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Research paper

Applying modern automotive technology on small scale gasification systems for CHP production: A compact hot gas filtration system

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ABSTRACT

Cost-effective and durable producer gas cleaning is a necessary step towards the promotion of sustainable gasification systems for electricity production. The automotive industry has vast technological experience on gas filtration both at experimental and theoretical level. In this study hot producer gas cleaning was attempted with the use of ceramic Diesel Particulate Filters (DPF) initially designed to operate in automotive applications. Different types of DPFs were used as downstream hot gas filters in two atmospheric air blown bubbling fluidized bed gasifiers. The experiments included short and long duration tests conducted with olive kernels under various gasification temperatures and air ratios. Being the first attempt on the application of “narrowly structured” ceramic DPF in a gas heavily loaded with particulate matter (PM), main objective was to investigate the operation performance in terms of overall collection efficiency, loading and pressure drop profile, as well as regeneration performance and structural robustness. The results showed high PM filtration efficiency, and highlighted fields for further research. Poor operation performance was experienced due to inlet surface plugging and in some cases limited structural robustness under uncontrolled regeneration conditions. Insight into the overall behavior of the DPF's was gained via axial tomography and imaging analysis. Further research is needed in order to adapt different geometrical structures and obtain better control of loading and regeneration processes.

1. Introduction

Gasification is the thermal degradation of carbonaceous material in the presence of one or more oxidizing agents (primarily air, oxygen or steam). The main product of gasification is a mixture of gases (“producer gas”) with the main components being carbon monoxide, hydrogen, carbon dioxide, water, methane and nitrogen (in the case of air gasification). This flammable product is in turn either combusted to produce heat and/or power or it is further processed to produce higher calorific value fuels or chemicals. The producer gas contains pollutants that need to be minimised or even totally removed from the gas prior to utilisation and the degree of necessary purification strongly depends on the final gas use [1]. The main pollutants present in the gas at the reactor exit can be categorised as follows: a) PM, b) tars, c) sulphur gases, d) ammonia and HCN, e) alkali compounds and heavy metals. Tar is characterized as the most crucial pollutant, in terms of concentration and equipment fouling, considered as the “weakest” point of gasification and the major barrier towards process commercialization beyond pilot scale applications [2]. Removal of the particulate load in the producer gas is also crucial to ensure problem-free operation of the gas utilisation technology for power generation or advanced fuel production. Two options are available for removing the particle content, hot and cold (or wet) gas filtration.

The choice of technology or combination of technologies for gas cleaning depends on the concentration of pollutants in the gas stream but also on the size and nature of particles and agglomerates present in the producer gas. Often adopted PM abatement technologies, considered as commercially available due to their extended usage in solid fuel combustion applications are wet scrubbing, electrostatic precipitation and bag filters [2,3]. Cyclones, wash towers and swirl scrubbers have a limited collection efficiency for particles smaller than 1.5 mm in diameter and hence the particles from biomass are only partially separated. ESPs and filters present high efficiencies for a wide range of particles ranging from the nano-scale to 100 μm in diameter [1]. Those technologies are

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Nomenclature

BFBG	Bubbling Fluidized Bed Gasifier
CHP	Combined Heat and Power
CI	Confidence Interval
CT	Computed Tomography
DICOM	Digital Imaging and Communications in Medicine
DPF	Diesel Particle Filter
ER	Equivalence Ratio
ESP	Electrostatic Precipitator
ICE	Internal Combustion Engine
PM	Particle matter
SEM	Scanning Electron Microscopy
XRF	X-ray Fluorescence

susceptible when producer gas contains tars, since gas cooling results in tar condensation leading to fouling and plugging phenomena [4].

Hot gas filtration gives the advantage of direct filter coupling with a catalytic device while the producer gas temperature is high enough for the activation of catalytic reactions concerning tar cracking. The optimum reaction temperatures for effective catalytic tar reforming range from 750 °C to 850 °C [5]. In addition. the absence of PM loading at the catalyst when installed downstream of the filter favors catalyst efficient performance and durability [6]. High temperature gas treatment also offers the advantage of sustaining tars in the gaseous phase thus avoiding condensation and fouling problems that could lead to inevitable shut down, while sustaining hot gas sensible heat. It is in this direction that the development of ceramic and metallic monolith filters is gaining pace due to their high temperature resistance. Reported drawbacks are structural failures due to either thermal stress during the cleaning loop (via injection of ambient temperature compressed air), runaway combustion of the accumulated PM, and inefficient operation due to partial removal of the formed PM layer leading to the phenomenon of bridging [3,7]. Thermal stability of ceramic filter media depends on the material used. Temperatures up to 1000 °C and higher are possible. Filter elements made of stainless steel are typically applied for temperatures up to 420 °C. Filter media made of high temperature steels can be applied up to 650 °C [8].

Ceramic monolithic substrates are widely applied in the automotive industry as engine exhaust after-treatment devices. Modified monoliths can be specifically used as particle filters in diesel engine exhaust. Their channels are alternately plugged so that each channel is only open at the inlet or the outlet, while the other end is plugged. These monoliths are known as Diesel or Gasoline Particle Filters - DPFs or GPFs. They offer the advantage of thinner walls, high specific filtration surface, low-pressure drop, good mass transfer performance, and ease of product separation [9]. Utilization of DPF in gasification applications has not been reported up to now. Bishop and Raskin [10], in the context of a filter development program, showed short duration (300 h) tests in a coal combustion set-up. More recently, Corella et al. [11], published research on honeycomb catalytic monoliths for tar reduction but with no technical data on the monolith and Reichert et al. [12] integrated a flow-through honeycomb catalyst in a firewood stove reporting reduced CO, HC and PM emissions accompanied by extensive honeycomb surface clogging.

This study presents the first outcomes of an attempt to transfer technological know-how, acquired in the field of automotive exhaust gas after-treatment, to the conditioning of a heavily loaded gas in a reducing environment. Basic scope was to investigate operation performance in terms of overall collection efficiency, loading and pressure drop profile as well as regeneration performance and structural endurance.

2. Filtration mechanism description

Particle traps consist of parallel channels, typically of square cross-section, running axially through the part. Adjacent channels are alternatively plugged at each end in order to force the particles through the porous substrate walls which act as a barrier filter. Particle traps are most commonly available in cylindrical shapes. Cylindrical ceramic DPF is a well established technology in automotive applications where PM reduction is efficiently accomplished by passing the loaded gas through a wall flow structure as shown in Fig. 1 [13].

The filtration mechanism of monolithic wall-flow filters is a combination of cake and depth filtration. Depth filtration is the dominant mechanism on a clean filter as the particulates are deposited in the pore network inside the wall material. As the PM load increases, a particulate layer develops along the wall surface in inlet channels and cake filtration becomes the prevailing mechanism. The particle traps present high efficiencies (~99%) when cake filtration is achieved [14]. Filtration efficiency is defined as the ratio of filtered particles to total particles entering the filter. Particles are calculated via concentration measurements expressed in particle mass per gas volume, usually g m^{-3} or mg m^{-3} (all volume flows in this study are normalized to Standard Temperature and Pressure −0 C and 10^5 Pa).

The accumulation of particles in the filter walls and channels is accompanied by pressure drop increase which in turn affects the upstream pressure conditions in the fluidized bed. As a result, the filter pressure drop is a critical value for smooth system operation and it is directly linked to the accumulated particle mass and distribution in the filter channels.

As mentioned, DPF loading operation is clearly distinguished in two phases, wall and cake filtration. Initially, the filter is clean and its pressure drop is at the lowest level. As particles start depositing within the pores of the filter walls, the pressure drop starts increasing with time in a non-linear manner. During wall filtration, pore properties like permeability and filter porosity continuously change due to the increasing PM deposit inside the pore network. After the filtration capacity of the wall pores becomes saturated, PM

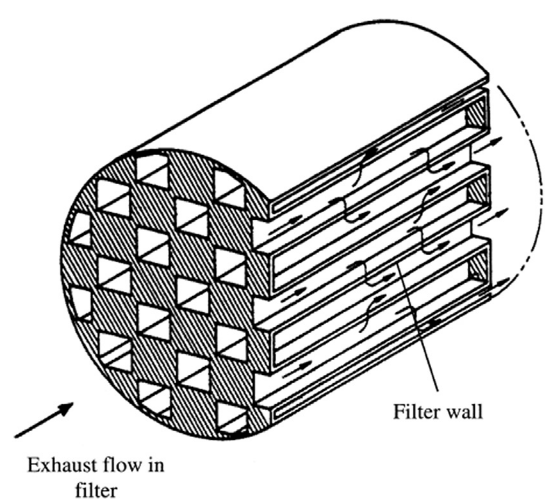

Fig. 1. Sectional view of a wall flow DPF [13].