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Fouling effect in a shell-and-tube heat exchanger with twisted tape inserts applied to a small-scale biomass gasification power plant

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Abstract. In this work the over-time behaviour of a shell-and-tube type heat exchanger applied to a commercial and small-scale wood biomass gasification system was investigated. The heat exchanger, equipped with twisted tape turbulators, was used to cool down the syngas produced by the power plant. An experimental campaign was conducted to evaluate the performance trend in the first 15 hours of operation. The results showed an increase in heat transfer which led to a progressive reduction of the gas outlet temperature from 105.4 °C to 90.0 °C. The data collected confirm the literature studies on the positive effect that the deposits of particulate matter and tars have in reducing the clearance between the heat exchanger pipes and the turbulators, providing information for the temporal optimization of the cleaning strategy of the heat exchanger itself.

1. Introduction

A gasification power plant consists in a system that, through a series of thermochemical reactions, decomposes the molecules of the biomass into simpler ones generating a fuel gas, commonly known as *producer gas* or *syngas*. This is a multiphase fluid, mainly formed by a gaseous phase of H_2, CO, CO_2, H_2O, CH_4, N_2 [1] that also carries a series of pollutants in vapour phase, i.e. tars and in a solid phase represented by soot, ashes and particulate matter in general [2]. In fixed bed reactors, the higher heating value of the clean producer gas ranges from 4 to 7 MJ/Nm^3 depending on the fuel used and the gasification conditions [3]. This gas mixture is mostly used to fuel internal combustion engines to produce combined electrical and thermal power [4].

Several architectures and technologies can be employed in the design of a biomass power plant but the *fil rouge* that links all of them is the presence of crucial components such as a gasification reactor (gasifier) where the thermochemical reactions occur, a gas conditioning system that includes cooling and filtering stages and, at the end, a power unit that converts the fuel gas into electrical and thermal power.

Since the producer gas exits from the reactor at temperatures close to 600 °C, the cooling stage is needed in order to cool down the gas and to avoid damages to the filtration stage and the internal combustion engine. This work focuses on the assessment of the performances of a shell-and-tube heat exchanger applied to a commercial small scale gasification power plant: the Power Pallet 30 manufactured by the US company All Power Labs [5]. In particular, a series of tests were conducted in order to investigate the effectiveness of the heat exchanger after several hours of running. The heat exchanger, specifically prototyped for this study, is made of 7 straight tubes 38 mm diameter and 1.5 m long where the producer gas passes in. Twisted tape inserts, 35 mm in width, and 200 mm of pitch (based on 180°), were inserted into the tubes to enhance the heat exchange. The fluid flowing in the shell is the same water running in the engine cooling system, therefore the engine electronic thermostat and radiator are used to maintain the cooling water temperature in the range between 85 °C and 90 °C.

Temperatures of the producer gas were logged at the heat exchanger inlet and outlet during tests. The experimental campaign is carried out through a series of runs at constant engine power output, and so, at constant producer gas mass flow rate. During the tests, an increase in the gas temperature difference between inlet and outlet was monitored. This difference led to an increased effectiveness of the heat exchanger during the first hours of running. During the heat exchanger inspections and maintenance after the tests, a reduction in the clearance between the twisted tapes and the tubes was recorded due to the deposition of soot and tars contained in the gas stream. According to the literature findings [6, 7], the fouling seems thus to generate a tight-fit configuration that tends to increase the heat transfer coefficient (HTC).

2. Materials and methods

This section describes the experimental setup used to evaluate the performance of the heat exchanger.

2.1. The gasification facility

The gasification power plant used as a test bench for the heat exchanger is the Power Pallet 30 by All Power Labs [5].

The Power Pallet unit can be divided into 3 main subsystems that are:

- the biomass feeding system and the gasification reactor, which converts the solid wood into syngas. The Power Pallet 30 can be fuelled with both wood pellet and wood chips [8,9] and, in this work, standard A2 pellets were used for the test to guarantee a proper repeatability of the experiments.
- the gas conditioning stage, which is composed by a gas/water heat exchanger (henceforth called HX) object of the study, and a filter unit that is used to reduce the particulate matter content and the tar amount in the syngas, avoiding its later condensation in the pipelines downstrams [10]. The original cooling system was replaced with the shell-and-tube HX [11,12] described in the following section.
- the power generation unit consists of an internal combustion engine connected to a 30 kVA generator capable of generating both electrical and thermal power, recovering the heat from the engine block and exhaust gases.

The Power Pallet 30 original system is shown in Figure 1.

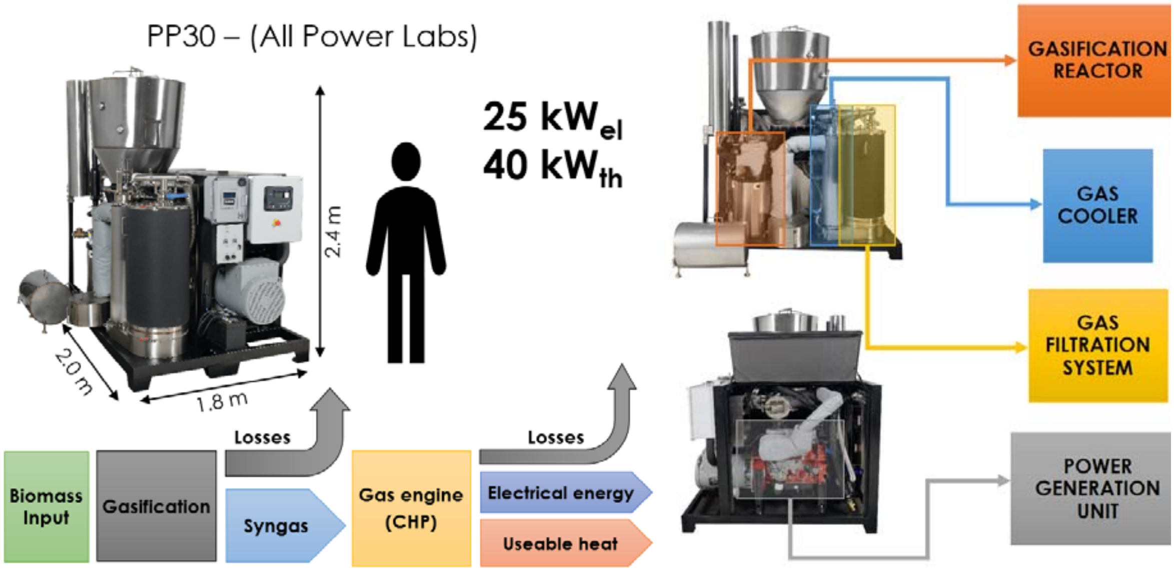

Figure 1. Block diagram of the PP30 and representation of the several subsystems.

2.2. *The gas cooling system of the Power Pallet 30*

2.2.1. *Syngas cooling strategy*

The gasification process of wood biomass takes place at temperatures that ranges from 700 to 1000 °C [1, 3] and the syngas outlet temperature depends on the reactor geometry and type. The Power Pallet 30 is powered by a single-throat downdraft reactor where the biomass and syngas run through the reactor in the same direction. In this type of reactor, the intake air, used for combustion, is generally preheated using the sensible heat of the syngas, which leaves the reactor at a temperature close to 600°C and drop at 350-400°C after the cyclonic separator used to collect the coarse fraction of the particulate matter [13].
The stages following gasification (i.e. syngas filtration and power generation) have necessarily lower working temperatures since, on the one hand, the filter often consists of polyester filter bags with a maximum operating temperature of 105 °C [14]; on the other hand, the internal combustion engine needs to operate with the lowest possible mixture temperature in order to increase its volumetric efficiency and to prevent detonation [15,16].
However, during the cooling down of the syngas, it is necessary to consider that the fractions of tars and water in the syngas in the form of vapour may condensate. For this reason, in order to avoid the accumulation of tarry water, it is necessary to keep the whole system above the syngas dew point. Previous studies estimated this value to range between 50 and 60 °C [17,9].
For this reason, in the Power Pallet 30 the syngas is cooled using the same coolant loop of the internal combustion engine, the fluid has a temperature between 80 and 90°C, and it prevents the system from going below the syngas dew point.

2.2.2. *The tubes-in-shell heat exchanger*

The original PP30 HX has been replaced with a custom HX in which, as previously described, the syngas flows inside the pipes, while the cooling water flows between the baffles inserted in the shell (Figure 2). This configuration allows testing of different solutions for the heat transfer enhancement and, in this case, twisted tape inserts were inserted in each of the 7 tubes of the HX.

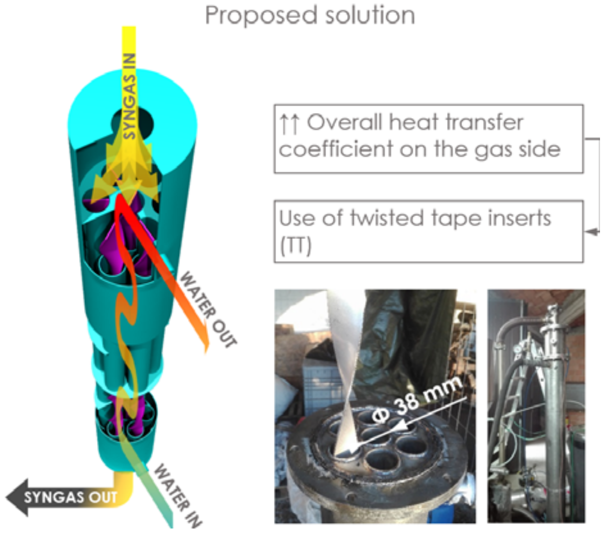

Figure 2. custom HX used for this test.

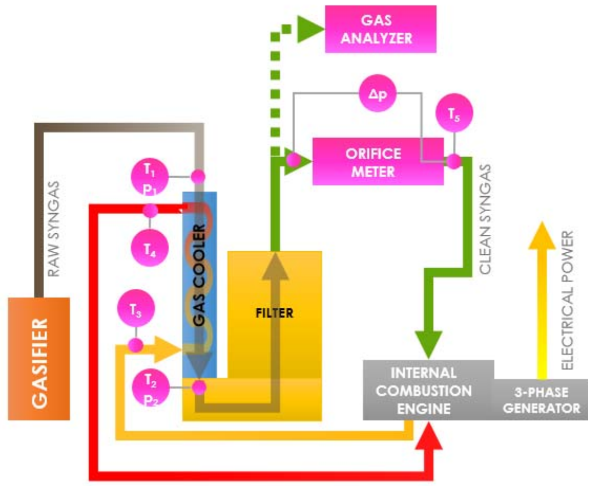

Figure 3. Block diagram of the test rig.

The custom HX is the same used in the previous work by Morselli et al., 2019 [11] and its dimensions are reported in the following scheme (Figure 4 and Figure 5).

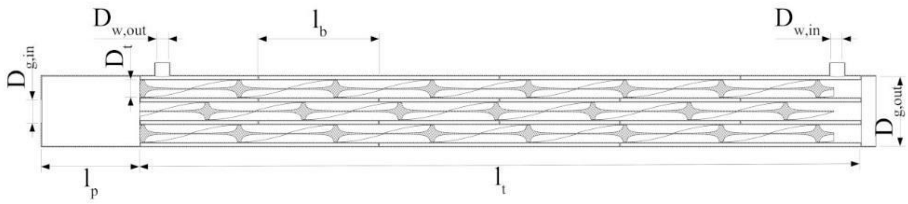

Figure 4. Longitudinal section of the HX.

l_b = 300 mm
$D_{g,in}$ = 60.3 mm
$D_{g,out}$ = 168.3 mm
l_t = 1500 mm
l_p = 250 mm
D_t = 38 mm
$D_{w,in} = D_{w,out}$ = 33.7 mm
w = 35 mm
p = 200 mm

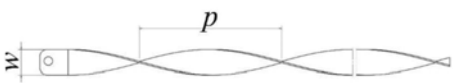

Figure 5. Dimensions of the twisted tape inserts used.

It is important to underline that a clearance of 1.5 mm has been maintained between the width of the twisted tape and the internal diameter of the pipe to guarantee a proper sliding of the twisted tapes for tube cleaning.

Due to tar and particulate matter deposition, this clearance is progressively reduced during the power plant uptime, the aim of this work is to evaluate the performance over time of the HX according to the test setup described in the next section.

2.3. Test rig description

To evaluate the performance of the HX, it is necessary to measure the thermal power exchanged between syngas and cooling water (Figure 3). For this purpose, K-type thermocouples were installed at the inlet (T_1) and at the outlet (T_2) of the syngas side of the HX. T-type thermocouples were used to measure the mean cooling water temperature (T_3 and T_4). In fact, in previous experiments [10] it was noted how difficult it is to properly measure the power absorbed by the cooling water, as the ΔT measured is in the order of 1 °C and comparable to the accuracy of the T-type thermocouples used

[18]. The data logging system used consists in a Picotech TC-08 [19] which has an integrated cold-junction compensation system that, via software, corrects the temperatures read. The measurement uncertainty for T-type thermocouples is ± 1°C while for K-type thermocouples it is ± 2°C.
The mass flow rate of syngas was measured through a calibrated orifice located downstream of the filtering section to reduce fouling and therefore reduce the reading error. The density of the gas was calculated by measuring the chemical composition of the syngas through a micro-gas-chromatograph [20]. To evaluate the performance of the HX over time, 3 tests were performed over three consecutive days. Each test lasted for 5 hours. The tests included the running of the internal combustion engine at a constant power of 11 kW for the entire duration of the test. Since the power required by the engine is maintained constant, assuming that the efficiency of the engine as well as the gasification conditions within the reactor are invariant during the tests, it is possible to consider the mass flow rate of syngas as a constant. For each test the flow rate of syngas was monitored continuously and gas samplings were performed in order to verify the stability of the gas composition. Whenever a variation of the composition was recorded, the density and the syngas' higher heating value were corrected in the calculation of the gas flow rate as well as in the air-fuel energy content drawn by the engine. Working at constant mass flow, it was possible to directly compare the ΔT generated by the HX in the three different tests and, in the next section, the results obtained in the various tests are reported.

3. Results

In Figure 6 the temperature trend during the three tests is reported, showing the inlet and outlet temperatures of the gas from the HX, the average coolant temperature and the temperature drop of the syngas (Gas ΔT).

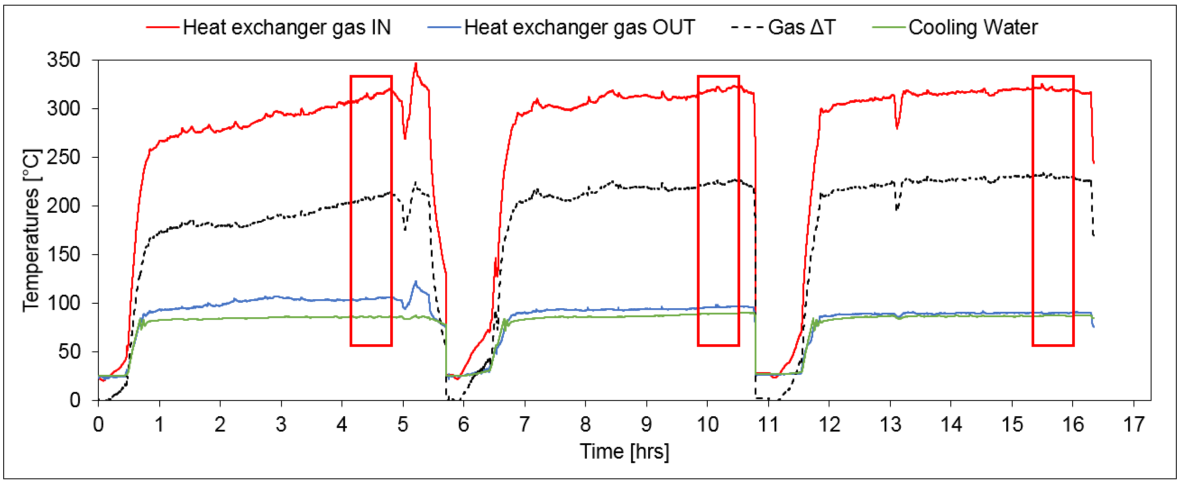

Figure 6. Trend of the temperatures over time for the 3 tests at constant syngas mass flow rate.

It can be noted how the inlet temperature to the HX tends to increase during the test. This phenomenon is, on the one hand, due to the stabilisation of the thermochemical reactions inside the gasification reactor, and on the other hand due to the accumulation of sensible heat in the metal structures of the different stages of the gasifier. Nevertheless, comparisons between the different tests were performed in the test portions under steady state conditions, highlighted by the red rectangles in Figure 6. The average values of these test portions are shown in Figure 7.

The average values of the syngas inlet temperatures vary from 316 °C for the first test to 320 °C for the and third tests; a variability that remains within the uncertainty range of the K-type thermocouples used (± 2°C [4]). The same result is obtained for the cooling water temperature which does not vary significantly in the inlet side (85-86°C). The only data that varies beyond the measurement uncertainty is the syngas outlet temperature from the exchanger and therefore the ΔT of the syngas associated with each test. The syngas outlet temperature from the HX were respectively for the three tests: 105.4 °C, 96.0 °C and 90.0 °C, leading to a ΔT equal to 210 °C in the first, 224 °C in the second and 230 °C in the third test respectively, confirming a significant increase in the effectiveness of the HX during the three tests. Figure 8 shows the syngas composition values during the 3 tests. At the same time, the HHV and syngas density values are reported. No variations in the syngas properties were found such as to justify a possible reduction in the mass flow rate of syngas processed by the HX.

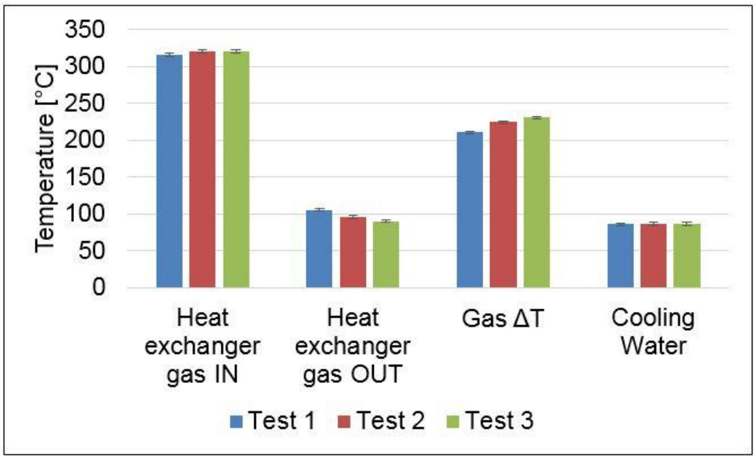

Figure 7. Average temperatures of the syngas and water side of the HX.

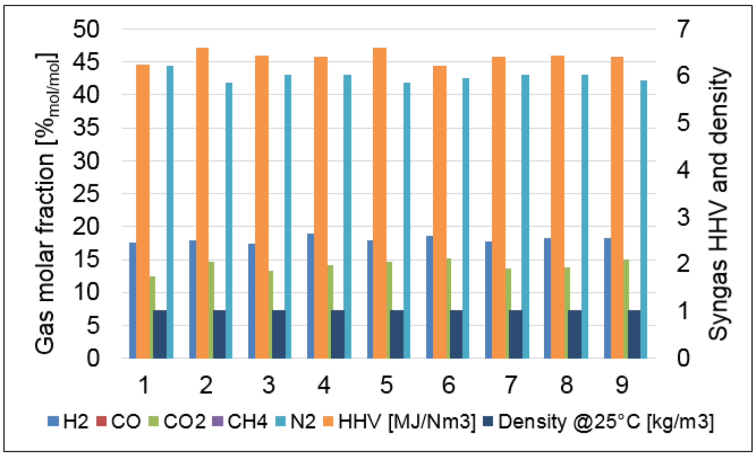

Figure 8. Syngas quality and properties.
(Test #1 samples from 1 to 3; Test #2 from 4 to 6; Test #3 from 7 to 9)

At the end of the third test, the HX was disassembled and inspected (Figure 9a,b), observing a considerable deposit of tar and particulate matter on the surfaces of the twisted tapes and pipes. The deposit had completely eliminated the clearance between the twisted tape and the pipe, reducing leakage and forcing the syngas into the swirl motion induced by the twisted tape.

According to the literature findings [6,7], the fouling seems to generate a tight-fit configuration that tends to increase the HTC, more than counterbalance its reduction due to soot layer formation as reported by SERI [21] (Figure 9b). Future work will be focused on the evaluation of the HX effectiveness (ε). This parameter is usually determined as the ratio between q and q_{max}.
The value q_{max} is the maximum heat that could be transferred between the fluids and it depends only on the fluid properties and the inlet temperatures. Therefore q_{max} can be considered as a constant in all the cases analysed. The value q is the measured heat exchange by the HX. This work proved that the temperature difference of the gas flowing through the HX progressively increases test after test, leading to a higher value for the heat transferred. Therefore it is possible to state that also the effectiveness ε increases during the tests.

Figure 9a. Soot deposition on the top of the HX: rack of twisted tapes after the tests.

Figure 9b. Soot and tars deposited over the twisted tape inserts.

4. Conclusions

In this work, the performance of a shell-and-tube type HX for cooling the syngas produced by a small commercial gasification plant was tested over time. The HX was instrumented and the inlet and outlet temperatures of the syngas were monitored, conducting various tests at constant syngas mass flow rates. The results showed that, under the same working conditions, the effectiveness of the HX increases during the first 15 hours of operation, as a consequence of the reduction of the outlet temperature of the syngas. The phenomenon was ascribed to the reduction in the clearance between the twisted tape inserts and the tubes of the HX, which reduces the leakages and increases the swirl motion of the gas thus reducing the thickness of the thermal boundary layer.

Further studies should be conducted to address the duration of this phenomenon over the lifetime of the HX, investigating the possibility to optimise the cleaning strategy of the HX before the thickening of the soot layer insulation completely cancels out the gained advantages.

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