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Cite as: AIP Conference Proceedings **2191**, 020006 (2019); https://doi.org/10.1063/1.5138739
Published Online: 17 December 2019

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Use of Light Scattering for Online Detection of Tar and Particulate Matter from Biomass Gasification

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Abstract. Gasification is one of the most promising technology for an efficient use of biomass fuels. A gate-keeper issue that is holding this technology from being widely used is gas conditioning. All gasifiers architecture suffer in some degree due to tar and particulate content in the gas stream. Depending on the final application, different level of pollutant may preclude a specific use. The cleaning level is more and more relevant moving from IC engines to gas turbine or fuel cells. For this reason this work want to explore an on-line method for tar and particulate detecting using a light scattering system. The proposed solution is based on a dual stage gas dilution combined with the use of a commercial air monitoring device.

INTRODUCTION

The effectiveness of gasification-based biomass systems relies on several factors like efficiency, stability of the process and gas quality [1]. Quality can be evaluated looking at the gas heating value, composition and presence of polluting species. Depending on the specific application different level of gas cleaning is required. Tars and particulate matter are the major pollutant in biomass gasifier. A common way to define tars consists in considering all the organic compounds with a molecular weight higher than benzene. An assessment of the total tar is the basis to understand the gasification system performance and to further proceed with the design and sizing of the gas conditioning stages. Literature suggests several tar testing methods that can be classified in two groups: online and offline [2] [3] [4] [5] [6] [7]. Online methods produce real-time results, while offline methods requires a sampling followed by hours to obtain results. The overall objective of this work is to investigate possible solutions for tars and particulate sampling through light-scattering measurements. The major subgoals of the proposed apparatus were:

- To measure the amounts of tars produced during gasification of biomass.
- To measure the amount of fine particulate matter associated with the gasification gas product.
- To obtain quality information about the particle size distribution of particulates or tars droplets.
- To obtain quality information on the fraction of char and sand particulate in the gas stream.

The facility chosen for the preliminary tests is the bubbling bed gasifier sited at the UBC Pulp & Paper Center, University of British Columbia. This gasification unit had no previous data related to the particulate content in the producer gas.

MATERIAL AND METHODS

Gasification facility

The main specs of the bubbling bed facility used in this work are reported in Table 1 as well as in [8].

74th ATI National Congress
AIP Conf. Proc. 2191, 020006-1–020006-8; https://doi.org/10.1063/1.5138739
Published by AIP Publishing. 978-0-7354-1938-4/$30.00

TABLE 1. Bubbling bed gasifier at the UBC Pulp & Paper Centre [8]

Hopper	0.22 m^3
Steam super heater	12 x 240 V x 1800 W, 21.6 kW, 3.7 m long
Gasifier	Cylindrical: ID = 100 mm, L = 1.2 m
Gasifier heaters	Two semi-cylindrical: 125 mm ID, 225 mm OD, 0.92 m long One full-cylindrical: 125 mm ID, 0.15 m long
Bed material	Silica sand
Bed height	0.25 m
Cooler	Double pipe type: 12 m long, heat exchange area of 2.0 m^2

In this facility the gas exiting from the reactor is forced to pass through an internal cyclone for bed recirculation, and then through two cyclones in series in order to reduce the dust content of the gas stream. Due to the age of the facility and numerous modifications over the years, it was not possible to find accurate information about the geometry of the cyclones, so it was not possible to deduce their cutoff dimensions. For this reason, during two preliminary runs, it was decided to try and calculate back to the solid content in the stream, analyzing the weight difference of the glass wool used for solid separation before tars condensation branch. However, the small flow rate and the presence of cold spots in the sampling line (where local tars condensation occurs) nullified the effectiveness of this approach. The results of this test are reported in Table 2.

TABLE 2. Experimental masses during gasification run

Biosolids+biomass Run	Glass wool mass difference for 250 liters of gas processed
Initial mass	3.723 g
Final mass	3.88 g
Difference	0.157 g

The glass wool was also analyzed by electron scanning microscopy (SEM). The SEM analysis of the glass wool revealed why the mass difference was so small. The first image (Fig. 1 left) reproduced here shows that the glass wool did not retain large particles. In fact, it was necessary to observe the surface of the fibers with high magnification to show the deposits (Fig. 1 right). This suggests that most of the particles were separated from the gas stream when they passed through the cyclones.

The contents of the material separated by the two cyclones were analyzed. In Figure 2, it is possible to identify the three major components of the solid matter in the gas stream: a. char, b. ash, c. soot.

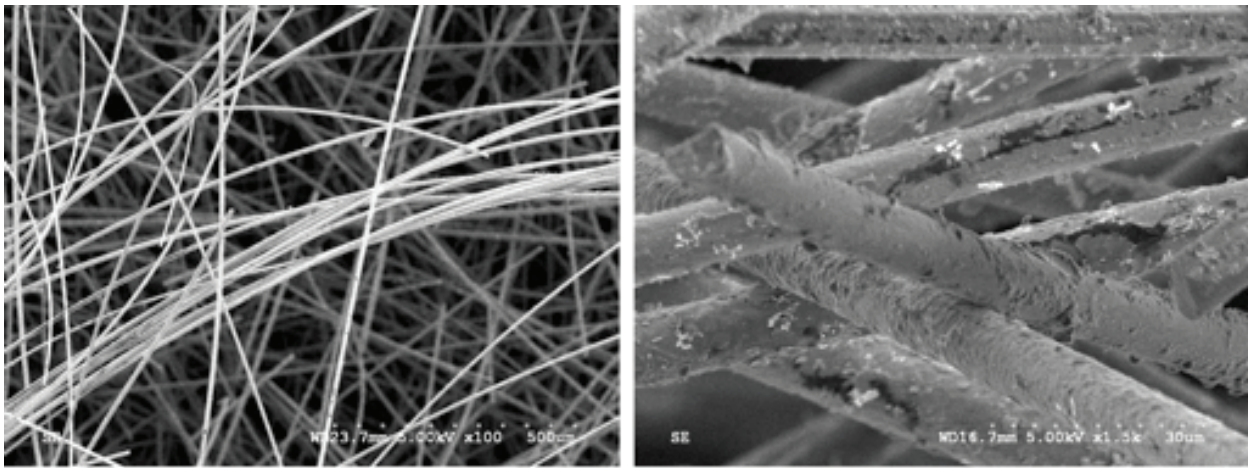

FIGURE 1. SEM picture of glasswool used for solid separation in tar sampling line of the gasifier (left); High magnification SEM picture of glasswool used for solid separation in tar sampling line of the gasifier (right)

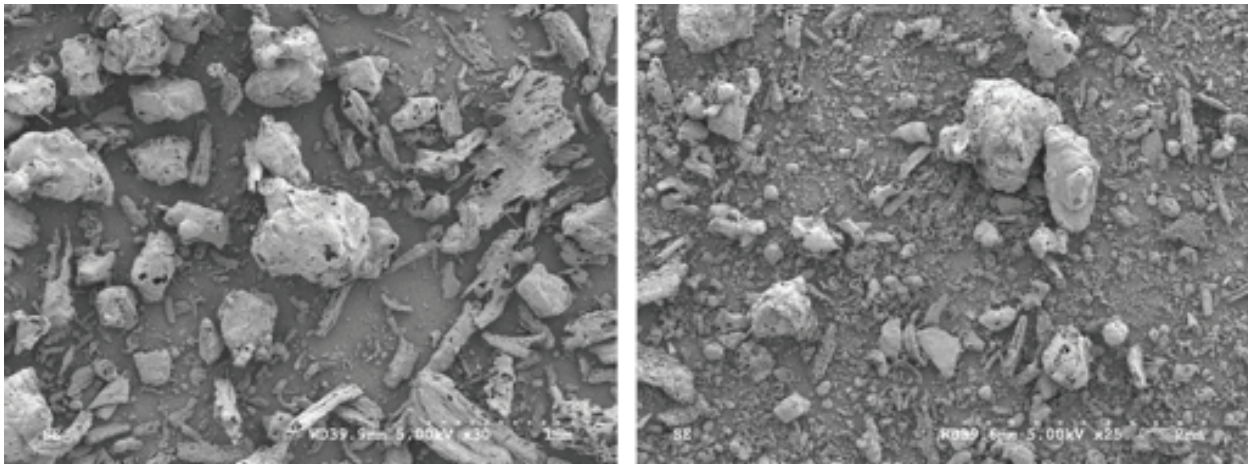

FIGURE 2. 1st Cyclone content after woody biomass gasification run (left) and 2nd Cyclone content after woody biomass gasification run (right)

Apparatus design

The apparatus for gas sampling was designed starting from two project constrains:

- The sampled gas in the end will be analyzed in a DRX DustTrack system. It consists in a battery-operated, data-logging, light-scattering laser photometers that provide real-time mass concentration readings for aerosol contaminants such as dust, smoke, fumes and mist. The sampling volumetric flow rate is imposed by the internal pump [9].
- To perform the dilution the design decision ended on the use of perforated tubes (known as porous steel isostatic tubes).

The use of an ambient air quality monitoring device imposes a limit to the maximum amount of pollutants that can be detected. For this reason the gas flow rate requires to be strongly diluted before entering in the light scattering device. The dilution rate of the gas stream was chosen to be maintained over 1:100. The designed apparatus needed to satisfy some design and applicability limits. First, the use of perforated tube is strongly recommended. This kind of tube has the major advantage that the gas used for the dilution is distributively injected through the wall, protecting the tube from tars deposition and, at the same time, this increases the chance of condensing the tars in the stream. The perforated tubes used for this work have an OD of 12.7 mm (1/2") and a length of 151 mm (6"). The inner diameter is 9.6 mm (3/8"). The second group of conditions that needed to be considered during the design were the flow rate and the maximum particulate mass flow rate imposed by the sampling instrument. For this work, a DRX dust-track was used. This instrument always processes 3 l/min of gas and is able to read aerosol concentration range from 0.001 to 150 mg/m^3. This flow rate and the tube diameter impose the maximum gas velocity in the perforated tube. The apparatus was installed to capture particles entrained from the bubbling bed gasifier in the UBC Pulp & Paper Centre during a run in which woody biomass was being gasified during this work. In order to ensure no interaction between the tar sampling test and the gasifier run, the apparatus was placed in one of the catch basins for condensation downstream of the last cyclone of the plant. The perforated tubes in this work have no specification about the maximum dilution obtainable or the optimal pressure difference across the tube surface. Therefore, the total 1:100 dilution was obtained in a two stage process, using two different perforated pipes as shown in Figure 3.

Design 1.0

The first design attempted resulted in a conceptual design of the apparatus, as shown in Fig. 4.

The perforated tubes are held in the two 1" pipes that compose the two diluting sectors of the apparatus. In both cases the external pipe and the inner tube are held in place by machined metal plates. The grooves in the plates were equipped with silicon or graphite gaskets. Three threaded rods held the apparatus tight, ensuring sealing and mechanical stability of the system.

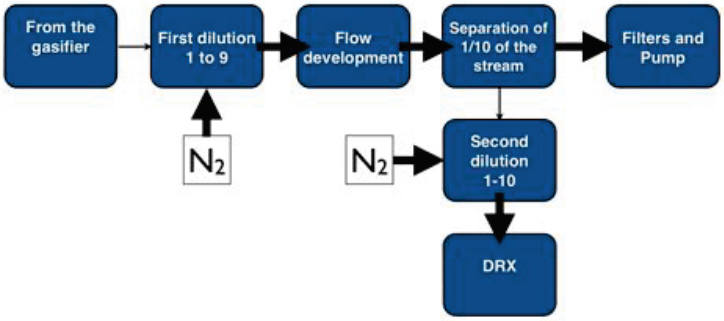

FIGURE 3. Schematic of 1:100 dilution method

FIGURE 4. Conceptual design of the apparatus (left); sectioned view with design flow rates(right)

The last unknown required for a complete determination of the system was the diameter of the small tube used for 1/10 separation of the stream. Figure 4 shows a needle cut tube, cut from the axis of the 1" pipe to the wall. Once the tube diameter is fixed, it is possible to correlate the flow drawn from the pump to the area of the cut tube projection on a plane orthogonal to the pipe axis for isokinetic sampling. Two solutions were considered as shown in Fig. 5 (right). The second one featured a bent tube with no cut. In this solution the tube faces the gas stream with a smaller area, imposing a higher velocity in the 1" pipe and a higher flow draw from the pump. The higher velocity in the 1" pipe has the main advantage of a shorter permanence time that reduces tars deposition in this part of the apparatus. For this configuration the flows are reported in Figure 4.

The distance between the end of the first perforated tube and the small tube for stream separation needs to be long enough to ensure flow development. With these proposed flows, the resulting length was about 18 cm or 7 ".

TABLE 3. Diameters, velocities and Reynolds numbers

	Perforated Tube	External Pipe
Inner diameter [m]	0.00953	0.0253
Inlet velocity [m/s]	0.01446	0.226
Outlet velocity [m/s]	1.59	0.205
Re_{in}	2.98	123
Re_{out}	328	112
0.06ReD [m]	/	0.187

Note that the small velocities increased the influence of the weight of the particles on the fluid dynamics force equilibrium. For this reason the apparatus was designed to hang vertically.

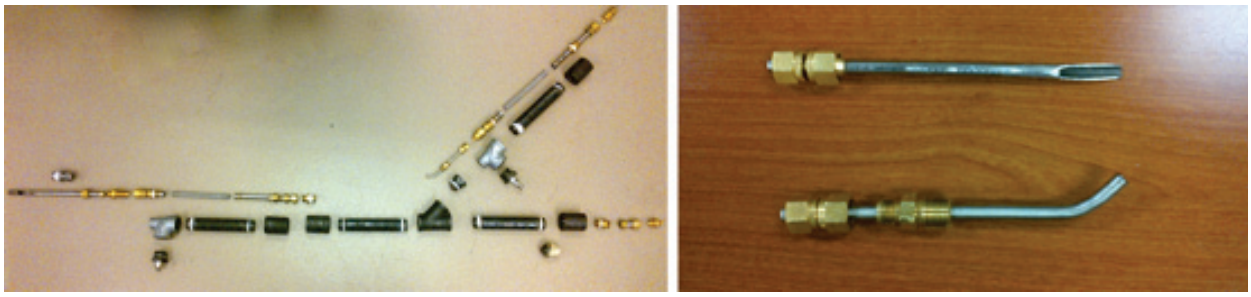

FIGURE 5. Bill of materials (left); Two solutions designed for separation of 1/10 of the gas stream (right)

Limits and problems

This design is just a concept solution of a possible large scale product gas diluter. It includes all the parts necessary to accomplish this goal. The major problems related to this configuration are its cost and the time necessary to fabricate all the special parts. After the design, the short time left to finish the preliminary tests required the adoption of commercial components. Hence, it was not possible to reach the optimum solution, but these components ensures low costs, wide availability and high reliability (with all components guaranteed for temperature and pressure stresses).

Design 2.0

Commercial components, bill of materials (See also Figure 5) External pipes:

- 4 Standard wall Blk Steel Threaded Pipe Nipples 1” pipe size x 7” length
- 2 Low Pressure Galv. Iron Threaded Pipe Fittings 1” X 1” X 1/2” Pipe Size, Right Angle Reducing Tee
- 4 High Pressure Forged Blk STL Threaded Pipe Fittings 1” X 1/2” Pipe Size, Female
- 1 Low pressure Blk Malleable Iron Threaded Fitting 1” pipe size, Wye (1”x1”x1”)

Inner Tubes:

- 2 x 6” perforated tubes
- 1 x Type 304 Smooth bore seamless SS Tubing 1/4” OD, .0.21” ID, 0.02” thick wall
- 3 x 1/2” OD steel tubes used for connections

Fittings:

- 6 x Standard Brass Compression Tube Fitting Adapters for 1/2” Tube OD X 1/2” NPTF Male Pipe
- 3 x Standard Brass Compression Tube Fitting Adapters for 1/4” Tube OD X 1/4” NPTF Male Pipe
- 1x Brass YorLok Tube Fitting Reducing Couplings for 1/2” X 1/4” Tube OD

Modifications

1/2” ID collars were used to hold the perforated tubes in place. This method was used in order to ensure that the apparatus could be completely disassembled. The perforated tubes were not welded as the sintered material cannot maintain its mechanical and physical properties (including porosity) when welded. As reported above, the apparatus was inserted into the hot gas line after the main gasification tests on the facility. This was necessary to ensure no influence of the dilution test on the gasification conditions during the main biomass gasification test. Moreover, in this way, it was possible to use the same GC for syngas analysis during the first test and dilution rate back-calculation during the apparatus testing. For this purpose the apparatus was equipped with an intake tube long enough to slide into the gas line and reach the middle of the gas stream. The gas line in the bubbling bed facility was equipped with a stainless steel compression fitting with a ptfe ferrule (to facilitate tube sliding). The two nitrogen lines and the tube from the apparatus to the pump were equipped with rotameters and valves for flow monitoring and adjustment.

RESULTS AND DISCUSSION

The apparatus was tested during a full biomass gasification run in the bubbling bed facility of the UBC Pulp and Paper Center. The gasifier hopper was filled with extra biomass in order to ensure enough fuel to complete the gasification test and the additional time of about an hour when the apparatus was connected to the facility to test the gas with the DRX.

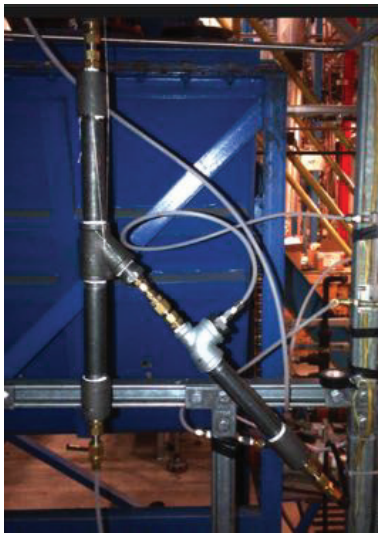

FIGURE 6. Apparatus inserted in gas line between the cyclones and heat exchanger

DRX signal output

Once the DRX dust-trak had been plugged in the diluted line, it started to record concentration data mg of particulate in every Nm^3 of gas. Fig. 7 is the full output for the entire test. Looking at the trend, it is possible to divide it into three different parts reported in 7.

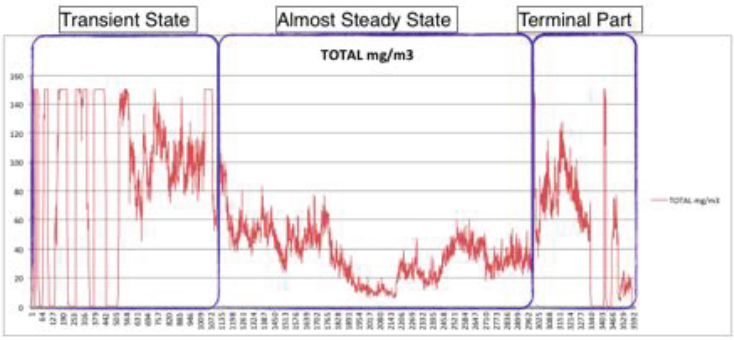

FIGURE 7. Test subdivision in three parts: Transient state, almost steady state, terminal part

It is important to highlight that this test is the very first attempt to use this apparatus. For this reason during the first part of the test (here called transient state) it was necessary to set the valves properly to stabilize the flows trying to keep the flow values close to the design ones. After about 15-20 minutes of big fluctuations, the flows were stabilized and minor adjustments were necessary from that moment. For this reason, this part of the test was called 'almost' steady state. The steady state condition lasted for about 50 minutes. After 54 minutes something changed in the operating conditions because, for no apparent reason, the flows started to be really unstable, and after a few

attempts to stabilize the flows (terminal part) the test had to be terminated. Probably these instabilities in the last part of the test were caused by the fouling of the inlet tube of the apparatus, Fig.8. In fact this component was placed in the hot, not diluted syngas steam creating an obstacle for the flow, expediting the dust and tar deposited on its surfaces.

Design flows vs real flows

In order to stabilize the flows, the experimental setup in the steady state part differs from the design one. The nitrogen flow in the primary dilution (through the first perforate tube) had been decreased from 6.8 to 6.7 l/min, on the other hand, the pump flow had been risen from 6.5 to 7.55 l/min, reducing the primary dilution rate and increasing the speed of flow in the tube inserted in the gasifier. This solution drastically decreased the dilution rate from 1:100 to 1:58. It is important to outline again that the first part of the test was used for flow stabilization changing the dilution rate. There was an attempt to reach the 1:100 dilution but, every time the dilution was increased, the amplitude of the fluctuations of concentration brought the value under the sensitivity of the DRX. On the other hand, small decreases from 1:58 dilutions were experienced to bring the concentration values over the maximum acceptable value for the DRX. These instabilities made the tuning operations particularly difficult. Figure 9 is the cropping of the almost steady state part of the diagram shown in figure 7. It is possible to distinguish two different fluctuations, high frequency fluctuations with apparent frequency of 1 Hz (it is also the time step of the DRX) and slow fluctuations that seem to have no particular repeatability.

FIGURE 8. fouling of the inlet tube

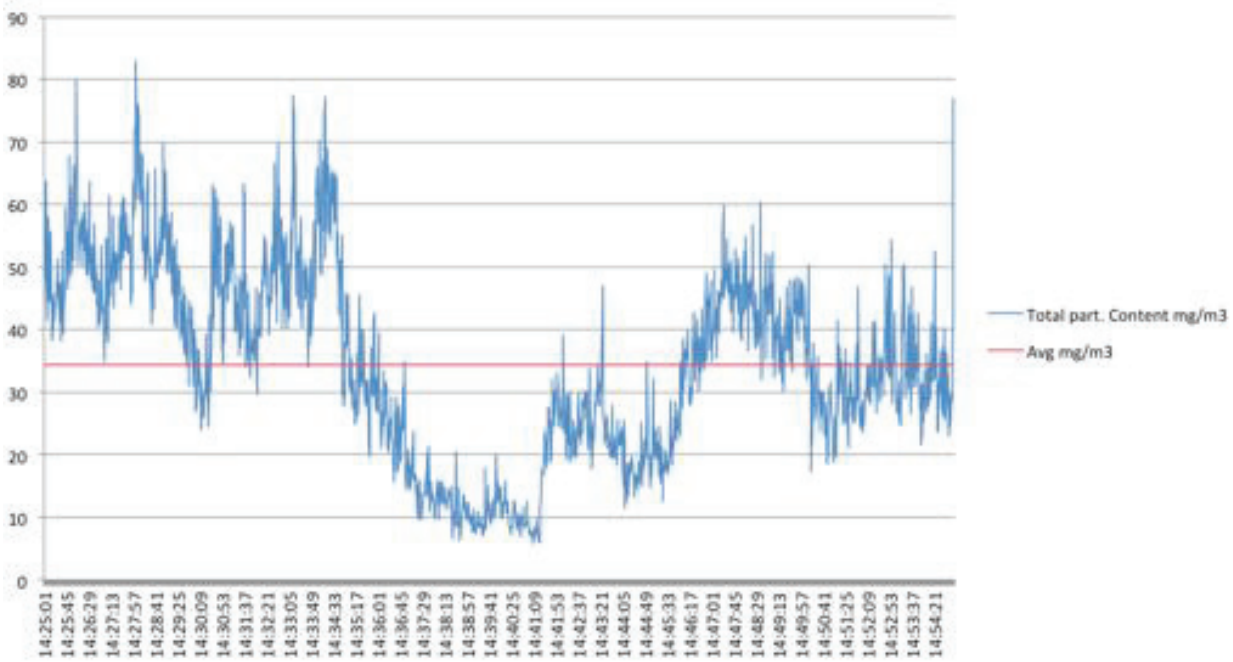

FIGURE 9. Particulate concentration trend in the almost steady state part of the test

In this part of the test the average particle concentration in the diluted gas stream is 34.4 mg/m^3.

Dilution rate check with micro GC and comparison with other online methods

The dilution value was calculated starting from the flows shown by the rotameters. This value was checked with a micro GC. During the test different gas samples were taken with 'Tedlar' bags. Then the bags content was analyzed in a microGC looking at the nitrogen concentration. The value of nitrogen concentration obtained from the diluted gas analysis needed to be compared with the starting nitrogen concentration in the not diluted syngas of the gasifier.The starting gas had a nitrogen content of 51.59%. The bags test gave an N_2 content of 99.371, 99.032 and 99.435%. These three values refer to the three GC analyses made during the steady state condition. The dilution rate based on GC analysis calculated starting from these valued ranges from 1:48 to 1:73 with an average value of: 1:67.Because of the high nitrogen content, the GC error is close to the value of non nitrogen gases. For this reason, both the flow rate based and the GC based dilution rates are considered correct and two different concentration of particulate in the undiluted gas are calculated. The particulate concentrations in the syngas calculated starting from rotameters based dilution rate and GC-based dilution rate are: 1993.46 and 2308.36 mg/m^3. The system proposed has two major advantages: it is easy to implement and it gives real time results with almost no time delay. Other systems such as [4] and [5] are labelled as 'real time' while, in reality they, they require a certain amount of time. i.e. [5] necessitates the sampling cuvette to fill with isopropyl alcohol before each tar content evaluation. On the other hand, the system proposed here does not recognize the differences between particulate matter and condensable droplets. In addition, a second point of concern is the durability of the apparatus. Its resistance to fouling can be tested only during long runs.

CONCLUSIONS

This work is here discussed looking at its main goal: analyzing the tar and particulate contents in a hot gas stream through dilution with perforated tubes and analysis in a DRX dust-tracker. The results have shown the capability of the proposed method to reach its goal, but the system has different points of optimization. A fundamental step that needs to be taken consists in introducing the possibility of solid separation (e.g. with glass-wool or a hot ceramic filter) before the dilutor. If the solids (char, ashes and soot) are separated before the dilutor and the DRX, it is possible to study the capability of the system to process tars. Then the separator can be removed and the test can be run again, processing tars and particulates together. In this way the differences between the results from the filtered and unfiltered streams allow to completely understand the influence of tar droplets and solid particulates on the DRX output, distinguishing the causes of the total output value obtained during this work. Moreover sampling from different points in the facility (i.e. before and after the gas heat exchanger) can give different results:

- A sort of effectiveness of the facility filtering and condensation system can be evaluated.
- It is possible to investigate the origin of the fluctuations recorded in the DRX output. Maybe a different sampling point brings a less fluctuating output.

From a technical point of view, it should be possible to improve the system reducing the part of it where tar deposits can still occur (i.e. using shorter tubes and less fittings).

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