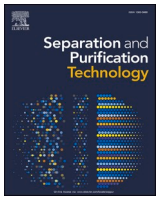
Separation and Purification Technology 347 (2024) 127629

Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur



Research and development of a mature and reliable method for filtration of hot producer gases

Mateusz Szul *, Jarosław Zuwała, Tomasz Iluk

Institute of Energy and Fuel Processing Technology, Zamkowa 1, 41-803 Zabrze, Poland

ARTICLE INFO

Editor: Luo Guangsheng

Keywords:
Hot gas cleaning
Filtration
Gasification
Biomass
Fixed bed

ABSTRACT

The paper aims to summarize the technical and process development of hot gas filtration technology that was tested and optimized under the conditions of producer gases generated through the gasification of wood chips in a fixed-bed 60kWth GazEla reactor. The paper describes the results of testing two generations of hot gas filters, four types of filtration elements, as well as a range of auxiliary subunits (i.a. methods for secure fixing and sealing of the filters). Additionally, an in-depth analysis was performed on the efficiency of pulse-jet cleaning, which through a statistical study indicated change-effect relationships between the main pulse-jet parameters. Based on this learning curve, the paper presents a set of guidelines that can be used for the development of robust hot gas filters, as well as for resolving their unstable operation.

1. Introduction

In many small and medium-scale gasification applications, the feedstock used is typically either bio-based or, preferably, derived from wastes or waste biomasses like SRF, lignin, or sewage sludge. Gasification inherently requires cleaning or upgrading the producer gas to meet specific requirements dictated by its intended use. These requirements determine the extent of gas cleaning necessary. Hot gas filtration is a cornerstone in most gas cleaning strategies, offering over 99.9 % dedusting efficiency and being applicable in temperature ranges from 200 to 1200 °C [1]. Therefore, rigid hot gas filters are commonly relied upon for particulate separation from producer gases, preceding further cleaning steps like removing organic and acidic/basic compounds, as well as prior to reforming or syngas upgrading operations.

The utility of hot gas filters extends beyond simply removing solids. The concept of comprehensive impurity removal from producer gas without the need for repeated cooling and heating is grounded in thermodynamic principles. This approach aims to minimize energy losses within the system [2]. For instance, in the most efficient Fischer-Tropsch synthesis plants, all impurities should ideally be eliminated within the temperature range spanning from the gasifier's operating temperature to the synthesis reactor's temperature (850 °C–200 °C) [3]. Such a system avoids the necessity for multiple gas cooling and reheating cycles. Moreover, the benefits of hot gas cleaning are particularly pronounced in pressurized gasification systems, as they can operate without requiring syngas compression [4]. To effectively utilize catalytic and sorption processes for syngas purification, it is imperative to thoroughly eliminate solids, low-boiling salts, and contaminants potentially detrimental to catalysts, such as sulphur (S) and chlorine (Cl).

Despite being a technology known for over 40 years, the limitations of hot gas filters still pose challenges. On one hand, the rigidity of filter candles hampers their the efficiency of their pulse jet cleaning [5,6]. On the other hand, this feature also ensures high filtration efficiency, system safety, and longevity. In this paper, the authors detail an 8-year research and development endeavour aimed at unravelling the complexities of filtering hot gases from biogenic feedstocks.

The Institute operates a hot gas filter that is a part of a pilot producer gas/syngas cleaning unit. This gas cleaning setup allows for the purification of 30–40 Nm^3/h (based on dry gas) or 100 m^3/h (in the conditions under which the filter is operated). Over recent years, the filter unit has undergone extensive testing, redesigning, and modifications aimed at enhancing its functionality and reliability. Significant advancements have been achieved in various aspects of the filter, including the intake design, gas distribution, design of the dirty side (including the dust hopper), filter candle pitch, filter sealing, and fixing system. Initially, these enhancements were trailed by redesigning a 1st generation filter, and upon successful technical validation, the solutions were incorporated into a 2nd generation of the device.

It is known that the primary factor limiting the functionality of hot gas filters is their inability to effectively dedust gases containing mineral

* Corresponding author.
E-mail address: mszul@itpe.pl (M. Szul).

https://doi.org/10.1016/j.seppur.2024.127629
Received 29 December 2023; Received in revised form 8 April 2024; Accepted 21 April 2024
Available online 23 April 2024

matter or organics with some degree of reactivity or existing in a liquid state. Pore blockage, increased shearing strength of the filter cake, and enhanced cohesion between particles or adhesion to the filter material are among the aspects discussed in the literature as causes of filtration stability loss [6–8]. However, it is undeniable that the main shortcomings of hot gas filters stem from two factors. Firstly, the inefficiency of most pulse-jet regeneration systems, and secondly, a lack of understanding of the operational windows in which the filters need to be maintained [9,10]. The latter aspect remains poorly defined, linking with various factors that should not be generalized, as not all issues leading to increased residual pressure drop of the filter can be attributed to the instability of a filtration process. Nevertheless, it holds true that some pulse-jet solutions available on the market exhibit limited efficiency. Consequently, a significant portion of ITPE's work focused on identifying the factors influencing the efficiency of pulse-jet cleaning. Building on this foundation, a redesigned pulse-jet method with significantly higher efficiency was developed. This research was conducted using a specially designed test rig, enabling precise analysis of several pulse-jet system designs. Subsequent measurements facilitated the proposal and implementation of an optimized pulse-jet cleaning method. All proposed design and process changes were validated through experimental runs conducted under real conditions of hot producer gas. This development process laid the groundwork for understanding strategies to counteract many of the problems frequently described in the literature concerning the stability of hot gas filtration systems.

2. Filtration of hot gas from the gasification process

According to the definition popularized by the German Society of Engineers VDI 3677-3 (2012), the process of filtration of gases with temperatures >260 °C is called Hot gas filtration, High-temperature gas filtration, or from German Heißgasfiltration. By analogy, the filtration of gases with temperatures below this limit is often referred to as the filtration of warm and cold gases.

The coarse dedusting of hot gases can be conducted using inertial dedusters (settling chambers, cyclones). Unfortunately, these devices do not allow for sufficiently efficient removal of particles having a size <5–10 μm. Similarly to flue gas cleaning, the producer gases can also be dedusted using electrostatic precipitators. These constructions allow effective removal of the finest dust fraction, but so far have not been demonstrated in industrial conditions at temperatures >510 °C [11]. Moreover, the operation of an ESP in the atmosphere of a hot, explosive gas always entails a measurable risk. Furthermore, a few examples of fabric filters that can be operated at the conditions of hot gases are present on the market, but the operational temperature of the most resistant fabrics known to the authors allows for continuous operation only up to 480 °C (1).

2.1. Filtration theory in the aspect of filtration of hot producer gases

According to filtration theory, there are three basic mechanisms responsible for particle transport and, consequently, their separation (see Fig. 1). These mechanisms determine phenomena occurring in both solid and liquid separation processes. They include particle collision due to inertia forces, interception, and diffusion. The direct collision mechanism is most important for large particles, which deviate from flow lines of the continuous phase and, due to inertia forces, collide with an obstacle (filter material, another particle forming a filter cake in the porous media, etc.). The interception mechanism occurs when a particle approaches an obstacle within one radius distance, resulting in its removal due to direct contact with the material. This mechanism enables the removal of particles following fluid flow lines near the obstacle. The final filtration mechanism, Brownian diffusion, explains why filters can efficiently filter particles significantly smaller than their pore size.

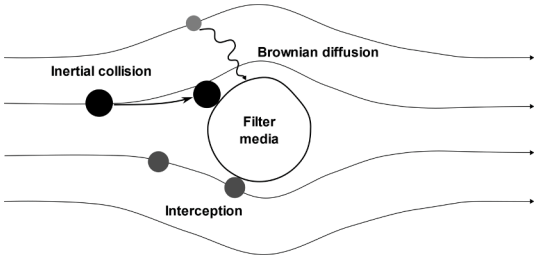


Fig. 1. Main mechanisms responsible for filtration of particles.

It was proven that, for the separation of particles above 1 μm, the direct collision mechanism predominates and thus has the greatest impact on dust removal efficiency. For particles between 0.1 μm and 0.6 μm, the interception mechanism predominantly impacts the efficiency of separation. Finally, for particles <0.1 μm, the diffusion mechanism is primarily responsible for the efficiency of separation [12,13]. The above theory directly translates to the filtration of hot producer gas. Hence, for particles <1 μm, it is said that the efficiency of dust separation improves with increasing temperature. This is because for small particles, separation due to diffusion force predominates and filtration mainly occurs within the filter cake. On the other hand, based on a theoretical analysis conducted for a single fibre model, it was shown that for particles where inertial collision is the primary filtering mechanism, separation efficiency decreases with increasing temperature. This, however, is explained by the increase in gas viscosity. Nevertheless, in the actual hot gas filtration process, the total proportion of particles captured by inertial impact remains negligibly small, as the filtration of the largest particles mainly occurs via the mechanism of size exclusion [14,15].

The main factors affecting the efficiency of using barrier filters for dedusting of hot producer gases are as follows:

- Pressure drop across the filter and the rate of change of filtration resistance.
- Filtration velocity.
- Physical and chemical properties of the filter medium and dust characteristics (cohesion, adhesion).
- Efficiency (the amount of energy/pulse-gas input related to the amount of cake residue remaining on the filter) and operating program (pulse times, intervals between pulses, pulsing scheme, etc.) of the filter regeneration system.

2.2. Main contaminants of producer gas influencing its filtration characteristics

Up to this point, the search for potential sources of instability of hot gas filters has primarily focused on organic contaminants present in the producer gas. Given that organic impurities constitute an extremely complex matrix of compounds, it is understandable that certain classes of tars remain elusive even to the most modern and precise analytical methods. One of the most frequently adopted conventions that standardises the understanding of tars is outlined in a document published in 2008 under the working title "Tar Protocol." [16]. Despite the efforts put into the preparation of the Tar Protocol, as well as the classification established by TNO [17], we remain ill-equipped for a precise description of gravimetric tars, which exhibit the highest influence on the filtration process.

Generally, tars consist of a mixture of various organic compounds that may form as a result of the breakdown of the carbon structure of the fuel (primary tars). They also include products resulting from subsequent transformations, such as decomposition, recombination, and polymerisation reactions (secondary tars). In simple terms, tar pollutants are divided into two types: gravimetric tars and GC tars (VOC/GC-tars). The second group can be characterised using gas chromatography (GC/MS/FID/PFPD), while for gravimetric tars we can determine only their quantity. This inadequate precision in the description of gravimetric tars (class I) remains one of the biggest hurdles for hot gas

filtration of producer gases.

Based on the qualitative and quantitative analysis of GC tars, using the method proposed by TNO, it is possible to indicate what is the temperature point when the tars contained in the gas start condensing. However, without a grasp of the influence of gravimetric tars, this information needs to be used with caution.

The second important aspect of producer gas, which often significantly influences the stability of its filtration, is the content and characteristics of mineral contaminants. These species are often referred to as dust or particulates, but this notion can be imprecise at elevated temperatures as low-melting salts are known to adopt a liquid phase. Minerals contained in the producer gas stand as the second source of potential liquid species, which are known to greatly influence and destabilise the filtration of hot gases.

The particulates suspended in the producer gas consist of two main fractions: the char and the mineral fraction. However, they are generally referred to as chars. These fractions are interconnected but are formed by different processes. The carbonaceous fraction, which is the brittle and degassed carbon structure, acts as a substrate in the gasification process. However, it also serves as an adsorbent for both the organic impurities and metals. When chars are filtered from producer gases, they form filter cakes of high elasticity and cohesiveness.

High-temperature behaviour of particulates contained in producer gases is dictated by their mineral fraction – salts of metals and non-metals (Na, K, Ca, Mg, Fe, Mn, Hg …). Their content originates from the conditions occurring in the location where the biomass was grown, as well as from inclusions introduced during its harvesting, transport, and preparation (such as sand, metal scraps, contamination with other fractions). Under gasification conditions, these fractions form complex heterogeneous systems, which continuously undergo physical and chemical transformations due to changes in the local thermodynamic equilibrium. They are responsible for the sintering of the bed, slagging of the reactor, or the heat transfer surfaces. Additionally, they influence the rate of gasification reactions, as they are known to catalyse/inhibit the gasification reactions or bind compounds that exhibit such activity. The characteristics of the mineral fraction of the fuel determine numerous technical and process solutions for the gasification reactors and all the components of the hot gas treatment system. It is usually assumed that below condensation temperatures, the salts can be filtered out from the gas.

2.3. The upper limit for the operating temperature window of hot gas filters

In the case of hot gas filtration, it is essential to determine the maximum or critical filtration temperature, above which the process becomes unstable. Methods based on ex-situ analysis of the physicochemical properties of solids sampled from the producer gas make a valuable contribution in this area but are non-exhaustive. This approach attempts to draw conclusions linking the nature of the observed changes to, for example, the instability of the hot gas filtration process. One basic example of processes that induce both an increase in cohesive forces and shrinkage of material is melting or sintering. Both physical transformations and reactions are accompanied by corresponding changes in sample mass, heat flow, or dimensions so that their presence can be observed under laboratory conditions using widely available methods and devices, such as dilatometers (DIL – dimensional changes), mechanical strength testers, or thermogravimetric analysers (TGA – mass changes) and calorimeters (DSC – heat flows) [9]. Therefore, it is hypothesized that, based on the observation of temperature regions where distinct physicochemical changes occur, it is possible to approximate the conditions under which the filtration process may become unstable. Unfortunately, the significant limitations of these methods lie in the fact that we are unable to fully map the process atmosphere and the complexity of the structure of the filtered particles. Additionally, the observed transformations may overlap, making it impossible to determine areas in which the material behaves stably. The aforementioned sintering serves as a model example of a transformation that is attempted to be observed in a test sample. However, it should be noted that besides evident phase changes, there also exist physicochemical transformations of a more subtle and hence easier to overlook nature. The decomposition of calcium carbonate ($CaCO_3$) can serve as an example [18]. Therefore, the above methods must be treated as indicative, and the analysis of their results must always be supplemented with in-situ experiments.

2.4. The lower limit for the operating temperature window of hot gas filters

As previously mentioned, the lower operating point of hot gas filters mainly arises due to the condensation of the organic contaminants in the gas. In theory, this temperature can be determined based on qualitative and quantitative analysis of tars; however, due to the complex nature of organics, it is not straightforward and should be analysed with caution. The method developed by TNO is often used to determine the organic dew point.

3. Introduction to hot gas filters

In general, hot gas filters comprise a dirty and a clean section separated by a sieve plate on which the filter elements are mounted. As the gas flows through the filter material, the particulates dispersed in the gas are separated from the continuous phase. The dedusted gas then enters the clean side of the filter and exits via the outlet port. In the clean section of a filter, a regeneration system for the filter surface is installed. Additionally, protective depth filters can also be installed to safeguard the device (either an entire section or a single filter element) against the emission of dust which may occur in case of damage to the filter cartridges [19]. In candle filters, the filtration direction is usually from the outer surface of the filter material inwards, which is related to the regeneration mechanisms of the filter elements used. The basic method of operation and construction of candle filters used in gasification systems are thus similar to well-known bag filters. However, due to a theoretical maximum operating temperature of 1200 °C and pressure of 80 bar, their design and construction materials are adapted to the harsher working conditions. Although in barrier filters, the filter material stands as the most important characteristic feature of the device that determines the maximum efficiency of separation of the solids, it is the combined effect of all the parts that add to its reliability. The following is a non-exhaustive list of aspects of hot gas filters that contribute greatly to the readiness level of this technology: the method of fixing and sealing of the filters, resistance to thermal/mechanical shocks, the maximum allowable temperature of continuous operation as well as the regeneration of the filter surface. Furthermore, the distribution of the dust gas inside the filter, the application of solutions that enable maintaining the filter within the operational window, the efficiency of the applied cake removal system, appropriate metering, control and diagnostics, protection in case of failure, as well as access and ease of servicing, should be equally important for the safe and stable operation of the device.

4. The research and development on hot gas filtration

4.1. Gasification installation

A 60 kWth fixed-bed reactor – GazEla type – was used during the development of the hot gas filter (Fig. 2). The reactor is a proprietary, mixed-flow gasifier developed by ITPE, dedicated especially to the conversion of woody biomass. This reactor, and its operation while using different feedstocks, have been described previously in the literature [20–22]. In this study, alder wood chips with a granulation of approximately 20 × 20 × 10 mm were used as fuel. Table 1 presented below summarises the technical and elemental analysis of the fuel.

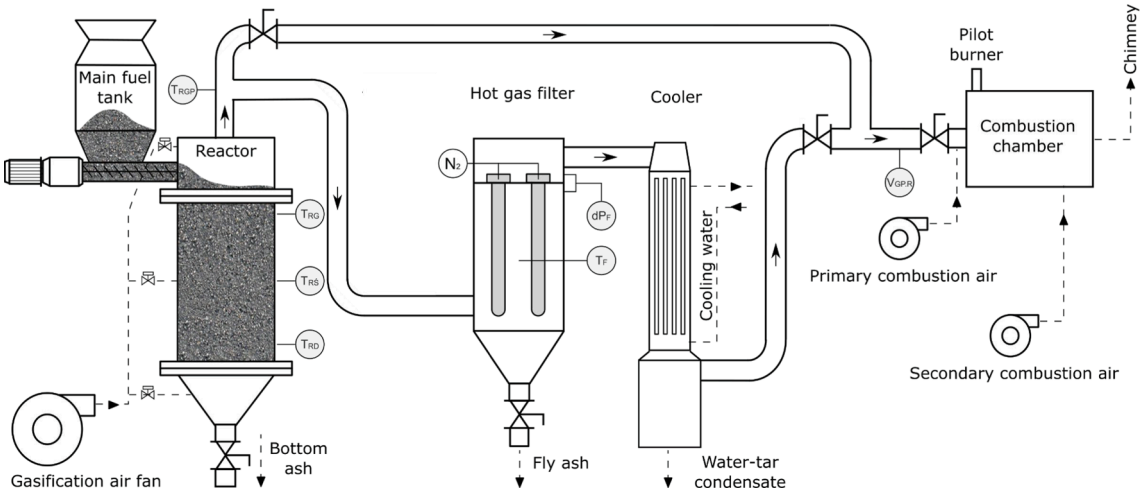


Fig. 2. Diagram of the pilot gasification installation with a GazEla fixed-bed reactor.

Table 1
Analysis of the gasified wood chips (a - analytical state, ar – as received, LHV – lower heating value).

C_a	H_a	N_a	S_a	Cl_a	F_a	H_2O_a	H_2O_{ar}	A_a	V_a	LHV_a
% (m/m)										J/g
47.6	5.29	0.15	0.04	0.08	0.003	8.9	18.0	0.5	76.66	17 164

4.2. Characterization of the tested 1st generation of a hot gas filter

Work on the development of a hot gas filter for the GazEla reactor has been ongoing at the Institute since 2014. The first tested design was a commercial product offered on the Polish market. This filter was based on a cylindrical tank with a flat top plate and a conical bottom. A maximum of ten candle filters with a length of 1 m and an external diameter of 60 mm could be used at the same time. The thickness of the filter wall is 10 mm. The inlet of raw producer gas was located at the bottom of the cylindrical shell, at the level of the lower ends of the filters. No solution for the distribution of the gases was used. The pulse-jet cleaning system allowed the cleaning of a single section of the filter. This, together with the attempt to increase the filtration velocities to the conventionally discussed level of 2–3 cm/s for filtration of hot gases, led to the conclusion that the number of filter elements installed in the unit was limited to four. The connection between the filters and the sieve plate was sealed using gaskets made of ceramic felt with a nominal thickness of 8 mm (before use). Fixing of the cartridges was conducted using a pressure plate. The device did not provide the possibility of continuous collection of dust during operation; hence, the cake was collected in the hopper and removed after completion of the test.

The boundary condition limiting the possibility of feeding the gas to the filter was linked to keeping the gas in a dry state, i.e., free of water or organic condensate. To achieve this, the filter and the gas supply line were heated using high-temperature electric heating cables. This heating had a total heat output of 2.2 kW and allowed the unit to be heated from ambient temperature to a minimum temperature of 350 °C over approximately six hours. The system was also used to maintain a set filtration temperature, even if its value was 100–200 °C higher than the temperature of gas leaving the reactor.

A pulse-jet regeneration system was responsible for the continuous operation of the filter. In its basic configuration, the regeneration system had no gas buffer tank, and the gas stream was supplied directly from a local N_2 gas grid (DN25, 15 bar). The pulse jet was generated by the regeneration gas flowing out of an ID = 30 mm manifold located approximately 30 mm above the top line of the filter elements. The manifold had Ø3mm holes drilled to serve as nozzles.

4.2.1. Tested types of filter elements

During the research, four types of commercial filter elements were evaluated. Their brief characteristics are given below, while their summary presents Table 2.

F_C_01 ceramic cartridges represented the simplest and at the same time the most common type of ceramic candle filters available on the market. The filters were produced by the sintering of homogeneous layers of non-woven ceramic fabric made of a mixture of aluminium oxides and silicon oxides. Such an arrangement of the filter ensures that filtration efficiency of >99.99 % is maintained; however, this structure also favours progressive clogging of filter pores as a result of depth filtration.

F_M_01 cartridges were made of non-woven metal, i.e. the fibres building the filter membrane had a random arrangement, which enables maintaining a uniform filtration layer having medium porosity and low thickness. This is also the reason these filters are easier to regenerate. The F_M_01 filters consisted of an inner reinforcement made of metal

Table 2
Characterization of the tested filter elements.

Filter code	F_C_01	F_M_01	F_M_02	F_M_03
Type of a filter	Sintered ceramic felt	Sintered metallic sheet with internal supporting mesh	Sintered metallic sheet with external and internal supporting mesh	Sintered metallic powder
Chemical comp. /material	65% SiO_2 35% Al_2O_3	AISI 304	AISI 316L	INCONEL 601
Porosity, %	87.5–91	~70%	~70%	~60%
Filter grade, µm	8	n.d.	n.d.	n.d.
Dimensions, mm OD × L	Ø60 × 1000			
Mass, g	775	900	980	1250
Max. working temp., °C	900	360	540	640
Permeability, @200Pa air, cm/s	<2.75	<3.0	<2.75	<2.5

Table 3
Characteristics of tested configurations of the pulse-jet nozzles.

	Description
D_O_01	holes ∅3 mm in diameter
D_R_01	nozzles with ID = ∅6 mm inserted into the filters, ending below the top surface of the filter flanges
D_R_02	four nozzles with ID = ∅16.5 mm ending approx. 2 cm above the top surface of filter flanges
D_R_03	four nozzles with ID = ∅20.4 mm ending below the upper surface of the filter flanges, plus additional orifices were mounted
Orifice	flat disc designed to serve as a restriction to the flow of pulse gases located at the outlet from the clean side of the filter – in this study ID = 30 mm

mesh (basket), ended with a flat flange on one side and a cap on the other. The non-woven material was connected to the basket by welding.

The third of the test cartridges, F_M_02, was made using a similar technique to F_M_01, but this filter was made of a non-woven fabric manufactured using AISI 316L steel. In addition, a reinforcing mesh with a size of 1 × 1 mm was also installed on the outer side of the filter. These two features were used to strengthen the filters, increase their max. allowable temperature and reduce their susceptibility to corrosion.

The last of the tested candle filters, F_M_03, was made by isostatic sintering of metal powders (INCONEL 601 alloy). In cross-section, the filters were uniform and had thickness similar to F_C_01. F_M_03 had the smallest porosity of all tested filters, but the chemical composition of the alloy used for their production theoretically allowed for continuous operation in a reducing atmosphere at 640 °C.

4.2.2. *Hot gas filtration experiments*

All data regarding the hot gas filtration experiments conducted using the 1st gen filter are presented below in Table 4.

For each filtration experiment, the start-up procedure and the control method of the reactor operation were kept similar. During the start-up of the gasifier, when the producer gas temperature did not exceed 400 °C, the gas was fed directly into the combustion chamber. During this time, the hot gas filter and the lines transporting the gas to and from the filter were heated using electric heating cables. After reaching the minimum above-mentioned temperature of the produced raw gas, the entire stream of gas produced in the reactor was directed to the filter. During the operation of the gasifier, the fuel level, air flow rate, and its distribution in the reactor were kept constant. Filtration experiments were continued until the target set for the test was reached, or until an unstable filter operation was detected. During a shutdown, the gas cleaning system was separated from the reactor and flushed with nitrogen.

To check the effect of filtering different flow rates of the producer gas, the reactor was operated at 50–100 % of its nominal power. The direct coupling of the reactor to the filter and the relatively small scale of the plant meant that all changes in the stream and characteristics of the produced gas were also directly reflected in the operating conditions of the filter. The characteristic features of fixed bed reactors are that the bed level (including the ash layer on the grate) is kept constant and that the power is changed only by varying the feed flow of the gasification agents. These factors affect the temperature profile in the reactor, and thus also the characteristics of the producer gas (including impurities). The above-mentioned characteristic of the reactor explains why, for some of the experiments discussed below, significant differences in the temperature profile of the reactor bed were observed. It also needs to be kept in mind that a temperature reading represents its value at a single point and does not reflect the distribution across the cross-section of the reactor. This fact is further exacerbated by the tendency of fixed-bed reactors for stratification and uneven flow. This is particularly true in upper zones, when no mixing is performed.

The filtration process was controlled by measuring the pressure drop between the two sides of the sieve plate (dP) and measuring the temperature: at the inlet and outlet of the device. The operating temperature of the filter resulted from the temperature of the flowing gas, heat losses in the filter, and the operation of the electrical trace heating. The result of using the trace heating can be observed in the effect of independent control and thus level of the temperature of the filtered gas from its temperature at the reactor outlet. Hot gas filters usually operate at pressure drops not exceeding 1–2 kPa, so the trigger level was set at dP = 2 kPa. In the course of the research, both the method of controlling the pulse-jet (manual/automatic, ball valves/electronic valves), the

Table 4
Results of the hot gas filtration research performed using the 1st gen unit.

Test No.	T_01	T_02	T_03	T_04	T_05	T_06	T_07	T_08
Type of filter element	F_C_01	F_M_01	F_M_01	F_C_01	F_C_01	F_M_02	F_M_02	F_M_03
Condition of the element	FU	FU	After T_02*	After T_01*	After T_04*	FU	After T_06*	FU
Type of the pulse-jet nozzle	D_O_01	D_R_01	D_R_01	D_R_02	D_R_02	D_R_02	D_R_03	D_R_03
Pressure in the pulsing system – P_{PS} [bar-g]	2–10	6	6–10	6	6	6	6	6
Duration of the pulse– t_P [s]	1–10	1–5	1–5	1–2	<0.5	<0.5	<0.5	<0.5
Source of the pulse gas	N_2 pipeline DN15	N_2 pipeline DN15	N_2 pipeline DN15	N_2 pipeline DN15	Buffer tank 4.5 dm^3	Buffer tank 4.5 dm^3	Buffer tank 4.5 dm^3	Buffer tank 4.5 dm^3
Gasifier temp. – top, T_{GT} [°C]	369.06 (39.56)	68.26 (11.47)	380.41 (102.84)	337.28 (44.35)	376.39 (126.14)	197.04 (40.31)	363.96 (84.24)	377.43 (52.34)
Gasifier temp. –middle, T_{GM} [°C]	602.4 (39.87)	580.9 (37.56)	633.58 (73.75)	612.36 (32.93)	605.77 (46.78)	478.87 (51.73)	634.84 (74.88)	670.67 (59.95)
Gasifier temp. – bottom, T_{GB} [°C]	892.85 (27.5)	1083.86 (35.12)	1012.17 (46.64)	945.13 (41.75)	734.17 (126.73)	1036.48 (34.88)	893.89 (53.71)	1009.11 (38.52)
Gasifier temp. – gas outlet, T_{GPG} [°C]	480.72 (20.56)	520.97 (28.33)	555.42 (51.5)	525.22 (19.76)	511.41 (41.39)	418.03 (28.01)	498.62 (74.73)	529.69 (54.06)
Temp. inside filter – T_F [°C]	510.12 (66.97)	446.29 (0.72)	505.16 (54.47)	n.d.	528.59 (59.48)	625.69 (16.77)	549.06 (57.55)	657.1 (32.48)
Producer gas flow rate – $\dot{V}_{GP.R}$ [m^3/h]**	57.67 (5.54)	85.28 (6.93)	65.7 (13.78)	n.d.	72.87 (11.46)	91.87 (13.64)	73.32 (13.29)	82.26 (20.24)
Char load entering the filter – $\dot{M}_{GP.K}$ [g/Nm^3]	6.85 (1.94)	4.35 (1.94)	5.92 (1.94)	2.05 (1.94)	7.16 (1.94)	5.82 (1.94)	2.67 (1.94)	3.44 (1.94)
Filtration velocity – v_F [cm/s] **	2.12 (0.2)	3.14 (0.26)	2.42 (0.51)	n.d.	2.68 (0.42)	3.38 (0.5)	2.7 (0.49)	3.03 (0.75)
Pressure drop on the filter – dP_F [kPa]	3.13 (1.28)	1.39 (0.81)	6.5 (2.26)	4.32 (1.35)	6.2 (1.35)	3.77 (1.32)	2.78 (0.95)	3.36 (0.42)

The data summarised in the table are average values over the balancing period. Format of presenting the results: mean value (standard deviation of the sample). FU – first use.
*Cleaned mechanically outside the filter. ** Process conditions, wet gas.

pressure of the regeneration gas (3–10 bar), and the duration of regeneration (0.1–10 s) were varied. Between the tests, the clean and dirty side of the filter was regularly inspected, and necessary services such as changing seals, weighing plate distances, replacing filter candles, or cleaning them ex-situ were conducted. Ex-situ cleaning of the filters was carried out by blowing off the collected layer of cake using a jet of compressed air.

Based on the methodology described above, the optimum operating window for the hot gas filter integrated with the GazEla gasification reactor was determined to lie between 300 °C and 600 °C. The lower limit stems from the calculation of the tar dew point, which for the raw gas and the gas downstream of the ceramic filter were determined to be 195.7 °C and 179.9 °C, respectively. These values should be regarded as approximate and subject to significant error regarding both the method of analysis and the measurement. However, based on experience, it can be concluded that in all parts of the plant, where the temperature is maintained above 300 °C, no traces of condensation or subsequent coking of organic impurities were ever noticed. While the upper-temperature limit was drawn from the TG/DSC and DIL analysis performed on the filter cake.

4.2.3. Tested types of pulse-jet nozzles

During the first few hot start-ups and filtration experiments, it became clear that the original design of the pulse-jet method was ineffective and needed to undergo a major redesign. Hence, during the following runs, a few concepts for improvement of the efficiency of the method were assessed. The tested configurations of the nozzles are listed in Table 3 while the details regarding the tested conditions and configuration of the pulse-jet method (pulse times, pressures, supply of N_2, buffer tank, etc.) are given in Table 4.

4.2.4. Results of the research on the development of a hot gas filtration method performed using the 1st gen. Filter

Several technical and process issues were identified in the course of testing the 1st generation hot gas filter. Each failure was closely studied to determine its root causes; however, at this point for any of the tested types of filter elements, configurations of the pulse-jet system, or parameters of the filtration process (temperatures, filtration velocities, pressure drop, etc.), stable filtration of the hot producer gas obtained by biomass gasification in the GazEla fixed bed reactor was not achieved.

Using F_C_01 ceramic elements, a continuous increase in pressure drop across the filter was observed for each of the conducted filtration tests. Moreover, no effect of pulse regenerations could be observed (Fig. 3). These observations were attributed to the high difficulty of regeneration of F_C_01 and the inefficiency of the pulse-jet system, which was later supported by the ex-situ examination of the elements. Similar observations were made for the F_M_03 metal cartridges. Despite a less pronounced trend towards increased filtration resistance, regeneration of the F_M_03 candles was also highly ineffective. In this respect, both types of sintered fibre metal cartridges evaluated (F_M_01 and F_M_02) were characterized by more favourable properties. The drawback of the elements, made from both the AISI 304 steel and AISI 316L steel, was that their filtration membranes were prone to damage under the filter operating conditions (Fig. 4). This, together with the insufficient efficiency of dust removal of the F_M_02 filter elements, disqualifies them from use in the filtration of hot producer gases. Conclusions drawn from the performed experiments are that only the ceramic filters F_C_01 proved their filtration efficiency and reliability. These filters were also the least expensive and had the shortest lead times. However, due to their tendency for depth filtration, the need to develop a method for precoating was paramount. Moreover, as a supplementary measure also the use of the precoating materials as continuous filtration aids was proposed to reduce the cohesion of produced filter cakes.

Even though during the tests T_02, T_06, and T_08 the filtration velocity exceeded the normally stipulated upper limit of 3.0 cm/s, it was at these tests where the observed filtration pattern was more stable. Importantly, these observations were made at a pressure drop of the filter >3.5–5 kPa. Collation of the changes in pressure drop during the hot gas filtration tests carried out using the 1st gen. filter is presented below in Fig. 5. Operational experience gained in the development of bag filters indicates that one of the main factors that can destabilize the filtration process is overloading the filter with gas or dust. Therefore, the basic strategy for stabilizing the operation of a filter usually refers to reducing the stream of gas fed to the device. Since during these experiments, no clear indications of a positive effect of such an action were observed, the observed instability of filtration was mainly attributed to the low efficiency of the pulse-jet system.

A series of attempts were made to increase the regeneration efficiency of the filtration surface. These studies focused mainly on the impact of changing the design of pulse nozzles, and solenoid valves and using a buffer tank for the regeneration gas. It was found that a clear improvement in the regeneration efficiency was observed as a result of using a buffer tank as well as a pulse solenoid valve in place of a traditional one. Moreover, increasing the size of the pulse nozzles also proved to give higher efficiency in cake removal. Importantly though, conclusions drawn from experiments where the distance of the pulse nozzles was changed or a constriction at the gas outlet of the filter elements (orifices) were applied remained inconclusive. It was also found that triggering the regeneration system at pressure drops <2 kPa did not result in the removal of the filter cake. These observations are in line with the theory stating that as the cake size increases, the value of the force required to exceed its tensile strength decreases [23–25]. As a result, it was stipulated that designing an improved pulsed regeneration system for hot gas filters was a complex issue, which needs to be tackled through dedicated basic research.

Due to the observed clogging of the filters and the discussed contribution of organic compounds to this process, during the subsequent test runs the operating temperature of the filter was raised significantly

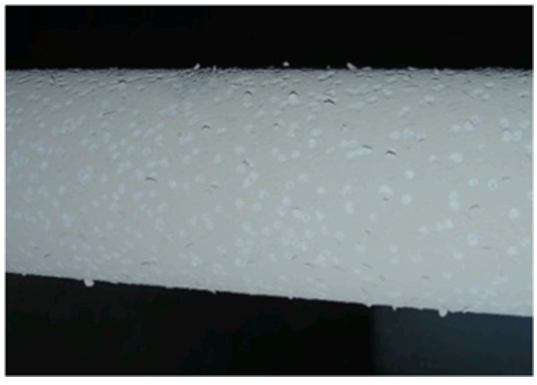


Fig. 3. Picture of F_C_01 filters with only a few patches of removed filter cake.

Fig. 4. Mechanical failure of filter membrane (F_M_01).

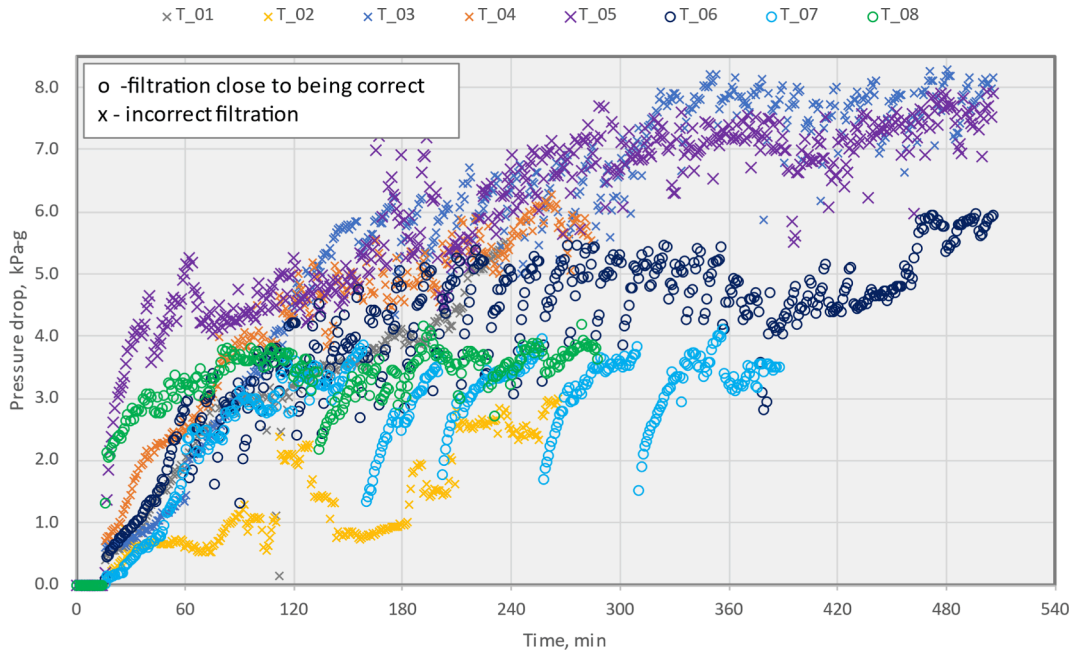


Fig. 5. Collation of the changes in pressure drop during the hot gas filtration tests carried out using the 1st gen. filter

above the temperature at which the gas should remain dry. In addition, seeking an explanation for the reason behind the change of colouring of ceramic filters, their segments were cut and subjected to an isopropanol wash. Subsequently, the composition of the extract was analysed using GC/FID, however, no organic compounds were detected. This does not mean, that the pores of the filters do not become clogged as a result of condensation and subsequent carbonization of tars. It rather indicates that using chromatographic methods, it is not possible to confirm such a theory. Moreover, the carried-out experiments led to the conclusion that for this producer gas, dedusting at temperatures >550 °C does not translate into stabilization of the process.

In addition to the described process issues, one of the main technical problems observed was the lack of tightness of the connection between the cartridges and the sieve bottom. Failures of the seals used resulted in a decrease in filtration efficiency, introduced disturbances in the operating pressure of the installation, and led to several emergency shutdowns. Hence, solving this problem was the second most important challenge of this research.

4.3. Research on the development of robust solutions for hot gas filtration

4.3.1. A method for fixing and sealing the filter elements

The original method for fixing the filter elements was based on pressing the filters onto the sieve plate by a 9 mm thick steel plate (weighing 6 kg), and this often led to damage to the ceramic felt seals.

The new fixing method was based on a low-torque threaded connection that was designed to operate continuously at a maximum temperature of 650 °C. A multi-screw, low-torque tensioning nut and a centrally located threaded rod are the main components of this connection. Such solutions are designed for applications exposed to elevated temperatures, vibrations, and angular deformation. The use of indirectly tensioned threaded connections allows for achieving extremely high preloads while using minimal torque. This concept has also finally made it possible to increase the mechanical strength of the connection by increasing the threaded rod size to M30 × 3.5 according to DIN 13, instead of the 4x or 6x M6 or M8 connections typically used in other construction of filters. A review of available material solutions led to the selection of heat-resistant AISI 314 steel as the material that has been applied for the manufacturing of all the components of the connection (threaded rod, pressure nut, support ring, stress bolts).

Moreover, additional rings were applied around the flanges of the filters. Their goal was to minimize the possibility of damaging the felt seals during the pulse-jet regeneration or as a result of plant vibrations. The height of the rings was set so that, when the threaded connection is tightened, the surface of the pressure plate is prevented from coming into contact with the rings. On the other hand, to establish the minimum distance between the lower surface of the pressure plate and the upper surface of the sieve bottom, a set of spacer sleeves was designed. Their height was selected according to the thickness of the other components of the system: the flange of the filters, the gasket, and the orifice rings, so that the pressure plate, once it has reached the preset preload, cannot under any circumstances cause excessive compression of the felt seals. The proposed tightening and sealing method also negates the influence of possible deviations in the thickness of the filter flanges or the precision of the machining of different elements.

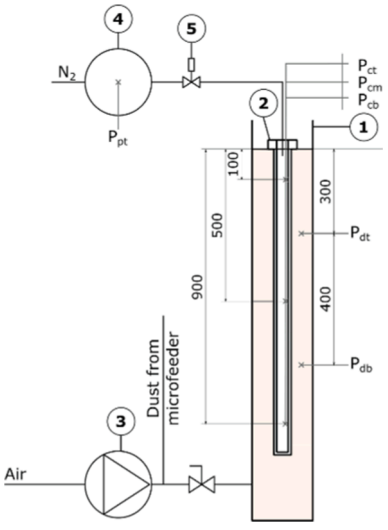


Fig. 6. Scheme of a lab stand designed to test different configurations of the pulse-jet cleaning elements.

4.3.2. Pulse-jet cleaning method – Laboratory experiments

To perform the necessary basic research on pulse-jet systems, a dedicated laboratory stand was built (Fig. 6). The unit consists of a filter housing (1) capable of containing one standard ceramic cartridge with a length of 1000 mm and a diameter of ∅60 mm (2). The housing is made of transparent PMMA The filtered medium is air flowing through the filter element at velocities of 0.5–4 cm/s. The air is supplied by a fan (3) providing a maximum pressure of 20 kPa (Ventur SC20C 150 T). The flow rate is regulated by using a frequency inverter. After passing through the filter, the air goes directly into the atmosphere. A specially designed micro-feeder is responsible for dosing dust into the gas stream. The pulse-jet regeneration system consists of a pressure buffer tank (4) with a volume of 4.5 dm^3 and a maximum permissible pressure of 10 bar-g. The pulse duration is regulated via a pulse solenoid valve (5) with a DN25 size (VNP208 MECAIR 1″). The pressure on the clean side of the cartridge is measured via dedicated impulse tubes, which allow pressure readings to be taken at three heights (designations in the diagram: ct – clean side top point, cm – clean side middle point, and cb – clean side bottom point). The measuring elements are pressure transducers with a sensitivity of <1 Pa and a response time of <1 ms (transducers: Keller PR-23SHB/23–2316-140 °C; data acquisition Advantech USB-4716). In addition, pressure measurement is also conducted on the dirty side of the filter and in the buffer tank. The latter makes it possible, among other things, to estimate the volume of gas used during regeneration or to diagnose and evaluate the operating characteristics of solenoid valves.

The test stand thus enables to conduct not only research on the filtration characteristics of the given filter element but also on the influence of the following pulse-jet parameters:

- regeneration gas pressure,
- opening time of the pulse valve,
- online and offline regeneration modes,
- filtration velocity,
- design of the pulse-jet system (nozzle diameter and height, manifold diameter and length, valve size and characteristic, buffer tank size and connections etc.).

Due to the impossibility of conducting unbiased coupon tests under conditions corresponding to hot producer gas filtration [26], research into the development of a higher efficiency pulsed system concept was carried out on a comparative basis. Hence, a reference system for which slight signs of removal of the cake were visible (D_R_01) was compared here with nozzles, which did show significantly more evident signs of filter cake removal (mainly while using filters F_M_01 and 02).

Fig. 7 presents a graphical representation of the tested layouts of the pulse-jet nozzles (a cross-section through the top of the filter element, the gas manifold and the tested nozzle design (size, position, use of orifice).

4.3.3. Pulse-jet cleaning method – Results of the experiments

The experiments were carried out using a new and not precoated ceramic filter, F_C_01. The following parameters were evaluated:

- three main configurations of the pulse-jet nozzles (Fig. 7),
- the use of flow constraints at the outlet from the candle,
- duration of the pulse (set by the duration of the time the solenoid valve was energized 50–450 ms),
- pressure in the buffer tank (220–830 kPa),
- position of the pulse nozzle in relation to the filter flange (−10–+30 mm),
- position in the filter (−900 to −100 mm).

Results for one exemplary series of tests conducted with the Type B nozzle positioned 30 mm above the edge of the filter cartridge flange are presented in Fig. 8. The charts present the course of pressure variations inside the filter element for a variable pulse valve opening time of

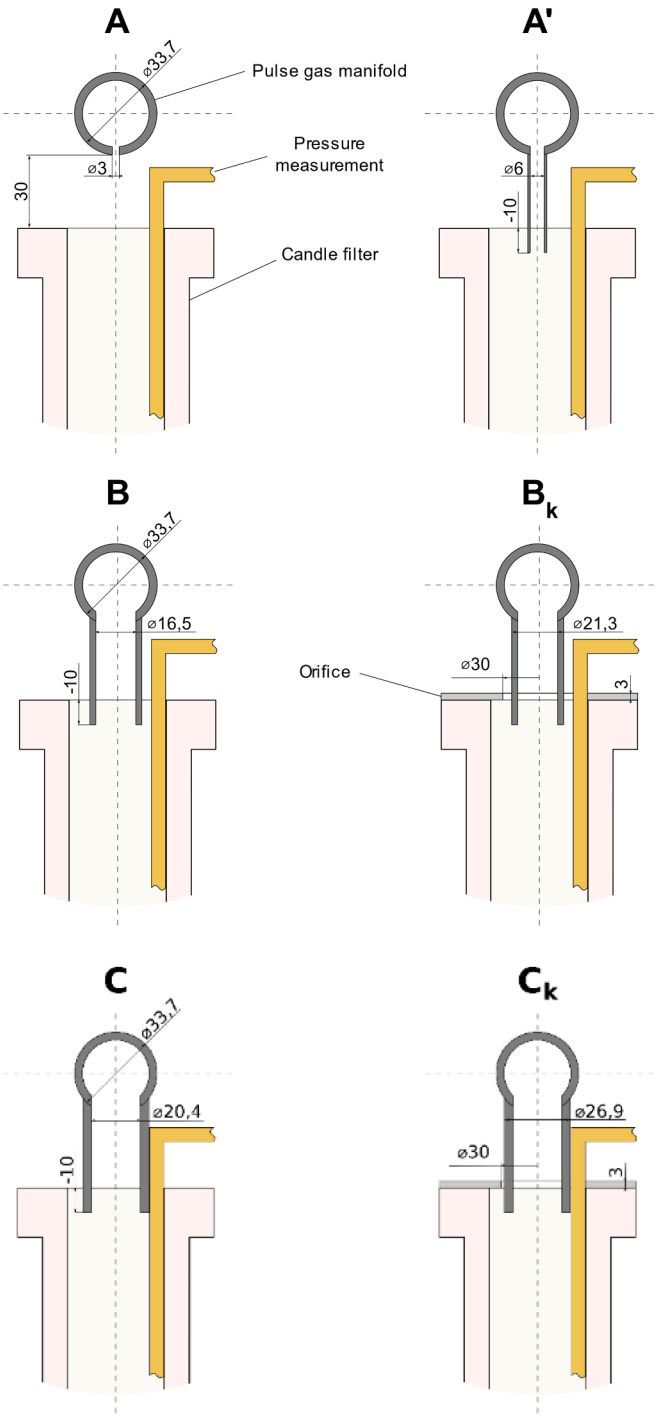


Fig. 7. Schematic representation of the tested pulse-jet nozzles.

50–450 ms at a fixed pressure of 630 kPa (1), for a variable pressure in the buffer tank at a fixed purge time of 250 ms (2), and a summary of pressure change measurements at three points in the filter element for a fixed time and regeneration pressure (3). The last chart 4 illustrates the impact of the buffer tank pressure and nozzle design on the delay in closing the pulse valve.

It can be seen that as the pressure in the buffer tank increased, the maximum and average pressures during regeneration also increased, however, the duration of regeneration remained very similar. Some reasoning for this can be found in analysing chart 4 which indicates that some of the combinations of pulse nozzles, pressures in the buffer tank and pulse times have resulted in the almost complete emptying of the

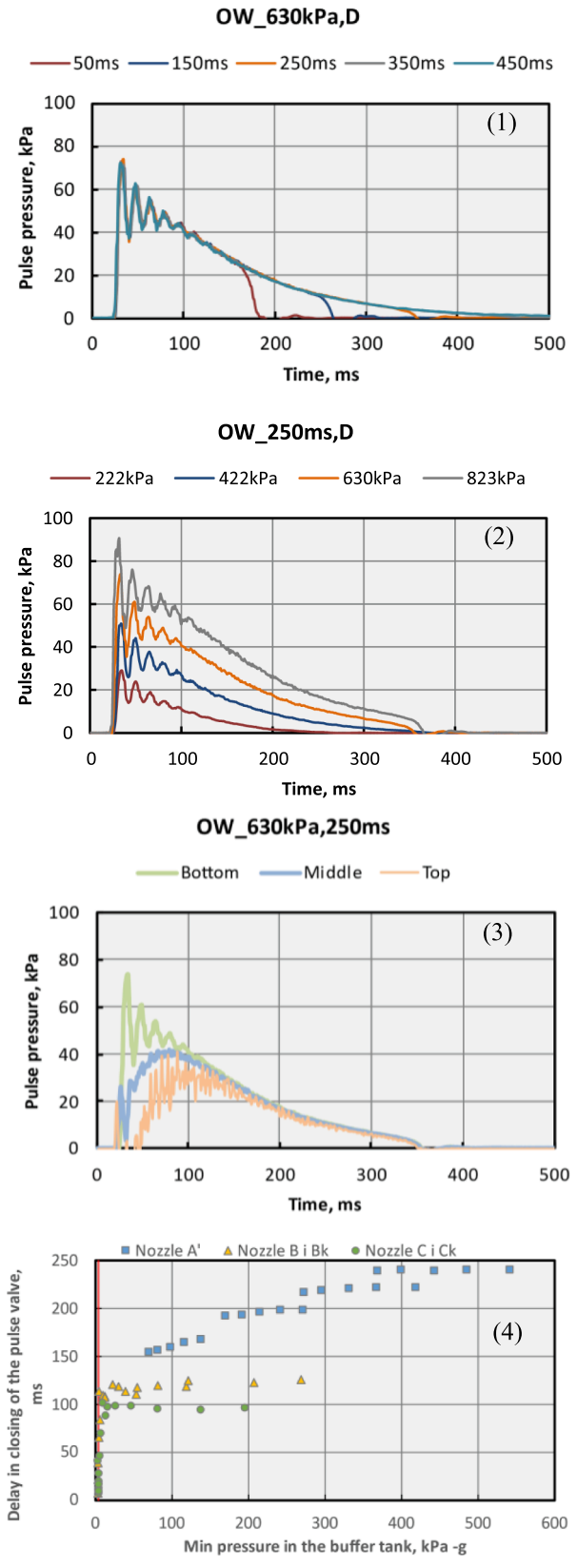


Fig. 8. Exemplary results presenting pressure readings registered using the lab stand for testing different designs of pulse-jet cleaning.

buffer tank. The maximum pressure peak during regeneration was observed in the first moment of the propagation of the gas pulse wave. The study also found that both the maximum and average pressure values during regeneration increased with the depth of the filter element, which coincides with empirical observations of increasing regeneration efficiency. A similar effect was expected as a result of an increase in the duration of pulse valve opening, but this phenomenon was not confirmed. In diagram 2, it can also be observed that between the lower and upper measuring points, the total pulse duration changes only slightly (interval 10–30 ms). For all tested configurations, the decrease in the duration of the overpressure occurred according to the following relation: bottom part (closed end of the candle) > middle part (gas flowing both from the top and from bounced pressure wave) > top part of the filter (open to the clean side of the filter, closest to the outlet of the nozzle). The reason for this observation is that as the front of the pressure wave travels through the filter for a short duration of the pulse, a vacuum builds up in the upper part of the filter. This also confirms the theory saying that gas from the clean side of the filter participates in the regeneration process (due to the Venturi effect). The combination of these phenomena is also the reason for the lower cleaning efficiency of the upper part of the filter elements. Analogously, analyses were conducted for each of the measurement series separately as well as for their collations.

To assess the efficiency of the studied nozzle designs, various parameters related to the duration of the regeneration process were analysed. The regeneration duration was defined here as the time between the first and last moment when pressure at the clean side of the element (Pc) > 1 kPa was recorded. The literature contains information indicating that for effective regeneration of the rigid filters, it is necessary to achieve a pressure difference between its clean and dirty sides exceeding at least 10–20 kPa. Therefore, it is also possible to determine a parameter for assessing the duration of an effective pressure pulse, i.e. one whose value theoretically exceeds the shear strength of the filter cake. Therefore, the time of occurrence of pressure Pc > 10 kPa was also one of the analysed parameters. A similar assessment parameter was the time of occurrence of pressure exceeding 80 % of the maximum pulse pressure (Pc > 80 % Pmax).

An analysis of the duration of pressure P > 80 % Pmax indicates that this parameter is distinctive to the nozzle design and the use of the orifice.

With increasing pulse valve opening time, an increase in the total regeneration time was observed, with no effect on the increase in the time at which P > 10 kPa or > 80 % of Pmax would be maintained. This undesirable effect is observed by lengthening the 'tail' of the pulse. Chart 4 presented in Fig. 8 unravels the causes of this phenomenon.

The collected data indicate a significant influence of the tank pressure and nozzle type on the valve closing delay time. It was found that as the nozzle size increased similarly did the valve opening time, and the impulse valve's closing delay time also decreased. On the other hand, an increase in pressure in the buffer tank had the opposite effect. The reason for this observation was probably the operating characteristics of the mechanism responsible for returning the valve to its resting position.

Collation of the data presented above stems down to the notion of efficient utilization of the regeneration gas as with larger and longer manifolds, more filters pulsed at a time, and smaller size of the buffer tank the effective time and pressure of the pulse acting on the filters drop drastically. In the laboratory setup, such an effective use was observed over the full range of tested pulse gas pressures only for an opening time of 50 ms, while for a time of 150 ms the buffer tank was large enough only when keeping the buffer tank pressures at 400–800 kPa. Similarly, when the pulse duration was extended to 250 ms the initial pressure in the buffer tank needed to be kept at 800 kPa. Furthermore, the effective performance of nozzles C and Ck was possible only for pulse durations of 50–150 ms and while keeping the buffer tank pressures at 400–800 kPa.

Moreover, an orifice with a central opening of a size of Ø30 mm was used during this research. The reason for this choice was to try maximize

the overpressure induced by the regeneration gas pulse, while minimizing the pressure drop during filtration.

Collected results allowed for performing a statistical study of the influence of the above-mentioned parameters on i.a. regeneration time, as well as the average and maximum pressure during regeneration. The results of this analysis are presented in Fig. 9.

The analysis was conducted based on the change-impact relation. The studied parameters were normalized against their baseline values and converted to standardized maximums and minimums. Thus, the ratio of the mean value at a given point to the mean value at the baseline was determined for each of the test points. The lowest pressure in the buffer tank, the smallest nozzle size – internal diameter, or the furthest nozzle offset from the flange of the filter – were taken as the baseline values. From the thus obtained results, minimum and maximum values were then determined, against which normalization was performed. A rule was adopted, where the highest value of change took the value of 10 on the abscissa axis, while the highest and lowest influence values took the values +5 and −5 respectively on the ordinate axis. In this way, a quadratic arrangement with the starting point (minimum/beginning point) at the origin of the coordinate system was obtained. Non-numerical variables, e.g. orifice application, were converted by adopting the value of the logistic test not applied/applied, which respectively took values 0 or 10.

The following relationships were found for the above:

– regarding the regeneration time (□):
  (a) increasing the size of the nozzle reduces its value in the most significant way,
  (b) the introduction of a nozzle into the filter is the second most effective way of lowering the regeneration time, but the effect of this action is small,
  (c) it increases slightly with the position in the filter (depth) or as a result of using an orifice plate.
  (d) of the tested parameters, the increase in the pulse valve opening time and the increase in pressure in the buffer tank have the strongest effect on the increase of regeneration time.

– -regarding the mean pressure during regeneration (△):
  (a) the increase in pressure in the buffer tank has the most significant effect on the increase in mean pressure during regeneration,
  (b) the second most substantial increase is caused by the increase in nozzle size,
  (c) increases linearly with the depth inside the filter,
  (d) bringing the outlet of the nozzle closer to the filter reduces the mean pressure during regeneration,
  (e) the effect of using an orifice on the mean pressure value is statistically insignificant,
  (f) the mean pressure value during regeneration decreases most strongly with increasing pulse valve opening time.

– regarding the maximum pressure during regeneration (○):
  (a) the increase in pressure in the buffer tank and the increase in nozzle size cause the strongest increase in the maximum pressure value during regeneration,
  (b) this parameter assumes a maximum value for the bottom of a filter and does not change linearly with its height,
  (c) the opening time of the impulse valve does not significantly affect the change in maximum pressure during regeneration,
  (d) bringing the outlet of the nozzle closer to the filter flange and the use of an orifice decrease the maximum pressure during regeneration.

This research led to a conclusion that for the case of this hot gas filtration method, the optimum design of the pulse-jet nozzle should be based on the type Ck – a nozzle with an outer diameter of ∅26.9 mm and using an orifice having ID = ∅30 mm.

4.4. Development of the 2nd generation of a hot gas filter

Based on the gained experience, a new construction of a hot gas filter was proposed (see Fig. 10). The device was designed to work in similar process conditions: <650 °C, <30 kPa total overpressure, 2–3 cm/s filtration velocity, 10 filter elements located in two sections, pulse-jet cleaning). Importantly, several technical and technological changes

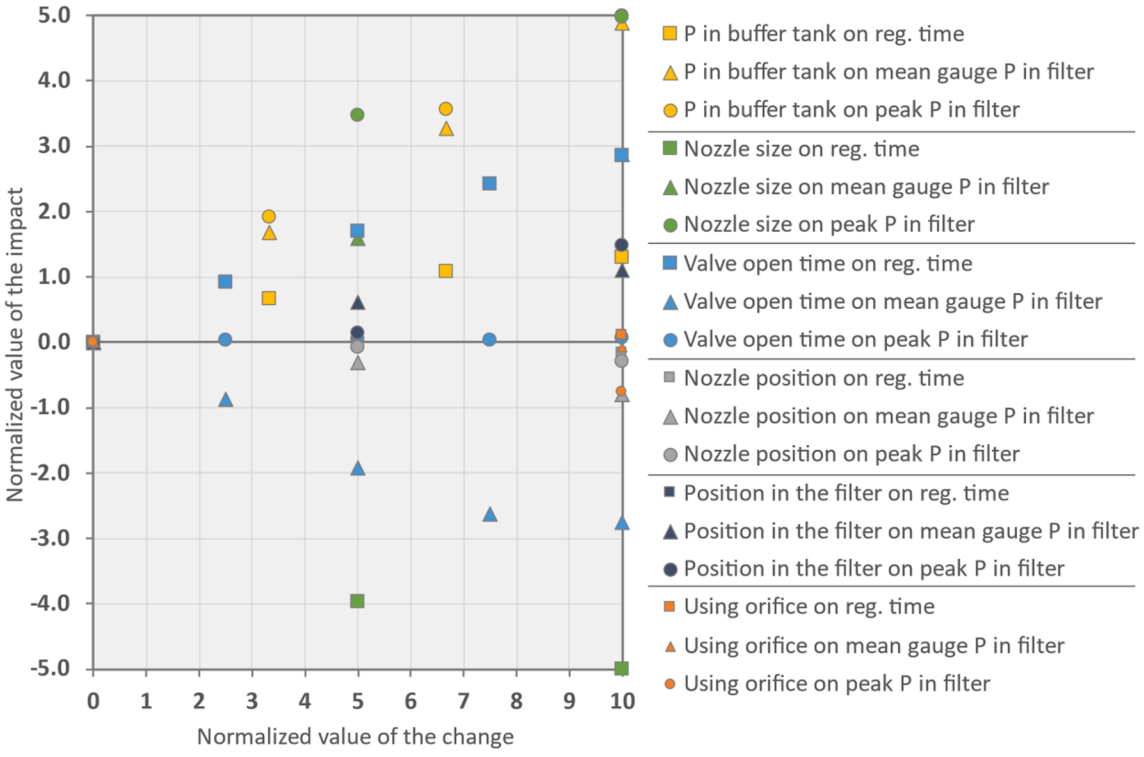


Fig. 9. Presentation of the normalized change-impact relationships of the tested variables of the pulse-jet cleaning system.

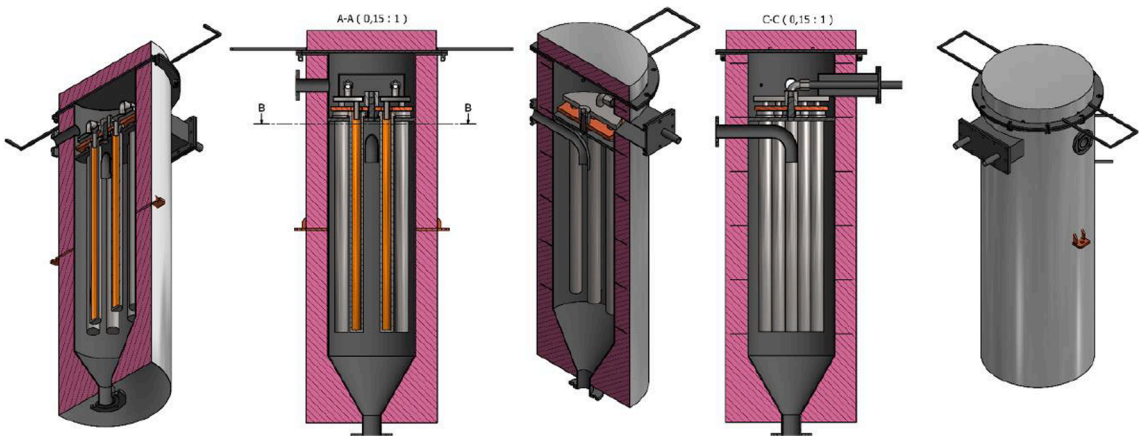


Fig. 10. 3D CAD model of the 2nd generation hot gas filtered designed and implemented by ITPE.

were proposed. Some of them were described in the above sections, nonetheless, also the following changes were introduced:

- relocation of the gas inlet close to the sieve plate, and directing the stream of filtered gas vertically downwards in the axis of the device,
- changing the pitch of the filters to 110 mm,
- implementing a lock hopper system for continuous removal of the cake and a mechanical stirrer to counteract its tendency for arching and blocking in the conical bottom,
- relocating the screws fixing the top cover of the filter to a position having a lower temperature (<200 °C),
- introducing a method for feeding pre-coats and filtering aids.

4.4.1. *Pre-coats and filtration aids*

One of the most common pre-coating materials is mineral chalk. As it finds major applications also in agriculture and breeding, hence it is commercially available in fine powder form (<20 μm). To determine the potential of using other minerals as well as to test whether their chemical compositions can play a role not only in stabilizing the operation of the filter but also in cleaning the producer gas (e.g. from tars), also dolomite, halloysite, and kaolinite were tested. The four minerals were thus selected as representatives of compounds rich in Ca, Ca/Mg, Si/Al/Fe, and Si/Al respectively. Before using as precoat materials, the minerals were milled (d(50) < 60 μm) and roasted (800 °C, 6 h). To determine the chemical composition of the additives a fluorescence spectroscopy method with wavelength dispersion was used – ARL OPTIM'X spectrometer from Thermo Fisher Scientific with a 200 W Rh X-ray tube and a Be gap of 75 μm. Samples for the test were prepared by roasting at 815 °C and then compressed into a tablet with the addition of 20 % wax. The results were converted from the oxide forms and compared with the chemical analysis of the cake produced in the filter during the T_05 test (char). The results are presented in Table 5.

The following precoating procedure was applied on new filter candles as well as before changing the type of mineral used: inert gas at 50 % of the nominal stream of producer gas, feeding of approx. 100–200 g/h of pre-coat. no pulse-jet cleaning during precoating, pre-coating finished when approx. 1000 g of the mineral was fed (this refers to ca. 1 mm of pre-coat cake layer on the surface of the filters).

4.4.2. *Experimental validation of the filter design*

By using the same type of gasifier as well as running it using a similar feedstock and operating conditions, the real influence of herein proposed technical and technological solutions could be followed. The experimental data collected during testing of the 2nd generation hot gas filter are presented in Table 6. For three out of four tested additives, stabilization of the filtration process was confirmed. Only for T_14, when dolomite was used, the filtration process became unstable in just a few hours. At the same time, T_11-T_13 showed a stable filtration pattern, even though the filter F_C_01 was used (inherently prone to depth filtration). The new design of the pulse jet cleaning system not only introduced efficient regeneration of the filter elements but also allowed for a decrease of the pressure in the buffer tank to 4–8 bar, the duration of the pulses to on average. 250 ms and to keep the mean pressure drop during filtration <1 kPa. During the tests, the temperature of filtration was kept at a constant level of 430 °C, standing as the optimum level determined using TGA/DSC/DIL. As it was indicated previously, due to the constraint of the gasifier, larger streams of the filtered gas could not the tested.

The results of the filter resistance measurements carried out during the T_11-T_14 tests are also presented in Fig. 11. For better comparability with other filtration experiments (gasifiers, feedstocks, filters, process conditions), the experimental data were converted to a flow resistance coefficient using Eq. (1).

Table 5
Characteristics of the pre-coats and filtration aids.

		Chalk	Dolomite	Halloysite	Kaolinite	Char
Ca	% (m/m)	36.21	19.41	0.49	0.13	0.97
Si	% (m/m)	1.30	1.30	16.68	30.65	0.42
Al	% (m/m)	0.45	0.85	13.64	14.70	0.09
Fe	% (m/m)	0.34	1.04	14.95	0.82	0.08
Mg	% (m/m)	0.21	10.73	0.35	0.08	0.16
K	% (m/m)					1.78
P	% (m/m)					0.32
Na	% (m/m)					0.40
C	% (m/m)			n.d.		86.29
H	% (m/m)					2.00
N	% (m/m)					0.50
Cl	% (m/m)					1.37
S	% (m/m)					0.22
Remaining with O	% (m/m)	61.33	53.52	53.27	66.16	5.40

Table 6
Results of the experimental validation of the 2nd generation hot gas filter.

	T_11	T_12	T_13	T_14
Type of filter element	F_C_01	F_C_01	F_C_01	F_C_01
Condition of the element	FU	After T_11	After T_12	After T_13
Type of the pulse-jet nozzle	C_k	C_k	C_k	C_k
Pressure in the pulsing system – PPS [bar-g]	6	6	6	6–8
Duration of the pulse– tP [s]	0.25	0.25	0.25	0.2–0.3
Type of the additive	Chalk	Halloysite	Kaolinite	Dolomite
Share of the additive in the filter cake [%m]	71	80	78	53
Gasifier temp. – top, TGT [°C]	425.79 (80.05)	383.24 (34.15)	358.5 (33.89)	309.72 (24.47)
Gasifier temp. – middle, TGM [°C]	555.69 (59.49)	628.46 (28.51)	578.07 (43.91)	508.78 (51.58)
Gasifier temp. – bottom, TGB [°C]	938.83 (37.22)	929.95 (61.37)	951.92 (51.24)	966.06 (24.89)
Gasifier temp. – gas outlet, TGPG [°C]	548.33 (35.70)	544.54 (10.25)	520.07 (8.34)	499.8 (13.72)
Temp. inside filter– TF [°C]	428.92 (17.33)	423.95 (8.94)	422.76 (8.06)	418.11 (9.93)
Producer gas flow rate – V GP.R [m^3/h]**	99.99 (13.9)	85.02 (14.93)	89.95 (2.93)	88.9 (9.02)
Dust load[1] entering the filter – g/Nm^3	30.7 (11.33)	8.5 (11.33)	10.8 (11.33)	5.9 (11.33)
Filtration velocity – vF [cm/s]**	1.47 (0.20)	1.25 (0.22)	1.33 (0.04)	1.31 (0.13)
Pressure drop on the filter - dP [kPa]	0.70 (0.22)	0.74 (0.19)	0.84 (0.16)	1.26 (0.45)

[1] As a sum of char and mineral additives.

$$\boldsymbol{R} = \frac{\Delta \boldsymbol{P}}{\boldsymbol{\mu U}} \ [1/\mathrm{m}] \quad (1)$$

where ΔP – pressure drop on the filter [Pa], μ – dynamic viscosity [Pa·s], U – filtration velocity [m/s].

This way of presenting the results allows one also to relate herein gathered experimental data to other, well-documented reference values – e.g. characterizing dust filtered in other processes like combustion and gasification of coal.

The presented results directly illustrate the beneficial effect of the process changes introduced in the filter and the stabilizing effect of the use of chalk, halloysite, and kaolinite. Compared to T_07, the reduction in filter resistance averaged 33–48 %, while compared to T_03 the reduction in filter resistance reached 79–84 %. The measured >2× higher filter cake resistance factor for the dolomite test indicates the ineffectiveness of using this mineral as a stabilizing additive.

From the above data, it can also be concluded that the use of chalk and halloysite can preferentially allow for increasing the gas load on the filter or allow the device to operate at lower pressure drops.

4.4.3. Effect of using mineral additives on the concentration of gravimetric tars in producer gas

The hot gas filtration tests carried out with additives did not indicate the that application of these additives to a filter operating at 420–430 °C can translate into an increase in the efficiency of tar removal from the gas. Comparison of the measured removal efficiencies of the tests when the additives were used (T_11-T_14) to the T_07 during which no additives were introduced to the filter (Fig. 12) shows that the removal efficiency of gravimetric tar was similar for chalk and T_07 while for other additives it remains on a much lower level (ca. 10–17 pp.). Concluding, this observation is attributed to the impact of the condensation of gravimetric tars on the surface of the filter cake.

5. Conclusions

The design and process changes made to the filter allowed the filtration process to be stabilized and the unit to operate at a very low pressure drop of <1 kPa.

All presented above experimental validation tests were conducted using a single set of ceramic filters that did not demand any mechanical cleaning in between the tests. Two of the filters are presented in Fig. 13. Before introducing the herein-described technical and technological modification, the use of the ceramic, single-layer, homogenous ceramic filters, for filtration of the gas produced in the GazEla reactor by gasification of biomass was always associated with blinding of the filter pores. The solutions adopted in the 2nd gen filter, in particular in the fields of mounting and seals of the filter candles as well as removal of the filter cake or counteracting the bridging, increased the overall reliability of the device as well as stability of the process. During the experimental runs, the optimum stability of filtration was achieved for tests T_11-T_13. This proves that the developed pulse-jet system is efficient. Moreover, keeping the operational pressure drop at a mean level <1 kPa indicates that the layer of the filter cake residing on the filter elements can be greatly minimized without compromising the longevity of the filter elements. Importantly, the above was achieved using a

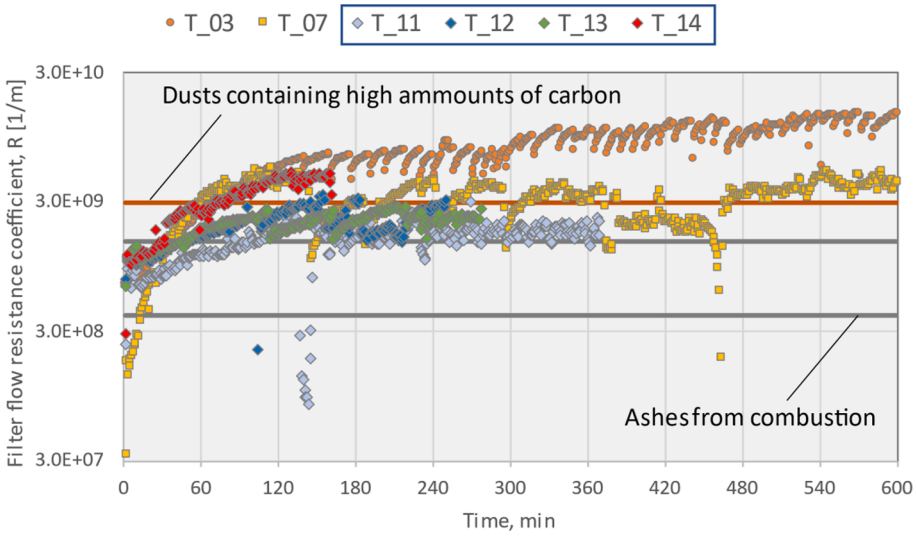


Fig. 11. Chart presenting the filter flow resistance coefficient calculated for two pseudo-stable filtration tests performed using the 1st gen. hot gas filter as well for the tests performed using the 2nd gen. unit.

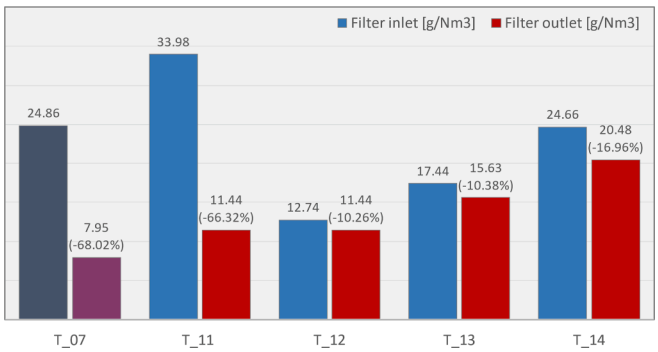


Fig. 12. Concentration of gravimetric tars in raw producer gas and after passing the hot gas filter.

Fig. 13. Picture of ceramic filters F_C_01 after 1.5 years of testing in the 2nd gen. filter.

conservative intensity of the pulse-jet regeneration (250 ms, 4–6 bar).

Given the additives dosed to the process, their constant feeding to the stream of producer gas introduces an effect of "dilution" of the char, and in this way leads to a reduction in the cohesiveness of the filter cake produced. The tests showed unquestionably favourable characteristics of using chalk or halloysite. At the same time, kaolinite allowed the stabilization of the filtration process only to a limited extent, while the introduction of dolomite into the filter translated into a complete loss of control over the process.

This development process was the ground for understanding efficient strategies, enabling one to counteract the so often described in literature problems in the stability of filtration systems operating on hot producer gas from gasification of biomass. Similar to the decarbonization problem, no golden rule or one solution fits all can be given based on the experience gained during this research. When tackling operational issues of hot gas filters, undoubtedly, the following issues need to be adequately analysed:

(1) Determine the main source of possible liquids or highly cohesive solids, which in gasification processes mostly derive from organic or mineral matter contaminants.
(2) Maximize the efficiency of the pulse-jet cleaning system used, without further destabilizing the process i.a. leaving a too-thin layer of the residual filter cake leading to depth filtration or locally cooling the gas to a level where the organic contaminants start to condense. Using orifices or other devices serving the purpose of creating a higher, longer-lasting overpressure within the filters helps to homogenize the efficiency of cake removal throughout the height of the filter candle, however at the cost of longer durations of the regeneration cycles and lower peak pressures.
(3) Optimize the filtration process parameters. Decrease the filtration velocity, and dust load introduced to the filter. Keep pressure drop low by consistent, and often pulse-jet cleaning controlled through both a set dP and a maximum time interval between the following pulsing. Regenerate sections located far away from the ones previously cleaned.
(4) Give adequate attention to all auxiliary aspects of the technology: a method for start-up and shut-downs, keeping the filter in a precise operating window, distribution of the filtered gas, and a method for keeping the bottom hopper free of the residual filter cake.
(5) While tackling possible challenges stemming from the content of low melting temperature salts, take into account the kinetics of solidification of the solids.
(6) Apply a precoat to all new filter elements. However, using the additives as co-filtration aids should be done as a last resort as it increases the load of solids filtered, the amount of generated solid wastes that need to be managed, and introduces additional operational cost.

6. Prospects for future work

- Coupling CFB adsorbers with a hot gas filter.
- Demonstrate the potential for using the filter at temp. $>$ 600 °C.
- Demonstrating the possibility of stable filtration under higher loads of gas and solids.

7. Notes

(1) eg. 3 M™ FB900 CG22.

8. Declaration of generative ai and ai-assisted technologies in the writing process

During the preparation of this work authors used ChatGPT in order to perform linguistic correction of the text. After using this tool/service, authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Mateusz Szul: Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jarosław Zuwała:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Tomasz Iluk:** Writing – review & editing, Project administration, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The results presented in this paper were obtained during the research project *Improvement of biomass and waste gasification technology in fixed and fluidized bed reactors (GazEla, IZPS, IZOP)* founded during the years 2014-2019 by Polish Ministry of Science and Higher Education.

The results presented in this paper were obtained during the research project *DevelOpment of a systeMic approach for recovery of Energy from*

sewage sludGe by means of gAsification process – OMEGA. financed by the Polish National Centre for Research and Development.

References

[1] S. Heidenreich, Hot gas filtration – a review, Fuel 104 (2013) 83–94, https://doi.org/10.1016/j.fuel.2012.07.059.

[2] P. Simell, E. Kurkela, P. Ståhlberg, J. Hepola, Catalytic hot gas cleaning of gasification gas, Catal. Today 27 (1996) 55–62, https://doi.org/10.1016/0920-5861(95)00172-7.

[3] A. Sauciuc, Z. Abosteif, G. Weber, A. Potetz, R. Rauch, H. Hofbauer, G. Schaub, L. Dumitrescu, Influence of operating conditions on the performance of biomass-based fischer-tropsch synthesis, Biomass Convers. Bioref. 2 (2012) 253–263, https://doi.org/10.1007/s13399-012-0060-4.

[4] R.A. Newby, R.B. Slimane, F.S. Lau, S.C. Jain, Development of the Ultra-Clean Dry Cleanup Process for Coal-Based Syngases. https://digital.library.unt.edu/ark:/67531/metadc781119/ (Accessed on 24 November 2020).

[5] C.-J. Tsai, A pilot-scale study of the design and operation parameters of a pulse-jet baghouse, Aerosol Sci. Technol. 16 (1998).

[6] M. Hata, C. Kanaoka, M. Furuuchi, T. Inagaki, Analysis of pulse-jet cleaning of dust cake from ceramic filter element, in: Proceedings of the 5th International Symposium on Gas Cleaning at High Temperatures, Morgantown, WV (US), 09/17/2002–09/20/2002, Kanazawa Daigaku, September 19 2002.

[7] W. Duo, J.R. Grace, C.J. Lim, C.M.H. Brereton, A.P. Watkinson, K. Laursen, The role of the filter cake in hot gas cleaning with ceramic filters, Ind. Eng. Chem. Res. 38 (1999) 260–269, https://doi.org/10.1021/ie980300d.

[8] D.H. Smith, U. Grimm, G.J. Haddad, Measurements of Filter-Cake Properties, 1996.

[9] G. Hemmer, D. Hoff, G. Kasper, Thermo-analysis of fly ash and other particulate materials for predicting stable filtration of hot gases, Adv. Powder Technol. 14 (2003) 631–655, https://doi.org/10.1163/15685520360731954.

[10] S. Berbner, T. Pilz, Characterization of the filtration and regeneration behaviour of rigid ceramic barrier filters at high temperatures, Powder Technol. 86 (1996) 103–111, https://doi.org/10.1016/0032-5910(95)03043-3.

[11] A. Villot, Y. Gonthier, E. Gonze, A. Bernis, S. Ravel, M. Grateau, J. Guillaudeau, Separation of particles from syngas at high-temperatures with an electrostatic precipitator, Sep. Purif. Technol. 92 (2012) 181–190, https://doi.org/10.1016/j.seppur.2011.04.028.

[12] Handbook of Petrochemicals Production Processes; Meyers, R.A., Ed.; McGraw-Hill handbooks; McGraw-Hill: New York, 2005; ISBN 978-0-07-141042-7.

[13] Perry's Chemical Engineers' Handbook; Perry, R.H., Green, D.W., Eds.; 8th ed.; McGraw-Hill: New York, 2008; ISBN 978-0-07-142294-9.

[14] EPA Air Pollution Control Cost Manual, sixth ed., 2002.

[15] Air Pollution Control Engineering, in: L.K. Wang, N.C. Pereira, Y.-T. Hung (Eds.), Handbook of environmental engineering; Humana Press: Totowa, N.J., 2004. ISBN 978-1-58829-161-5.

[16] Tar Measurement Protocol, http://www.tarweb.net/ (Accessed on 10 December 2022).

[17] Thersites: Classification System. https://www.thersites.nl/classification.aspx (Accessed on 17 March 2022).

[18] C. Kanaoka, M. Hata, H. Makino, Measurement of adhesive force of coal flyash particles at high temperatures and different gas compositions, Powder Technol. 118 (2001) 107–112, https://doi.org/10.1016/S0032-5910(01)00300-X.

[19] S. Heidenreich, W. Haag, A. Walch, B. Scheibner, R. Mai, H. Leibold, H. Seifert, Ceramic Hot Gas Filter with Integrated Failsafe System, September 18 2002.

[20] M. Kochel, M. Szul, T. Iluk, J. Najser, On the possibility of cleaning producer gas laden with large quantities of tars through using a simple fixed-bed activated carbon adsorption process, Energies 15 (2022) 7433, https://doi.org/10.3390/en15197433.

[21] A. Skorek-Osikowska, T. Bartela, J. Kotowicz, A. Sobolewski, T. Iluk, L. Remiorz, The influence of the size of the CHP (combined heat and power) system integrated with a biomass fueled gas generator and piston engine on the thermodynamic and economic effectiveness of electricity and heat generation, Energy 67 (2014) 328–340, https://doi.org/10.1016/j.energy.2014.01.015.

[22] A. Sobolewski, M. Szul, T. Iluk, W. Ostrowski, T. Billig, Cleaning of process gas from gasification of solid recovered fluid — results of experimental research, Trans. Inst. Fluid-Flow Mach. nr 137 (2017).

[23] J.P. Hurley, B.A. Dockter, Factors affecting the tensile strength of hot-gas filter dust cakes, Adv. Powder Technol. 14 (2003) 695–705, https://doi.org/10.1163/15685520360731981.

[24] H.O. Kono, B. Jordan, T. Ohtake, D.H. Smith, Formation and measurement of the porosities, tensile strengths, and deformation coefficients of gasification filter cakes at operating temperatures and pressures, Aerosol Sci. Technol. 29 (1998) 236–245, https://doi.org/10.1080/02786829808965566.

[25] N. Döring, J. Meyer, G. Kasper, The influence of cake residence time on the stable operation of a high-temperature gas filter, Chem. Eng. Sci. 64 (2009) 2483–2490, https://doi.org/10.1016/j.ces.2009.02.018.

[26] D. Koch, K. Schulz, J.P.K. Seville, R. Clift, Regeneration of rigid ceramic filters, in: R. Clift, J.P.K. Seville (Eds.), Gas Cleaning at High Temperatures, Springer, Netherlands, Dordrecht, 1993, pp. 244–265.