TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 137, 2017, 59–70

Aleksander Sobolewski, Mateusz Szul*, Tomasz Iluk,
Waldemar Ostrowski and Tomasz Billig

Cleaning of process gas from gasification of solid recovered fluid — results of experimental research

Institute for Chemical Processing of Coal, 41-803 Zabrze, Zamkowa 1, Poland

Abstract

The paper takes up the topic of energetic utilization of alternative fuels produced from wastes, particularly in case of solid recovered fuel gasification for cogeneration of heat and power in piston engine. Process gas cleaning for its energetic and chemical utilization has been discussed. Presented scope of research concerns technological designs for dry and wet gas cleaning methods developed by Institute for Chemical Processing of Coal. Furthermore identified main operational problems of both gas cleaning units have been presented. Description of the two types of gas cleaning units has been provided together with obtained results from laboratory analysis of moisture, tar and particle content measured in process gas generated from solid recovered fluid.

Keywords: Gasification; SRF; Process gas cleaning; High temperature filtration; Oil scrubber

1 Introduction

More than three decades of research on kinetic and thermodynamic aspects of thermochemical conversion of solid fuels, have brought us to the point where high technological maturity of developed designs of gasification reactors and their respective fuel feeding systems operate on technology readiness level (TRL) of 9 and higher [1]. While, the second most important block of gasification installations, i.e., the highly efficient process gas cleaning technologies present relatively low

*Corresponding Author. Email adress: mszul@ichpw.pl

level of development and availability. Furthermore proposed large scale, highly efficient gas cleaning solutions often present an unacceptably high investment and operating expenditures, which excludes possibility of their implementation in small and medium scale energy systems. Available on the market technologies for gasification and pyrolysis (for all types and configurations of reactors, process condition and gasification agents) stand today as first point on the way towards development and quick implementation of technologies enabling utilization of biomass or waste fuels for production of energy and chemicals (including liquid and gaseous fuels) [2–4]. Second element of the puzzle is hidden in process gas conditioning units, developed specifically for a given process gas/syngas utilization method. Important issue that also needs to be emphasized here, is division between gas cleaning methods (and their severity) for utilization of syngas as a feedstock for chemical synthesis application (methanation, methanol-synthesis, Fischer-Tropsch process, etc.) or for energetic purposes (combustion in a boiler, piston engine, turbine as well as in fuel cells) [5,6]. Moreover, even though large similarities exit between products from gasification and pyrolysis process, the demands set by those two processes before their respective gas cleaning units differ greatly. Common factor for all gas cleaning unit is the necessity for removal of compounds containing sulfur, nitrogen, metals (also heavy metals), tars and particles. The differentiating factor between demanded severity of gas cleaning is dictated by chosen method of final gas application. Process gas cleanliness guidelines and requirements (set separately for each kind of end use technologies) have a deciding importance in the matter of selection and application of appropriate methods and apparatuses for process gas cleaning [6–8]. In literature often a division of gas cleaning methods into two main directions is proposed, i.e., for dry and wet gas cleaning methods. The former ones, are based on utilization of sorption based methods (chemical and physical), often conducted at high temperature, for removal of metals and compounds of sulfur, chlorine or nitrogen [9]. Consideration of the added value of process gas cleaning at elevated temperature shows that there exist relevant advantages that advocate treatment of process gas at high temperatures. Main may be found in avoidance of problems related to tar condensation on apparatus and piping surfaces, usage of advantageous reaction rate and equilibrium conditions of sorbent-contaminant interactions as well as increase of the overall efficiency of installation due to lack of unnecessary gas cooling. For example, the only necessary gas treatment that needs to be performed before its direct combustion in a combustion chamber is removal of particles. In case of utilization of additional hot gas treatment methods (i.a. dry scrubbing) it is possible to significantly reduce emission of hazardous substances to environment or enable utilization of process gas as a fuel for gas engines or gas turbines. Dry and wet methods depending on applied thermochemical conversion may be supported by catalytic reactors for reduction or even elimination of the problem of tar generation, which belong to the most problematic aspects of biomass and waste gasification. Additionally, catalytic treatment of flue gasses may prove useful in reduction of concentration of environmentally hazardous compounds. The principle of wet methods relies on process gas cooling and utilization of absorbers (scrubbers) designed for removal of different kinds of contaminants contained in process gas. A factor that decides if a given method is classified as a dry or wet one, is the issue of generated additional (aside from the streams of process water and organics coming directly from thermochemical conversion of fuel) stream of waste waters, which may arise mainly from used absorbents – organic oils and technological water (grey and black water).

As a part of research on development of a technology for cogeneration of heat and power in piston engine from gasification of solid recovered fuel (SRF), Institute for Chemical Processing of Coal has developed and validated a concept for dry and wet process gas cleaning system.

2 Description of the installation

Installations for process gas cleaning, presented in this article, belong to research infrastructure of Institute for Chemical Processing of Coal (IChPW) that allow conducting full cycle of process development and scientific research on cleaning of process gasses from thermochemical conversion of solid fuels (i.a. biomass and wastes). One of the mentioned pilot research installations is an experimental installation for gasification of solid fuels (biomass and wastes) in fixed bed GazEla gas generator [10]. This reactor is an innovative construction of fixed bed reactor of 60 kW_t power input, dedicated for production of process gas for the sake of cogeneration of heat and power in piston engine. Construction of the reactor as well as its operational process parameters have been broadly described in previously published domestic and foreign publications [11–13].

Combined heat and power production in piston engine is realized by generation of process gas in a gasification reactor and subsequent process gas cleaning. The process gas cleaning research has been conducted in both of the developed dry and wet gas cleaning installations. The results from early phases of research conducted on dry cleaning of process gas from gasification of SRF has been presented in [14]. During realization of the project the installation has been retrofitted in order to increase its overall efficiency of contaminants removal as well as to increase the reliability.

Dry process gas cleaning system, presented in Fig. 1, comprises of: inertial deduster, high temperature filter, two stage gas cooler, fixed bed coke adsorbed and fabric filter.

Process gas generated in the reactor, at temperature of 500–700 °C and pressure of about 10 kPa, when directed to the dry gas cleaning system is firstly put to inertial deduster and a high temperature ceramic filter for complete removal of particulates entrained in its stream. Developed inertial deduster allows redirecting large particulates of entrained char back into the reactor for increased overall efficiency of the gasification process. Due to utilization of particle inertion phenomena, the apparatus is essential to obtain high degree of fuel conversion in GazEla fixed bed reactor. Next, process gas is directed towards high temperature filter in which concentration of solid particles is reduced to max. 15 mg/m$_n^3$. The filter is designed to have separate dirty and clean zones. These two zones are separated by a fixed plate in which filtration elements are set.

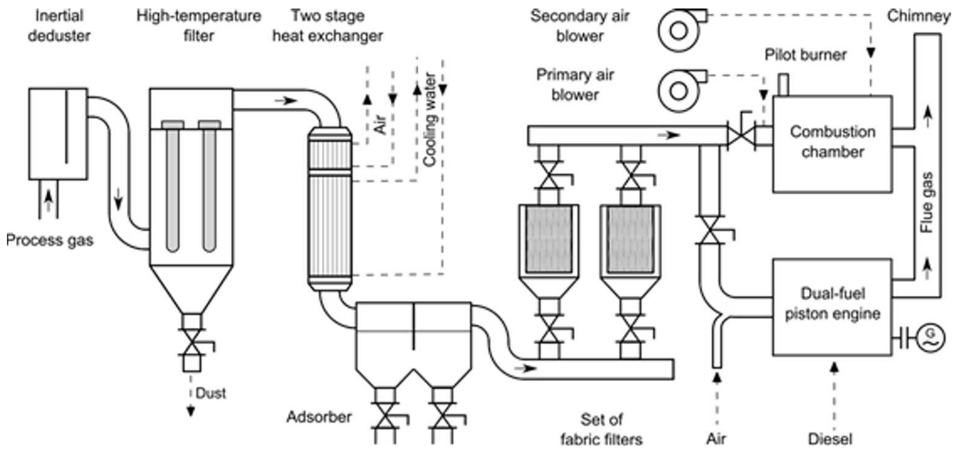

Figure 1: Schematic diagram of the installation for dry process gas cleaning.

During realization of the research, high parameters of process gas cleaning efficiencies and stable characteristic of process gas dedusting with use of both ceramic and metallic filter elements have been established. Due to lower price, satisfactory separation efficiency as well as high resistance to process atmosphere, the ceramic filter materials from sintered filaments based on aluminium and silicon have been selected for the main subject of further development of the technology. Operational parameters and physicochemical properties of applied high temperature filter elements have been presented in Tab. 1.

Table 1: Operational parameters of investigated ceramic candle filter elements.

Structure	Homogenous
Density, kg/m^3	∼350
Max. operational temperature, °C	900
Filtration area, m^2/el	0.18
Max. back-pulse pressure, MPa_g	1

Principle of high temperature filter operation relies on membrane separation of solid particles (dispersed phase) from the stream of flowing medium (continuous phase). Structure of filter elements consists of support backbone structure, on which the filter cake is produced. Generated filtration cake serves as a main filtration medium and in fact parameters of the cake determine boundary pressure loss on the filter, max. filtration velocity, separation efficiency as well as filtration stability. All the above mentioned parameters create a group of process variables, which determine operation of the high temperature filter. To keep pressure losses on the filter within set limits, (max. 5 kPa for an atmospheric installation), and thus stable separation process, common filter surface regeneration techniques have been adapted to high temperature filtration processes. For high temperature applications generally back-pulsing methods have found widest application. Such regeneration mechanisms rely on generation of a short pressure weave on clean side of filter element, which when passing through filter media up to dirty side of element, causes detachment and removal of agglomerated filter cake. For gasification and pyrolysis processes, nitrogen or recycled process gas under 3–10 MPa_g pressure are the common choices of back-pulse gases.

Subject filter has been developed for application in installations for thermochemical processing of biomass and wastes, which explains why during its development, impact put on high efficiency and small investment and operational costs has been high.

Dedusted gas in temperature above condensation point of the heaviest organic compounds (i.e., 350–400 °C depending on composition of tars contained in process gas), after leaving the high temperature filter is directed towards cooling and condensation in heat exchanger. Two stage shell and tube heat exchanger allows process gas cooling down to temperature of 30–40 °C, which is one of piston engine manufacturer' prerequisites. First stage of the heat exchanger is used for heating up the gasification agent, while second stage (cooled with water) is used for recovery of useful heat from gas. During process gas cooling, inside tube bundle a phase change of organic compounds and water takes place. Obtained stream of condensate, called a water-tar condensate, besides ash from gas generator and high temperature filter, constitutes as a main stream of process waste. At exit from the heat exchanger, stream of process gas transports generated water-tar aerosols. These aerosols are then separated physically on coke adsorber bed, which acts not only as a demister but mainly serves the purpose of adsorbent for removal of sulfur and chlorine compounds. Last element of the dry gas cleaning system is a set of fabric filters serving as a protection for engine in case of failure of any prior element of the gas cleaning unit.

Obtained operational experience from conducted research of dry process gas cleaning allowed determination of process parameters for development of an installation for research on wet process gas cleaning methods. Figure 2 shows schematic diagram of the developed wet gas cleaning installation. First two elements of dry and wet gas cleaning units, i.e., inertial deduster and high temperature filter, as well as the fabric filter are common elements for both units. In this way it can be considered that oil scrubber with its gas cooler in wet method replaces heat exchanger and coke adsorber in the dry gas cleaning system.

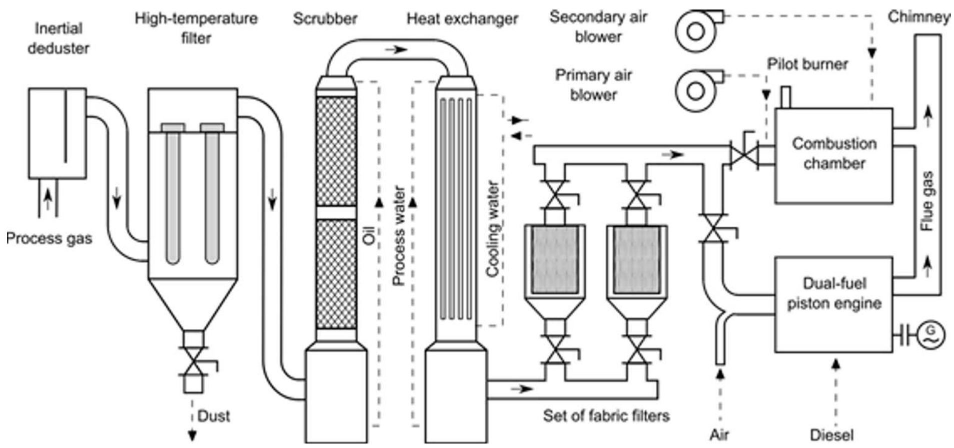

Figure 2: Schematic diagram of the installation for wet process gas cleaning.

In wet gas cleaning system, hot and dedusted process gas with temperature of ca. 400 °C comes into oil scrubber. As an absorption medium, the scrubber may be fed with a range of high boiling heating oils, in which physical dissolution and separation of tar compounds is attainable. Most often used absorbent for the process of gas cleaning are diesel oil and biodiesel. Construction of the scrubber consists of bottom oil tank, two separated randomly structured beds of packing (Raschig rings) and a demister. Temperature of process gas at the exit from absorption column ranges from 30–150 °C. In order to extract (condense) left in process gas fractions of light organic compounds and water vapour a dedicated process gas heat exchanger, of shell and tube type, with internal circulation of water has been designed. Developed solution of keeping a thin film of technological water on surface of the heat exchanger allows keeping high efficiency of heat exchange without the risk of its clogging with tarry substances. In the wet method, the dedusted, cleaned and cooled process gas is also fed to the additional fabric filters and later on to piston engine.

3 Results of experimental research

Experimental research on development of dry process gas cleaning have been mainly concentrated on development of the concept and perfecting the applied technological and structural solutions of high temperature filter. Experimental tests in first stage of research included actions aimed at increasing the efficiency of filter regeneration system through variation of gas nozzle geometry. Available commercial back-pulse systems operate on the principle of nozzles directing stream of compressed nitrogen through a Venturi nozzle into the clean side of filter elements. Schematic representation of such system operation has been presented in Fig. 3. The goal of utilizing Venturi nozzles in such back-pulsing methods is creation of a low pressure zone on the clean gas part of the filter, which induces suction of an additional volume of process gas into the filter element during back-pulse. During experiments performed in IChPW, low efficiency of commercial back-pulsing systems has been noticed (lack of possibility for keeping stable filtration due to low regeneration efficiency) and thus due to the above mentioned, a research on development of a new concept for high temperature filter regeneration method has been conducted.

As a subject of optimization tasks dealing with development of a new regeneration system, such elements as: nitrogen tank, gas collector, piping and nozzle design as well as geometrical parameters describing relation between construction and location of nozzles and exit from the filter elements have been conducted. Designed arrangements provide multiple times better regeneration efficiency in comparison to commercial systems, and thus it allowed conducting long-term tests of high temperature filter operation (24 h tests, filtration of process gas from biomass gasification).

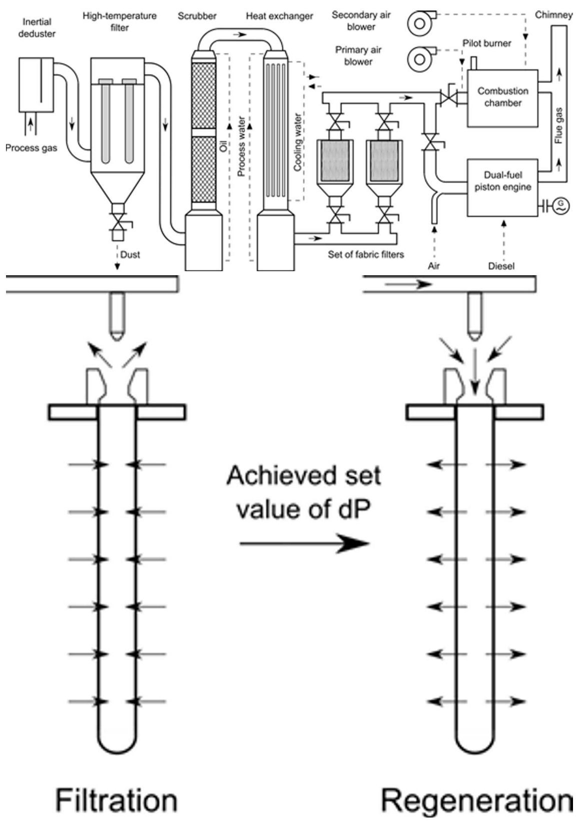

Figure 3: Schematic representation of filter element under operation and regeneration.

During next stage of research, a problem with lack of necessary reliability of filter element mounting and sealing has been identified. Original solution consisted of a plate clamp that counterbalanced the differential pressure across header plate of the filter. Drawback of this solution has been registered in brief loss of seal of the connection due to mechanical vibration of the installation as well as due to thermal stresses induced into filter's body during regeneration cycles. The problem has been solved through development of a concept of threaded connection, capable of stable operation in aggressive atmosphere of process gas at temperature higher than 500 °C. Due to the unfavourable operating condition of the threated connection, it was necessary to choose appropriate high-grade steels, allowing for avoidance of sintering and deformation of the connection. Through selection of appropriate materials and manufacturing regime of the fastener and threaded rod, obtained design solution has proven to give positive results. Due to spaced out force of clamp put onto many elements, a possibility to fasten the filter elements with very low torques (5–12 Nm) has been achieved. Thanks to that the obtained fastening solution operates under lower mechanical tensions and thus does not present high propensity for thread deformation. Presented below Tab. 2 gives operational parameters of the high temperature filter under steady operation of gasifier.

Table 2: High temperature filter operation – filtration under steady state conditions.

Property, units	Test 1	Test 2	Test 3
Filtration temperature, °C	590	410	442
Filtration pressure, kPa	2.5	4.6	5.1
Pulse-back system pressure, MPa_g	0.6	0.6	0.6
Pressure drop on the filter, kPa	1.8	3	4.3
Filtration velocity, m/s	1.7	1.7	1.6

During conducted long term research on high temperature filtration substantial influence of filtration temperature on stability of filter operation has been noticed. Particular importance had recognition of a set of process conditions at which in short time a severe loss of filter operational stability occurred, defined as steady pressure drop values between back-pulses at set time intervals. Due to complexity of this matter and multitude of aspects having influence of filtration process stability, a dedicated analysis of the above mentioned phenomena will be presented in a separate article.

During the research on efficiency of tar compounds removal in dry system, it has been noticed that maximal reduction attainable in the proposed system arrangement reached 75–85%, which relates to tar content in process gas at the outlet from the gas cleaning unit at the level of about 1 700 mg/m_n^3. Such value allows for combustion of process gas in power generating set integrated with the pilot research installation. On the other hand, in case of a commercial power generating set based on highly efficient gas engine, such high level of tar content would severely contribute to an excessive use of engine's mechanical parts. Summarizing the effects of conducted research on highly efficient removal of solid particles from process gas, increased the overall availability and removed the problem clogging of the dry gas cleaning unit.

Obtained results of research on removal of solid particles, led to the start of an experimental task concerning development of a highly-efficient method, for removal organic contaminants in wet process gas cleaning unit. This research mainly concentrated on optimization of oil scrubber operational parameters for increased efficiency of the apparatus in removal of tars. This goal has been mainly realized by a change of hydraulic parameters of the column. Diesel oil regulated under polish standards PN-EN590:2013 has been used as the tested absorbent. Optimization research provided necessary means for preparation of a sensitivity analysis of such parameters as change of oil flow rate directed to top of the column and to a nozzle used for direct gas quenching, as well as for oil temperature on efficiency of tar removal. Performed analysis allowed for assignation of a range of operational parameters of the absorption column as well as identification of areas in which it is necessary to perform some constructional modifications. The biggest problem encountered during performed research has been incorrect design of wire mesh demister installed at top of the column. Too large flux of oil led to flooding of the demister and its subsequent loss of efficiency for oil separation. Solution of the above mentioned problem has been found in application of a separate demister at the outlet of gas cooling column. Even though this solution produced satisfactory results it cannot be considered as permanent option.

Finally, conducted full scale technological research on wet process gas cleaning in high temperature filter and oil scrubber generated increase in overall efficiency in removal of particles, water and tar content of process gas from gasification of SRF. Concentrations of volatile organic carbon (VOC), water, tars and solid particles in process gas have finally all been brought down to levels satisfactory for gas engine producers (Tab. 3).

4 Summary

Developing market of European alternative fuels demand a constant search of novel technological designs capable of utilization of this feedstock. Especially interest should be paid towards methods that are able to meet demands given by the consumer market. Thus, one of interesting directions for utilization of alternative fuels may be gasification, which enables cogeneration of heat and power in small scale applications. Due to lack of availability of matured technologies for generation of energy in small and medium energy systems, Institute for Chemical Processing of Coal has developed a solid recovered fuel gasification technology based on GazEla gas generator, which is dedicated to distributed energy systems based on gasification of waste feedstocks.

Table 3: Obtained results of wet process gas cleaning unit.

Measurement point, units	After gasifier	After high temperature filter	After the absorption column
Volatile Organic Carbon, VOC, g/m$_n^3$	20.38	18.02	7.82
Water, vol.%	6.3	6.3	1.7
Tar content, g/m$_n^3$	5.4	5.3	0.3
Solid particles, g/m$_n^3$	1.0	<0.015	<0.005

The process of implementation of novel technologies based on waste fuels such as solid recovered fuel is conditioned by, i.a., development of technologically and construction wise matured solutions of process gas cleaning units. These units should be characterized by small degree of complication and rational investment and operational costs.

Presented results of research as well as all the above mentioned issues, point out that both of the developed methods of gas cleaning, dry and wet, concur to development of small and medium scale alternative fuel gasification systems.

Presented final configuration of researched gas cleaning unit enables reduction of solids below the level of 5 mg/m$_n^3$with simultaneous reduction of tar content to the level of 100 mg/m$_n^3$.

Cleaned and cooled process gas compiles to regulations of fuel quality standards set by gas engine manufacturers as well as allows for start of research on application of syngas in chemical synthesis for production of liquid fuels.

Acknowledgements Investigation presented in this paper is done according to the 23_2011_IP19_CoalGas contract between IChPW and KIC, the legal basis for implementation of the work is the approved research and development project 21.11.002 'Solid Recovered Fuel for renewable Combined Heat and Power production via gasification process'.

Received in November 2016

References

[1] Kardaś D.: *From biomass towards syngas.* Trans. Inst. Fluid-Flow Mach. **127**(2015), 63–89.

[2] Kotowicz J., Sobolewski A., Iluk T.: *Energetic analysis of a system integrated with biomass gasification.* Energy **52**(2013), 265–278.

[3] Sobolewski A., Bartela Ł., Skorek-Osikowska A., Iluk T.: *Comparison of the economic efficiency of CHP plants integrated with GazEla generator.* Rynek Energii **102**(2012), 5, 31–37.

[4] Rabou L.P.L.M., Zwart R.W.R., Vreugdenhil B.J., Bos L.: *Tar in biomass producer gas, the Energy research Centre of The Netherlands (ECN) experience: An enduring challenge.* Energ. Fuels **23**(2009), 12, 6189–6198.

[5] Heidenreich S., Foscolo P.U.: *New concepts in biomass gasification.* Prog. Energ. Combust. Sci. **46**(2015), 72–95.

[6] Chmielniak T., Skorek J., Kalina J., Lepszy S.: *Energy systems integrated with gasification of biomass.* Wydawnictwo Politechniki Śląskiej, Gliwice 2008 (in Polish).

[7] Faij A.P.C.: *Bio-energy in Europe: Changing technology choices.* Energy Policy **34**(2006), 4, 322–342.

[8] Chang J.S., Urashima K.: *Plasma fuel reforming: a critical review.* Trans. Inst. Fluid-Flow Mach. **119**(2007), 17–28.

[9] Dors M.: *Towards clean energy production.* Trans. Inst. Fluid-Flow Mach. **127**(2015), 91–116.

[10] Billig P., Ściążko M., Sobolewski A.: *Polish patent.* PL-208616, 2010.

[11] Kirkels A.F., Verbong G.P.J.: *Biomass gasification: Still promising? A 30-year global overview.* Renew. Sust. Energ. Rev. **15**(2011), 471–481.

[12] Kotowicz J., Iluk T.: *Installation of biomass gasification integrated with a combustion engine.* Rynek Energii **94**(2011), 3, 47–52.

[13] Sobolewski A., Kotowicz J., Iluk T., Matuszek K.: *Experimental research on gasification of biomass for cogeneration of heat and power in piston engine.* Przem. Chem. **89**(2010), 6, 794–798. (in Polish).

[14] Sobolewski A., Iluk T., Szul M.: *Gasification of SRF in a GazEla fixed bed reactor.* WIT Trans. Ecol. Environ. **186**(2014), 799–807.