tar plays a major role in fouling of cooler surfaces. Recently, the fouling mechanism has been clarified [2]. It has also been demonstrated that cooler probes can be kept clean by allowing enough large particles in the gas. The abrasive character of e.g. sand particles appeared to be able to completely prevent the formation of an insulating deposit. This observation has been the basis for the development of the HELGA cooler concept.

HELGA is a fluidised bed cooler that uses the abrasive forces of the bed material to clean the cooler surfaces. It offers high flexibility for cooling media (air, water, steam, …) and temperatures. Furthermore, a fluidised bed generally is characterized by very high heat transfer rates, which means that HELGA can be compact and cheap.

First tests have been performed with a small HELGA test unit at ECN. It appeared that cooler surfaces can indeed be kept relatively clean and high heat transfer rates were achieved. It however also became clear that the bed material developed a black coating that might become a problem upon time. Moreover, deposits tend to grow on the gas distributor of HELGA. The aim of the work reported here is to develop methods to deal with fouling of the bed material and gas distributor. A conceptual design will be made of a pilot-scale HELGA cooler to be connected to the existing 200 m_n^3/h CFB gasifier at ECN.

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1 by means of: engine, steam cycle, gas turbine, combined cycle, fuel cell
2 examples: diesel, methanol, synthetic natural gas (SNG), hydrogen

2. HELGA

2.1 Principle

HELGA is a fluidised bed cooler. Bed material moves around cooler surfaces that are immersed in the fluidised bed. The scouring forces of the bed material prevent deposition to occur. At the same time, heat transfer coefficients as high as 300 W/m^2K can be obtained, compared to approximately 50 W/m^2K for a conventional gas cooler consisting of (clean) steam tubes in the gas flow. Figure 2.1 shows the HELGA-concept schematically.

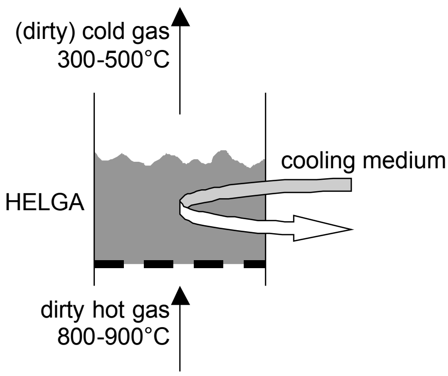

Figure 2.1 *HELGA concept for cooling dirty gas*

2.2 Previous work

A first version of the HELGA-concept has been operated at ECN downstream a lab-scale gasifier producing typically 2 m_n^3/h product gas. The inner diameter was approximately 8 cm and the bed temperature has been kept around 400°C by a cooling coil immersed in the bed. Both water and N_2 were used as cooling medium.

Tests *without* bed material resulted in the development of a porous layer on the cooler surface. The layer growth was as high as over 1 millimetre per hour. If bed material (silica sand) was applied, the fouling was limited and only a thin black dense layer was formed. The heat transfer on the outer surface of the cooling coil was around 300 W/m^2K initially and reduced to a stable 200-250 W/m^2K within several hours.

Fouling of the upstream side of the distributor plate[3] however, turned out to be a serious problem. A first design with many small holes of 1 mm diameter (total open surface 1%) fouled so quickly, that the test had to be aborted within 30 minutes because of high pressures. A second concept with one large hole of 8 mm and a “roof” to prevent bed material to fall down, appeared to be much better and has been running for 20 hours. The gas distribution however was not good and cooler fouling was observed in certain areas in the bed.
After each test, the bed material was coated with a thin black layer. Although this had not been a problem during any of the tests performed, this might be a problem during long period operation.

[3] A distributor plate separates the gas inlet chamber (also referred to as windbox) from the fluidised bed above it. It not only prevents bed material to fall down, it also serves as a means to distribute the gases radially in order to have a well fluidised bed with uniform temperature and concentrations.

From the work described above, designated as “proof of principle”, it has been concluded that a fluidised bed cooler like HELGA is capable of cooling dirty gas containing tar and dust very efficiently. Both high and stable heat transfer was achieved. Two aspects however need more attention: (1) fouling of gas distributor and (2) fouling of bed material itself. Furthermore, it appeared that the tests with the lab-scale HELGA were difficult to interpret because of the small size and the relatively high heat losses.

2.3 New test facility

Within the current project, a new HELGA-reactor has been designed and constructed. It has been decided to have it connected to the relatively large lab-scale MILENA-gasifier producing approximately 7 m_n^3/h product gas [3]. In order to minimize heat losses, the top section of the MILENA gasifier has been used to accommodate the HELGA cooler. The top section temperature can be controlled independently. The integration also offers the option to clean the upstream side of the HELGA by entrained bed material from the gasifier. Figure 2.2 shows the test facility.

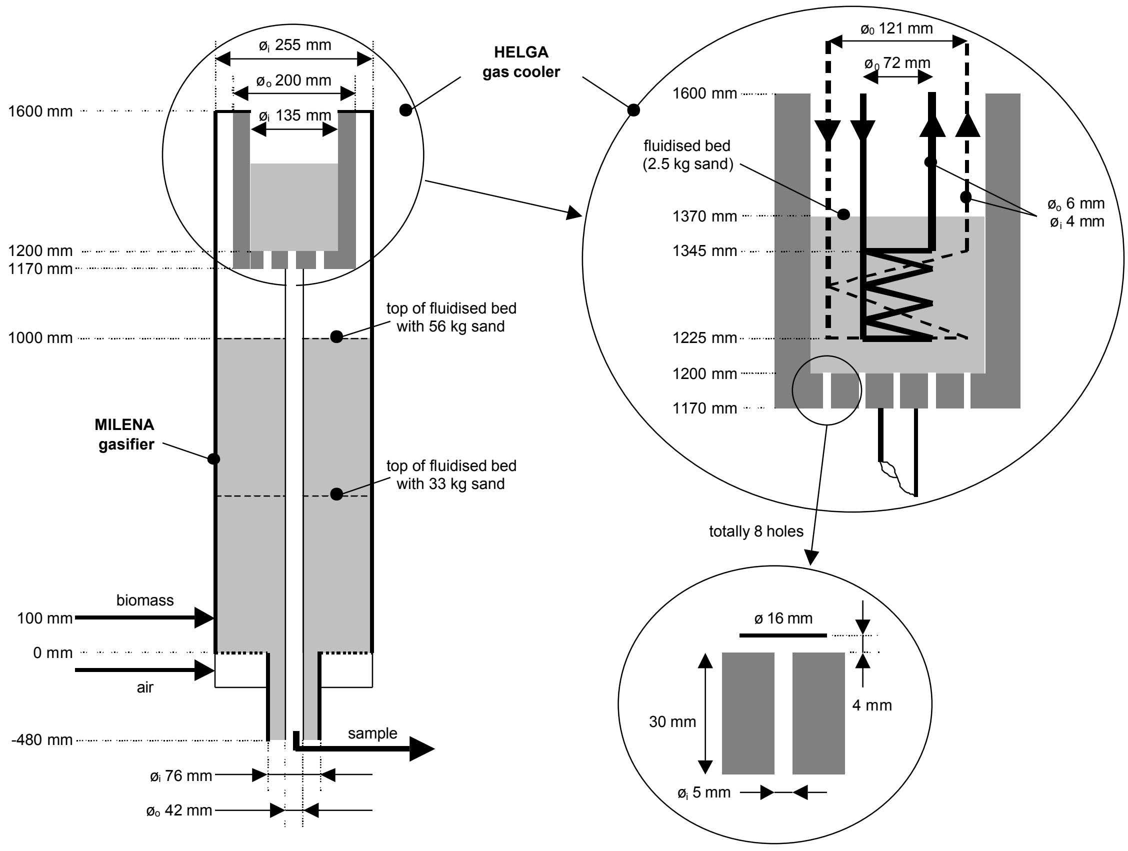

Figure 2.2. *HELGA cooler positioned in top section of MILENA fluidised bed gasifier*

HELGA is made of stainless steel and is covered with 3 cm of insulating refractory material. The MILENA gasifier has been operated with 33 kg as well as 56 kg silica sand. HELGA was filled with 2.5 kg of the same material with mean diameter of 250 μm. The gas velocity through the bed is approximately 4-5 times the minimum fluidisation velocity in both reactors.

Figure 2.3. *Picture of MILENA gasifier (left), upward view on refractory lined HELGA-reactor (centre), two cooling coils to be immersed in the HELGA fluidised bed (right)*

2.4 Test programme

Four tests have been carried out. Test 0 is the reference where the gasifier has been operated as combustion facility for methane. The hot flue gases of approximately 850°C passed the water-cooled HELGA-reactor. Test 0 is performed at four conditions. During test 0a, HELGA was empty (no bed material) to simulate a "conventional" water-tube cooler. Tests 0b, 0c and 0d were performed with bed material with increasing flue gas flow in HELGA.

Subsequently, the MILENA gasifier has been operated with 3.4 kg/h beech wood at 850°C with a lambda of 0.26. The product gas composition is given in Table 2.1. HELGA was kept at approximately 400°C. Three tests have been performed:

- Test 1: base case
- Test 2: increased bed material level in gasifier for *in situ* gas distributor cleaning
- Test 3: oil cooling instead of water cooling (higher surface temperatures) and two cooling coils instead of one to keep the desired cooling power

Tests 2 and 3 both have been carried out in two days. The gasifier/HELGA was kept overnight with a 10 liter/min N_2 flowing through both reactors to conserve the situation. During the tests, several temperatures and pressures were measured to control the facility and for evaluation. After each test, the HELGA-reactor was opened for visual inspection. Additional chemical and SEM analysis have been performed on bed material and deposits.

Table 2.1 *Gas composition, na: not analysed*

test:		test 0	test 1		test 2	test 3
fuel		methane	biomass		biomass	biomass
location [a]:			before	after	after	after
H_2	vol% dry	-	6.6	6.6	5.7	5.6
CO	vol% dry	-	21.5	18.6	18.9	20.3
CH_4	vol% dry	-	5.5	4.9	4.9	5.1
CO_2	vol% dry	-	13.2	14.2	14.2	13.4
C_2H_x	vol% dry	-	*na*	*na*	1.0	*na*
C_6H_y	vol% dry	-	*na*	*na*	0.4	*na*
N_2	vol% dry	80 – 81	*na*	*na*	51.9	*na*
O_2	vol% dry	13 – 16 [b]	-	-	-	-
H_2O [c]	vol% wet	5 – 7	*na*	*na*	18	*na*
tar	g/m_n^3 dry	-	21	*na*	17	*na*
particles	g/m_n^3 dry	-	*na*	7	7 – 17 [d]	10

a analysis done upstream (before) or downstream (after) the HELGA-reactor
b different methane/air ratio’s
c calculated from mass balances
d increases in time during test period

2.5 Heat transfer coefficient

From the data measured during each experiment, the heat transfer coefficient is calculated using the following procedure:

- The power extracted from HELGA is calculated using measured temperatures of cooling water/oil flowing in and out the reactor and measured mass flow.
- The overall heat transfer coefficient is calculated using the average temperature of the cooling medium (water or oil) inside the cooling tube and the average temperature inside the HELGA-reactor (2 temperatures).
- The heat transfer coefficient on the outside of the cooling tube (so called bed-side heat transfer) is calculated using the average temperature measured at the surface of the cooling tube (3 temperatures) and the average temperature inside the HELGA-reactor (2 temperatures).

3. Results

Appendix A shows the main parameters plotted against time for each test. In the following sections, the measurements will be interpreted and also visual and SEM results will be described.

3.1 Energy balances

For each experiment, an energy balance has been made. From Table 3.1 it appears that most balances are reasonably closed. It however is necessary to include the energy gained by convection and conduction from the gasifier though the wall and bottom plate of the HELGA-reactor.

Table 3.1 *Energy balance of the different tests based on average values during test period*

test:		0a	0b	0c	0d	1	2	3
gasifier fuel [a]:		M	M	M	M	B	B	B
HELGA inside [b]:		E	S	S	S	S	S	S
coolant [c]:		W	W	W	W	W	W	O
water/oil heating	W	810	2 110	2 310	2 470	2 190	1 950	2 020
gas cooling	W	-790	-1 380	-1 740	-1 970	-1 660	-1 560	-1 580
other gains [d]	W	-60	-520	-490	-450	-430	-370	-310
balance	%	-5%	11%	4%	2%	5%	1%	7%

a M: methane/air combustion, B: biomass/air gasification
b E: empty, S: sand bed material
c W: water, O: thermal oil
d calculated contribution of heat transfer from gasifier and walls to relatively cold HELGA-reactor

3.2 Heat transfer

The heat transfer coefficient has been calculated from the measured data according to the procedure described in Section 2.5. Table 3.2 contains a summary of the results concerning heat transfer.

Table 3.2 *Heat transfer coefficient* a *[W/m²K] during the different tests*

test:		0a	0b	0c	0d	1	2	3
gasifier fuel [a]:		M	M	M	M	B	B	B
HELGA inside [b]:		E	S	S	S	S	S	S
coolant [c]:		W	W	W	W	W	W	O
average overall α	W/m^2K	64	315	326	330	279	232	221
average bed-side α	W/m^2K	66	351	367	372	309	256	285
bed-side α start [d]	W/m^2K	66	353	369	374	337	344	419
bed-side α end [e]	W/m^2K	66	350	368	370	307	182	249
relative decrease		1%	1%	0%	1%	9%	47%	41%

a M: methane/air combustion, B: biomass/air gasification
b E: empty, S: sand bed material
c W: water, O: thermal oil
d average of first 20 minutes of test
e average of last 20 minutes of test

As expected, a huge increase of heat transfer rate is observed by using bed material around the cooling tubes. Heat transfer coefficients rise from 65 W/m^2K for a "conventional" water-tube heat exchanger to approximately 350 W/m^2K if a fluidised bed is present around the cooler tubes.

When HELGA is applied as cooler for *flue gas* (tests 0a-0d), short term heat exchanger fouling is not an issue. If however *product gas from biomass gasification* is directed through the HELGA heat exchanger, fouling can occur. The heat transfer coefficient reduces rapidly in test 2. In test 3 this also seems to be the case, but from the complete data graphics in Appendix A it appears that fouling comes to a stop after approximately 5 hours.

3.3 Cooler fouling

Visual inspection of the cooler surfaces after each test reveals a coherent picture for all tests. Some locations can be found where the original metal surface is visible. Most of the surface however is covered with a thin 200-500 μm thick compact dense black layer. Apparently, tar has been condensed on the relatively cold surface. Most of it has been hardened in time due to solidification/polymerisation. Some small ash particles are embedded in the sticky layer. These findings are very similar to those reported in [2].

Apart from the overall coverage of a thin compact layer on the cooler surface, at some locations a thick deposit of up to 1 cm has been developed. Although it apparently survived the erosive atmosphere inside the HELGA-reactor, it only requires little force to destroy it afterwards.

Figure 3.1 shows some pictures of the cooling tubes after the tests. The three above-mentioned zones are visible: clean metal, thin black coated surface and thick sand agglomerates.

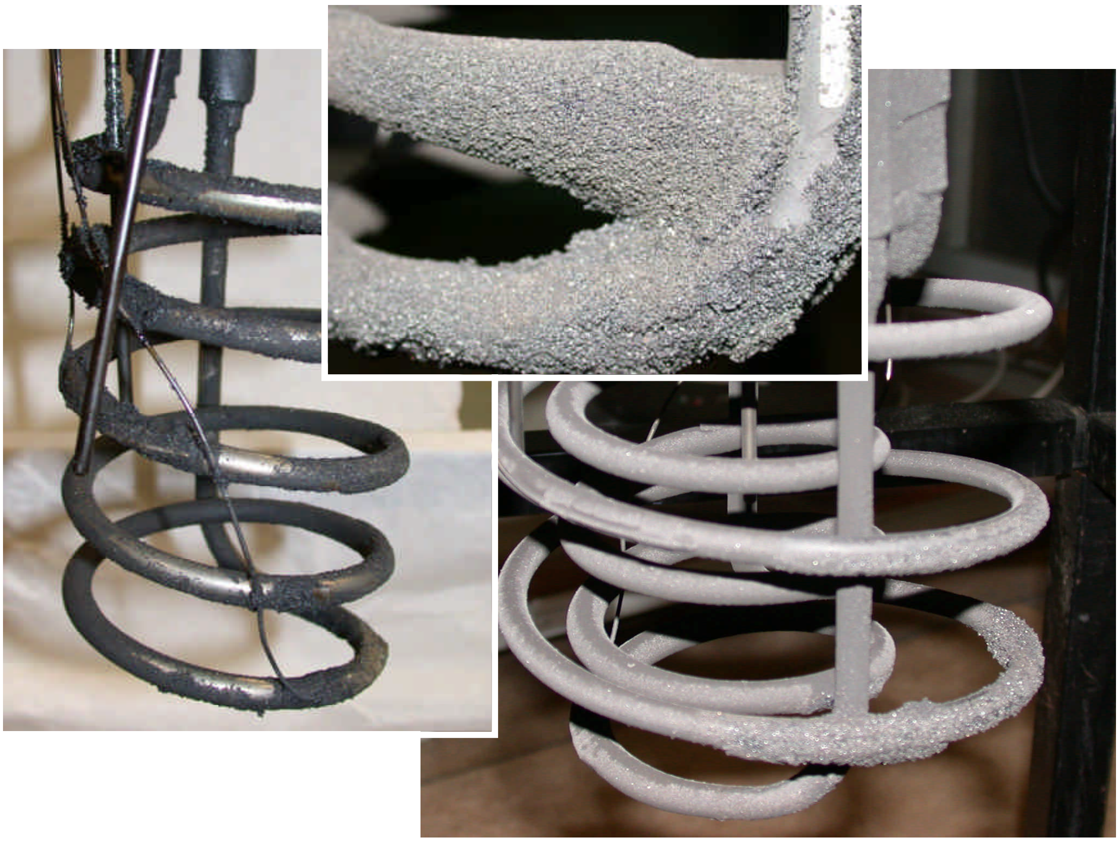

Figure 3.1 *Pictures of cooling tubes after test 1 (left) and test 3 (right) with close-up of local thick porous deposition (top centre)*

The sand clusters that appear locally at the surface of the cooler tubes have been analysed more thoroughly by SEM (Figure 3.2). It appears that the bed material (sand) particles have been glued together with tar. From the smooth structure and the concave shape of the connecting "glue", it is concluded that tar has been condensed on the surface, possibly followed by chemical solidification (polymerisation reactions).

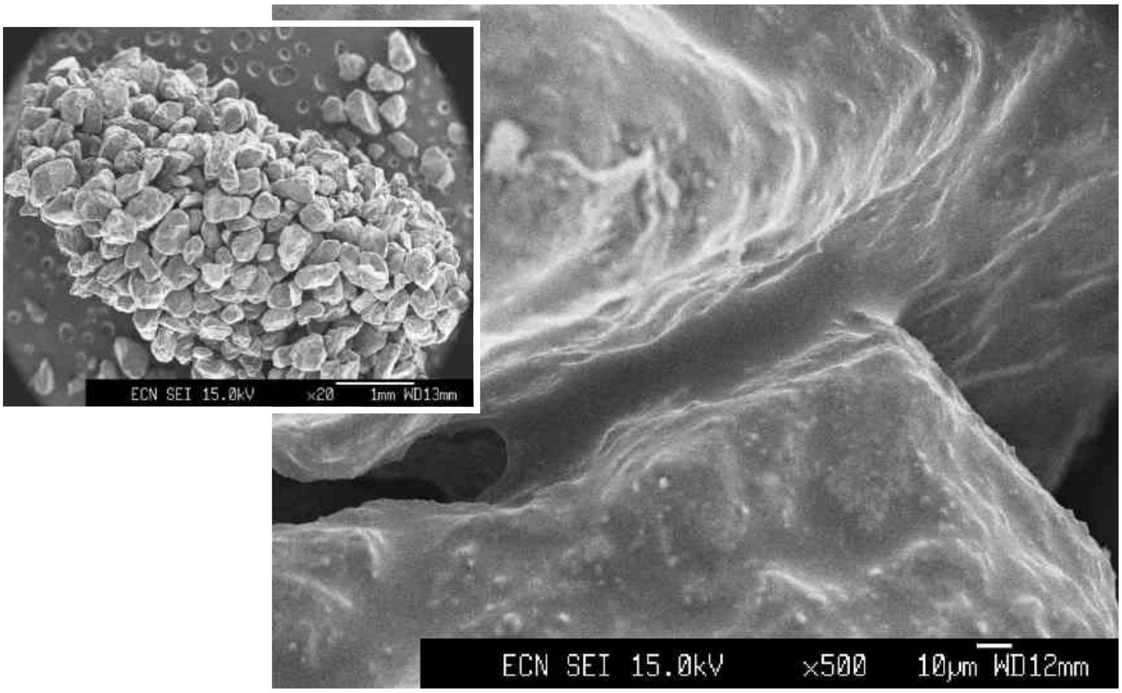

Figure 3.2 *Pictures of sand cluster found locally on the surface of the cooler tubes*

The sand clusters as shown in Figure 3.2 seem to be the greatest threat for the long-term behaviour of the cooler. These sand clusters however, appear only at locations that are badly fluidised. It therefore is concluded that the existence of the clusters is the result of bad local fluid dynamic behaviour rather than intrinsic reasons. It is expected that the formation of sand clusters can be avoided if the fluidised bed cooler is designed properly concerning this point.

The depositions observed and analysed as described above apparently are responsible for the reduction of the heat transfer coefficient as mentioned in Section 3.2. Assuming a thermal conductivity of 1 W/mK roughly corresponds to the measured heat transfer reduction. This is consistent with the results reported in [2].

3.4 Gas distributor

During test 1, the pressure drop over the HELGA-reactor increased steadily, see Appendix A. The test had to be aborted prematurely for this reason. Visual inspection afterwards showed considerable fouling of the gas distributor (see Figure 3.3). The deposit is brittle and easy to destroy by hand. The SEM analysis of the deposited material reveals that it is a collection of submicron wood ash particles.

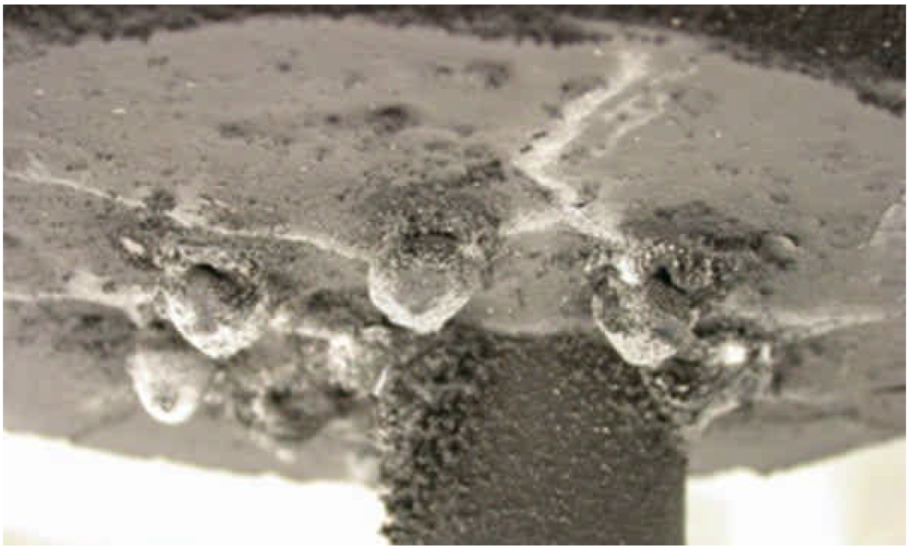

Figure 3.3 *Deposits on upstream side of gas distributor plate of HELGA cooler (test 1)*

Tests 2 and 3 have been operated with extra bed material in the gasifier in order to clean the gas distributor. This has proven to be very effective. The pressure drop over the system does not/hardly increase in time during these tests (Appendix A). Furthermore, visual inspection afterwards reveals no deposit at all on the gas distributor. There might be a thin layer formed within the nozzles of the gas distributor. This could not be quantified and in any case has not been a problem during the tests performed so far.

3.5 HELGA bed contents

A mass balance over the HELGA-reactor has been made. The original 2500 gram bed material contents decreased during test 1 to 2430 gram. In addition, 180 gram solid material was measured. downstream the reactor and apparently was entrained by the gas. The 2610 gram total mass consisted of 2460 gram inert material, which is very close to the original 2500 gram added to the reactor for test 1.

During test 2 however, HELGA inert bed content is increased by 160 gram during the test period[4]. This apparently comes from the gasifier. It is the result of the relatively high bed height in the gasifier during test 2, which was successfully applied to clean the gas distributor.

After each test, the original white/grey bed material from the HELGA-reactor has turned black. Combustion tests reveal approximately 1% combustibles. SEM analyses show a thin carbon-rich layer of less than 1 μm thickness on the surface of most sand particles. This is consistent with mentioned 1% combustibles. Apparently, tar has been deposited on the bed material surface. The amount of tar found on the bed material corresponds to 1-2% of the tar in the product gas flowing through the bed during the test.

4 This corresponds to approximately 2 g/m_n^3 of entrained bed material particles.

3.6 Evaluation

Heat transfer can be increased enormously by applying bed material as intermediate between product gas and coolant. The concept called HELGA is based on this principle and it has been experimentally proven that the original heat transfer coefficient of 65 W/m^2K with no bed material (reference: test 0) can be increased to 350-400 W/m^2K.

From the tests described above, it appears that the HELGA heat exchanger suffers from fouling. This however seems to reach a steady state corresponding to approximately 250 W/m^2K for the outside (bed-side) of a 200°C cooling tube. This however partly is caused by deposition of bed material at certain locations on the cooler caused by bad fluidisation and bad fluid dynamics. It is anticipated that a properly designed fluidised bed heat exchanger like HELGA can have a steady state heat transfer coefficient of at least 250 W/m^2K. This is 10 higher more than what is considered realistic for a conventional heat exchanger at steady state (fouled) conditions. The reduction of required heat exchanger surface area is enormous.

HELGA gas distributor problems can be very severe. During test 1, pressure drops increased very rapidly due to plugging of the holes by agglomerated fly-ash from the gasifier. Creating erosive power by changing the concept in a way that more sand bed material from the gasifier reaches the upstream side of the HELGA gas distributor, has proven to be very effective. Tests 2 and 3 have been performed very successfully on this point. Approximately 2 g/m_n^3 of bed material was entrained by the gas from gasifier to HELGA-reactor.

Experiments have indicated that a thin tar layer is formed on the surface of bed material particles. This is estimated to be 0.05-0.1 µm per hour. Given the average bed temperature of approximately 400°C during the tests, this might seem strange since tar condensation is not supposed to happen at these high temperatures [2]. One plausible explanation is that each bed material particle sometimes is in the vicinity of a cooling tube. At that moment, the particle temperature will drop, albeit for a very short time. The abundantly available tars will condense during this short period. Subsequently, the tar coating will solidify by chemical polymerisation reactions and form the hard black layer, which has been observed.

The addition of 2 g/m_n^3 fresh bed material to HELGA heat exchanger seems to be able to avoid serious distributor fouling. The added material should be extracted from the HELGA bed to avoid accumulation. For the lab-scale system tested in the present work, this would mean a bed refreshment of once every 200 hours. This would mean approximately 10 µm bed material coating by tar. This does not seem unrealistic, but higher refreshment rates might be needed.

Long-term tests are needed to determine if the above-mentioned 250 W/m^2K bed-side heat transfer coefficient actually can be maintained. Also the necessary bed content refreshment rate should be determined.

4. Pilot scale design

It has been shown that cooling dirty gas with tar and particles in a HELGA fluidised bed cooler only is possible if enough large particles are entrained by the gas to keep the HELGA gas distributor clean. This was achieved in the lab-scale test facility as described in the previous sections by integration of gasifier and HELGA cooler. This may not always be desirable or possible. The combination however, seems particularly attractive for plants up to a size of 10-20 MW_{th} biomass input. In that case, the diameter of the bubbling fluidised bed gasifier is only a few meters and fuel feeding and bed uniformity is considered to be not a problem.

A second option for HELGA is to have it as a separate reactor downstream the gasifier. In order to have sufficient cleaning of the HELGA gas distributor, the injection of bed material may be required. This however heavily depends on the kind of gasifier. If the gasifier is a circulating fluidised bed, sufficient bed material is blown over the top of the gasifier.

Figure 4.1 shows both options described above for HELGA to be the gas cooler in a biomass gasification plant. Also indicated is the method to avoid HELGA bed content accumulation. This can be a simple overflow system for the first option where gasifier and HELGA are integrated. For the second option, bed material drainage is necessary. The spent bed material can be recycled to the gasifier. The gasifier might also supply the sand needed to keep the HELGA gas distributor clean.

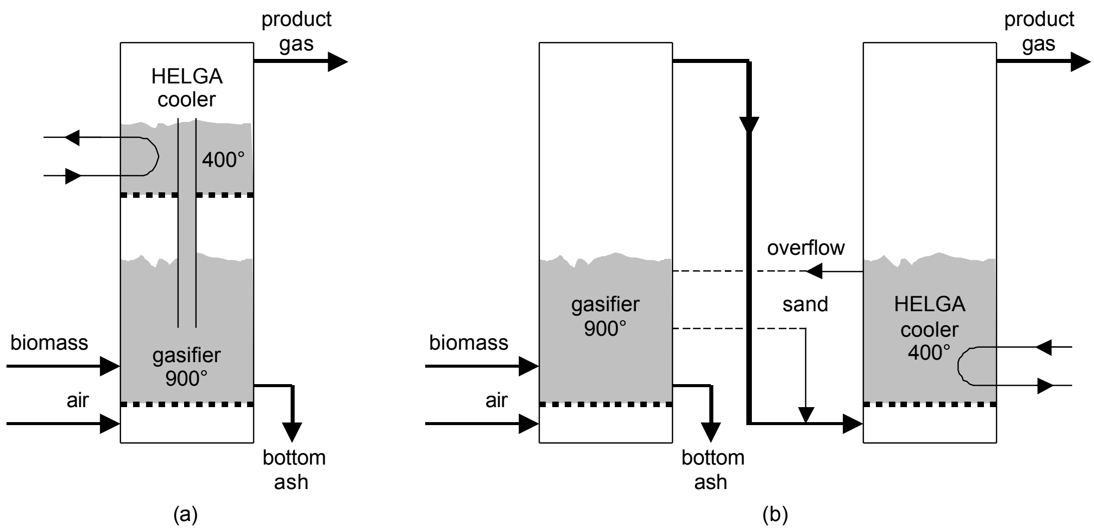

Figure 4.1 *Two options to integrate HELGA cooler and gasifier*

4.1 Case: 0.5 MW_{th} CFB-gasifier

If HELGA is to be positioned downstream the existing 0.5 MW_{th} CFB-gasifier at ECN [4], option (b) in Figure 4.1 is the appropriate one. The CFB-gasifier produces approximately 200 m_n^3/h product gas at 800-900°C and atmospheric pressure. The bed material generally is silica sand with an average diameter of 0.5 mm. The necessity to have bed material entrained by the gas to clean the upstream side of HELGA means that the CFB-gasifier should be coupled directly to the HELGA fluidised bed cooler (no intermediate hot cyclone). Furthermore, HELGA should preferably be operated with 0.5 mm silica sand as bed material so that bed material can be exchanged between CFB-gasifier and HELGA (in both directions). In Figure 4.2, a rough design of the HELGA-cooler downstream the existing CFB-gasifier at ECN is shown including some main parameters. The dimensions are based on a maximum analogy with the lab-scale system as described in this report (test 3). This means: similar fluidisation regime, cooling to 400°C with average coolant temperature of 200°C, and 200 W/m^2K overall heat transfer coefficient.

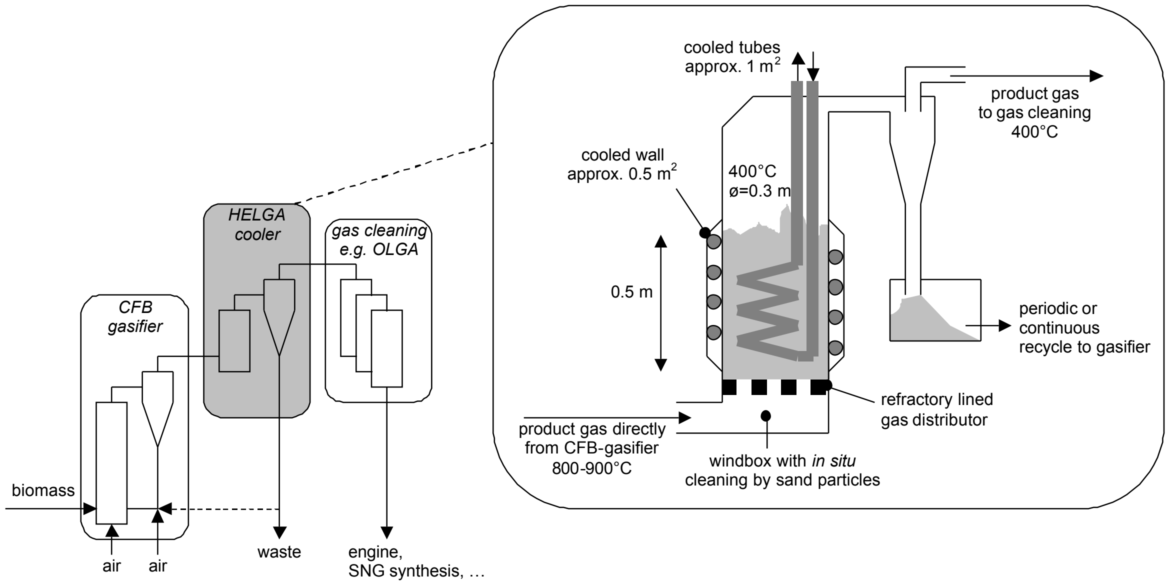

Figure 4.2 *Example of HELGA coupled to existing 0.5 MW_{th} CFB-gasifier at ECN*

5. Conclusions

The HELGA fluidised bed cooler is capable of cooling dirty gas containing tars and particles while maintaining a high heat transfer of approximately 250 W/m^2K (bed-side). A thin tar coating appears on the cooler surfaces. From the short-term experiments, it is concluded that this reaches a steady state within a few hours. The heat barrier is rather small and equals 500-1000 W/m^2K. More importantly, the coating might be considered as highly desirable since it serves as chemical as well as physical barrier for corrosion and erosion.

Apart from the cooler surface coating, also the bed material in the fluidised bed cooler is coated with a thin tar layer. This is expected to become a problem in time, but can easily be solved by periodic bed refreshment.

Fouling of the gas distributor of the fluidised bed heat exchanger turned out to be a serious problem. It however has been solved by ensuring that enough relatively large particles are present to physically clean the surface. This can be realised by allowing entrainment of bed material from gasifier to heat exchanger. The required addition of particles upstream the HELGA cooler nicely coincides with the necessity to refresh the HELGA bed regularly because of the tar coating formation on the bed particles. If particle entrainment is not an option (which is the case for certain gasification technologies), sand can be added from an external source.

A first design has been made of a HELGA-cooler downstream the existing 0.5 MW_{th} CFB-gasifier at ECN. A compact reactor of only 0.3 m diameter and 0.5 m bed height seems to be sufficient to cool the gas to 400°C with 200°C oil (or steam).

6. References

1. T. A. Milne, N. Abatzoglou and R. J. Evans: *Biomass gasifier tars, Their nature, formation and conversion* . 1-68 (1998).
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3. A. van der Drift, H. Boerrigter and C. M. van der Meijden: *Milena: lab-scale facility to produce a low-N2 gas from biomass*. In: The 2nd World Conference on Biomass for Energy, Industry, and Climate Protection, 10-14 May 2004, Rome, Italy (2004).
4. A. van der Drift, C. M. van der Meijden and S. D. Strating: *Hogere koolstofconversie in CFB-biomassavergassers*, ECN, Petten, ECN-C-03-053, 44 p. (2002).

Appendix A Test results

The following figures show the most relevant parameters measured during the different tests. The test conditions are described in more detail in Sections 2 and 3.

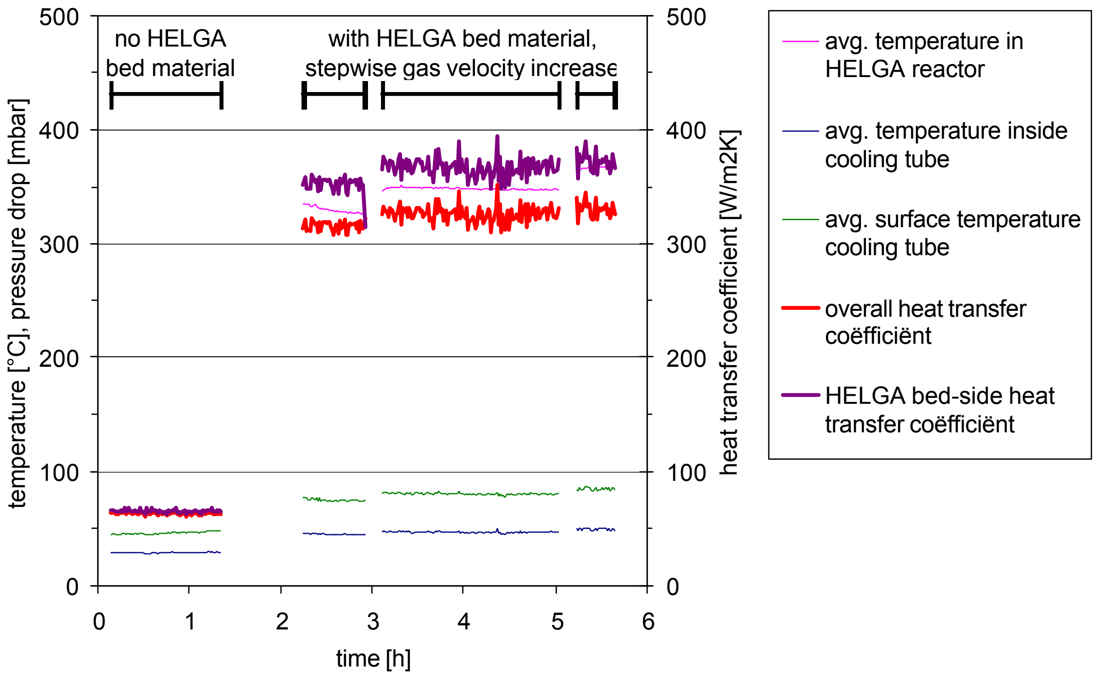

Figure A1. *Test 0: reference test with methane combustion at 850°C*

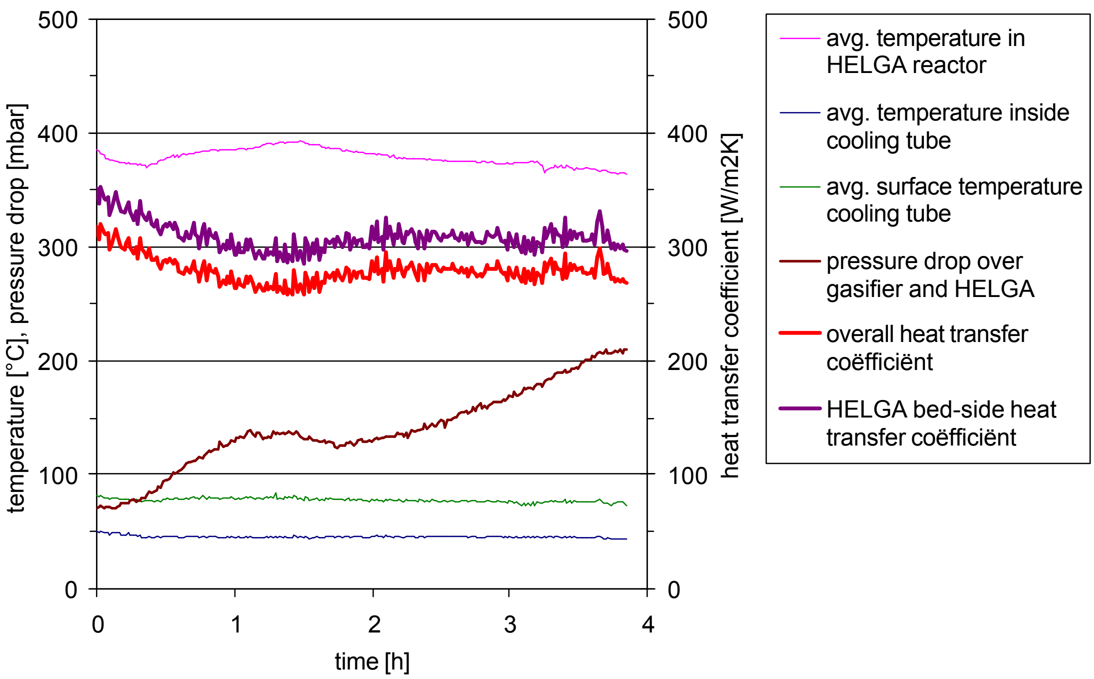

Figure A2. *Test 1: biomass gasification and water-cooled HELGA*

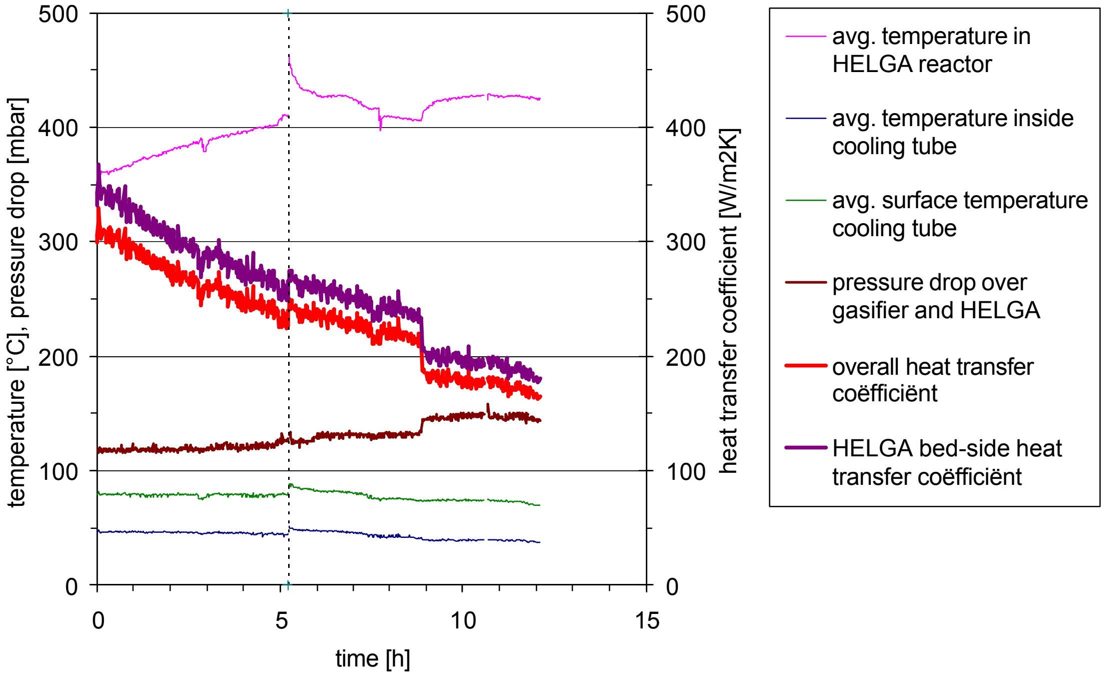

Figure A3. *Test 2: biomass gasification, water-cooled HELGA with HELGA distributor cleaning; dotted line: day change with overnight conservation*

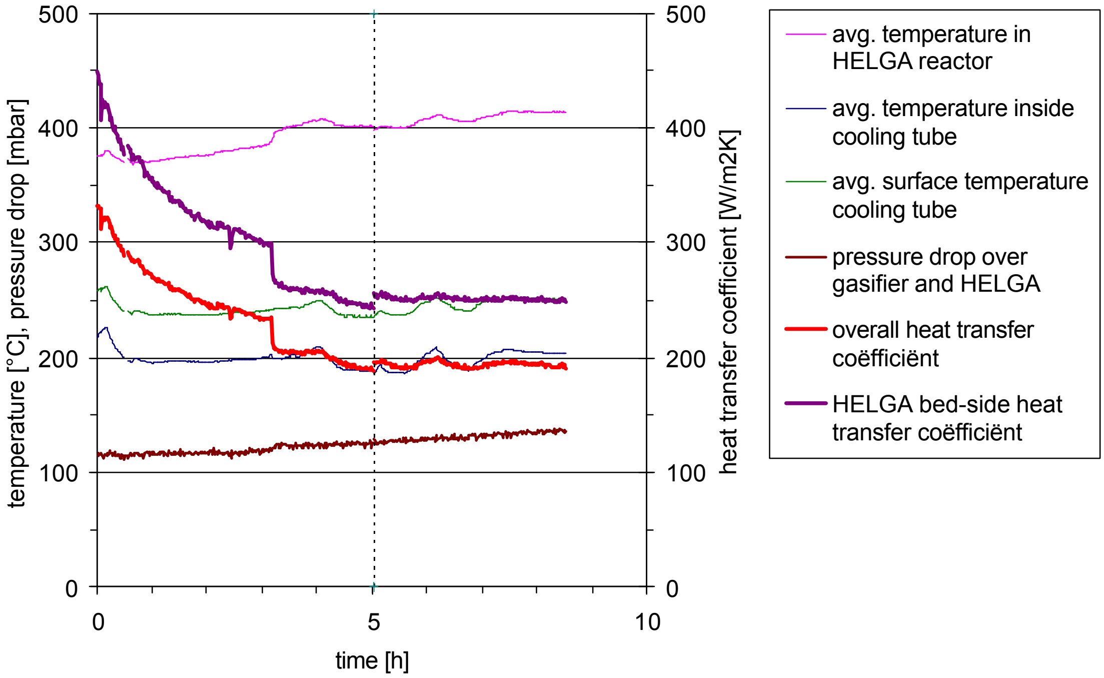

Figure A4. *Test 3: biomass gasification, oil-cooled HELGA with HELGA distributor cleaning; dotted line: day change with overnight conservation*