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A model for filter diagnostics in a syngas-fed CHP plant

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Abstract

Biomass gasification is an important opportunity for power generation and combined heat and power (CHP), as it allows for biomass use in high efficiency, low emissions energy systems, e.g., internal combustion engines. Biomass-based CHP is particularly interesting for the service sector, as it allows to use a programmable renewable energy source to produce both electricity and heat, unlike photovoltaic systems which are typically used in this sector. Yet, small-scale gasification and CHP systems have a poor diffusion, due to a lack of acknowledged reliability. To improve reliability and performance, accurate simulation models may be useful, in particular for system control and diagnosis. For this purpose, the project SYNBIOSE proposes the installation, testing and simulation of a commercial-grade system for the gasification of lignocellulosic woodchips and pellets coupled to CHP in the campus of the University of Parma. One of the project deliverables is a simulation model of the whole gasification and CHP plant, for system diagnosis. The model has a modular structure (to allow for improvements and applications) and is implemented in MATLAB®/Simulink®. The present work focuses on syngas filters, which are among the most critical components. The outcome is a model able to predict the operation of filters taking into account inlet gas characteristics and fouling. Model analysis, sensitivity analysis and validation showed that simulation outputs are consistent with the physical behavior and experimental data. The model proved to be useful for system and components simulation and diagnosis.

Keywords: Biomass; gasification; CHP; syngas; filter; diagnostics; simulation.

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Nomenclature

0	0-junction
1	1-junction
A	Surface area [m^2]
C	Capacity element
C	Concentration [g m^{-3}] or heat capacity [J K^{-1}]
D	Diameter [m]
G	Mass flow rate [kg s^{-1}]
H	Height [m]
K	Resistance of porous medium [m^{-2}]
L	Thickness [m]
N	Number [-]
Q	Heat flow [W]
R	Resistance element
R	Specific gas constant [J kg^{-1} K^{-1}]
Se	Effort source
Sf	Flow sink
T	Temperature [K]
TF	Transformer element
U	Filtration velocity [m s^{-1}]
V	Volume [m^3]
c	Specific heat [J kg^{-1} K^{-1}]
h	Convection coefficient [W m^2 K^{-1}]
p	Pressure [Pa]
t	Time [s]
Δ	Difference or variation
α	Specific resistance, divided by mass [m kg^{-1}]
ε	Porosity [-]
μ	Viscosity [Pa s]
ρ	Density [kg m^{-3}]
τ	Engine torque [Nm]
ω	Engine speed [s^{-1}]

Subscripts

0	Initial value or clean ceramic candle
TOT	Total
atm	Atmospheric
cc	Ceramic candle
dc	Dust cake
g	Gas
i	Internal
in	Incoming
o	External
out	Outgoing
p	Particulate matter or isobaric
pl	Filter plenum
v	Isochoric
w	Filter casing walls

Acronyms

CHP	Combined heat and power
ICE	Internal combustion engine

1. Introduction

Biomass energy can be regarded as carbon-neutral and – due to the actual greenhouse gases effects on climate changes – biomass energy conversion technologies are among key technologies for a sustainable power system. At present, the biomasses used for electricity generation are mainly wooden biomasses in steam power plants and fermentable biomass in biogas-fed internal combustion engines (ICEs). Within this scenario, the size of these type of plants prevents their implementation in an urban environment and the related heat recovery. Concerning small-size systems, lignocellulosic biomass combustion coupled with organic Rankine cycle plants, microturbines or Stirling engines has been proposed, but they usually suffer from a low overall efficiency (below 20 %).

A possible solution is the implementation of ICEs fueled by syngas from gasification of lignocellulosic biomass in distributed generation systems. Distributed generation-size ICEs benefit from sufficiently high efficiency values, well-established emission control techniques and the compatibility with combined heat and power generation (CHP). These systems can be particularly useful in the service sector, since they produce both electricity and heat, allowing for the exploitation of a programmable renewable energy source. In addition, suitable solid biomasses are locally available in several areas.

On the other hand, the commercial take-up is significantly hindered by the lack of experimental knowledge on the technology and performance/maintenance issues in the syngas cleaning line. In the present Italian context, there are no small-size syngas-fed CHP plants with a sufficient operational history to represent an adequate knowledge on the reliability of this technology. Operating plants associated with monitoring and theoretical simulation activities can be very useful to improve the reliability and to promote this technology.

Examples of existing studies on plant simulation are focused on the chemical model of the gasification process in Aspen Plus® [1, 2], on the model of the overall plant in Cycle Tempo®, MATLAB®/Simulink® or ISPEpro® [3-5], or on thermo-economic optimization in Dynamic Network Analysis [6, 7].

To the best of the authors' knowledge, diagnostic-oriented models are required to support research and to improve plant management and reliability. To provide useful information for plants integration, control and diagnostics, these models should be built up following a modular approach based on components sub-models.

In this context, project SYNBIOSE has been started with the aim to develop basic knowledge and to highlight operation and management best practices, in order to promote small-scale gasification and CHP for the tertiary sector. The project proposes the installation, testing and simulation of a commercial-grade system for the gasification of lignocellulosic woodchips and pellets coupled to CHP, in the campus of the University Parma. An image of the gasification and CHP sections is reported in Fig. 1a. The project involves the company Siram S.p.A, the Center for Energy and Environment of the University of Parma, and the Department of Engineering of the University of Ferrara.

One of the goals of the project is the set-up of a simulation model of the whole gasification and CHP plant for system diagnostics purposes. The model is arranged in a modular structure, to facilitate improvements and application to different cases, and has been implemented in MATLAB®/Simulink®. The porting into a free and open source environment (e.g., Scilab©) is envisioned.

Filters are among the most important components for the considered plants, since they are essential in the syngas cleaning line and also in several other sub-systems. In existing studies, filters have been simulated, e.g., through dedicated blocks in Aspen Plus® [2] or Cycle-Tempo® [3], or completely neglected [4]. To simulate any component of the plant, mass and energy conservation equations must be taken into account to describe time evolution of operating parameters. Fouling must also be considered, especially in the case of filters and for diagnostic purposes. Pressure drop through filters due to the filtering material resistance and to fouling has been investigated [8, 9]. The heat exchange between a fluid and a porous medium has been a long studied issue [10, 11].

The aim of this work is to propose a simulation model for filter diagnostics, by combining the approaches separately used in literature. The filter of the SYNBIOSE plant (shown in Fig. 1b) consists of a plenum wherein an arrangement of ceramic candles is suspended. Syngas is introduced in the plenum, filtered through the candles porous medium and extracted via a manifold installed on top. In the model, pressure drop (resistance) and gas accumulation (capacity) are considered. Also, heat exchange with the environment and energy accumulation in the materials are considered. This model, together with the models of other components, will be used in the simulation model of the plant.

2. Materials and methods

2.1. Plant model

In the first place, the causality of the overall model has been defined, in order to identify inputs and outputs of each sub-model and ensure the modularity of the comprehensive model.

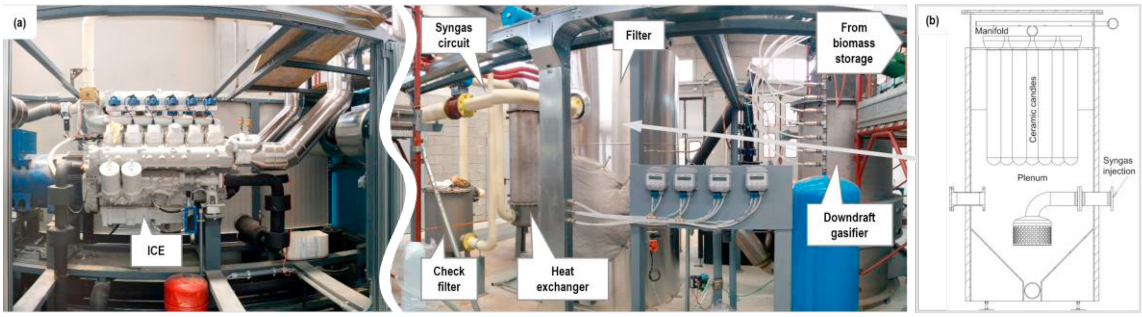

Fig. 1. (a) Image of the gasification and CHP sections of the SYNBIOSE power plant; (b) schematic of the filter

Following the defined causality, components are being modeled sequentially. The model is diagnostics-oriented, i.e., the outputs must match with measurable quantities and provide information on plant operation.

To establish the causality, the bond graph method has been used [12]. The bond graph of the syngas circuit has been drawn up, as reported in Fig. 2, to identify inputs and outputs of each sub-model. It should be noted that bond graph elements do not match one-to-one with plant components; rather, each component is modeled via one or more elements, based on the considered phenomena. For instance, the filter component is modeled as a resistance element and a capacity element.

Once the causality has been defined, sub-models are being developed and implemented in MATLAB®/Simulink®. The comprehensive plant model will be arranged in sub-systems corresponding to its components (e.g., filter) and lower level sub-systems implementing individual phenomena.

2.2. Filter model

Input and output parameters of the filter model, based on the defined causality, are reported in Table 1. A sub-model simulates the pressure variation, due to mass accumulation in the filter volume, and the pressure drop through ceramic candles. The pressure variation due to mass accumulation is expressed combining the mass conservation equation and the perfect gas law, as:

$$\frac{\mathrm{d}p_{\mathrm{pl}}}{\mathrm{d}t} = \frac{p_{\mathrm{pl}}}{T_{\mathrm{g}}}\frac{\mathrm{d}T_{\mathrm{g}}}{\mathrm{d}t} + \frac{RT_{\mathrm{g}}}{V_{\mathrm{pl}}}(G_{\mathrm{in}} - G_{\mathrm{out}}) \tag{1}$$

The pressure drop through ceramic candles can be expressed as the sum of two terms: (i) the pressure drop through the clean porous medium and (ii) the pressure drop through the dust cake [8]. Assuming a laminar flow, Darcy's law holds:

$$\Delta p = KU\mu_{\mathrm{g}}L \tag{2}$$

The pressure drop through the clean porous medium can be expressed as:

$$\Delta p_0 = K_0\mu_{\mathrm{g}}U\frac{D_{\mathrm{o,cc}}}{2}\ln\frac{D_{\mathrm{o,cc}}}{D_{\mathrm{i,cc}}} \tag{3}$$

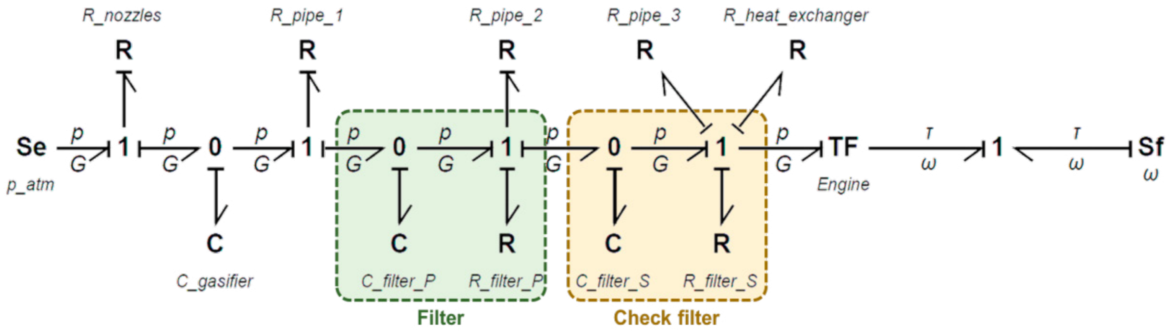

Fig. 2. Bond graph of the syngas circuit of the plant (highlighted are the filter elements)

Table 1. Input and output parameters of the filter model.

Inputs		Outputs	
Incoming and outgoing gas mass flow rates	G_{in}, G_{out}	Pressures in filter plenum and outlet, pressure drops	p_{pl}, p_{out}, Δp_0, Δp_{dc}
Incoming gas temperature	$T_{g,in}$	Outgoing gas and ceramic candle temperatures	$T_{g,out}$, T_{cc}

The pressure drop through the dust cake can be expressed analogously. In practice, the mass of the dust cake is easier to measure with respect to the thickness; therefore, the specific resistance (divided by mass) α_{dc} is introduced [8], such that:

$$K_{dc} L_{dc} = \alpha_{dc} C_p U t \tag{4}$$

Combining Eq. (2) with Eq. (4), the pressure drop across the dust cake can be expressed as:

$$\Delta p_{dc} = \alpha_{dc} \mu_g C_p U^2 t \tag{5}$$

The resistance of the clean ceramic candles and the specific resistance of the dust cake can be related with temperature based on experimental results by Lin et al. [8] and by Lee et al. [13].

In this work, fouling caused by dispersed particulate matter is addressed while fouling caused by tar is neglected, taking into account that filtration occurs at high temperature and the gasifier is of downdraft type.

Another sub-model simulates the evolution of gas temperature, due to energy accumulation in the porous medium and heat transfer to the environment. The temperature variation is expressed through the energy equation as follows:

$$\frac{\mathrm{d}T_g}{\mathrm{d}t} = \frac{(G_{in} c_{p,in} T_{g,in} - G_{out} c_{p,out} T_{g,out}) - Q_{cc\text{-}g} - Q_w}{c_{v,out} \rho_{g,out} V_{pl}} \tag{6}$$

The heat exchange with the environment is regarded as a heat transfer to the ambient air through the filter casing (i.e., forced convection between gas and walls, conduction through walls, natural convection between walls and air).

The heat exchange with ceramic candles is expressed as a convective heat transfer between the gas and a porous medium following Schumann's model [10, 11]. The temperature of the ceramic candles can be computed integrating the following expression:

$$\frac{\mathrm{d}T_{cc}}{\mathrm{d}t} = \frac{h_{cc\text{-}g} A_{cc\text{-}g} (T_{cc} - T_g)}{V_{cc}(1-\varepsilon_{cc}) \rho_{cc} c_{cc}} = \frac{Q_{cc}}{C_{cc}} \tag{7}$$

3. Results

3.1. Model validation

To validate the model, values of its parameters were assumed as reported in Table 2, to replicate experimental conditions [8]. Simulation results of the pressure drop across the ceramic candle are compared with experimental results [8], to assess if the developed model correctly simulates the physical phenomena. Reported experimental data are obtained for an F-40 ceramic candle filter made of mullite fibers, similar to ceramic candles used in the SYNBIOSE plant.

Table 2. Simulation parameters for model validation

Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
N_{cc}	1	H_{cc}	0.200 m	C_p	5.5, 8, 11 g/m^3	T_{cc}	298 K
$D_{i,cc}$	0.040 m	$A_{i,cc}$	$1.194 \cdot 10^{-2}$ m	G	$2.2 \cdot 10^{-4}$ kg/s	U	0.0354 m/s
$D_{o,cc}$	0.070 m	$A_{cc\text{-}g}$	$8.875 \cdot 10^{2}$ m	T_g	288.15 K	V_{pl}	0.950 m^3

The time evolution of the pressure drop for three values of particle concentration in the inlet syngas are reported in Fig. 3a. Simulation results replicate experimental data up to approximately 2000 s; then, experimental data show a steeper slope with respect to simulation results. In both cases the dust cake pressure drop linearly increases with time. The pressure drops (in the clean filter and in the dust cake) at $t = 5000$ s with varying particle concentration are reported in Fig. 3b. The dust cake pressure drop linearly increases with particle concentration. The simulated dust cake pressure drop properly matches experimental data for lower particles concentration; a slight difference is observed, for particle concentration above 8 g/m^3 (higher than that typical of syngas), for long simulation times.

The clean ceramic candle pressure drop against gas velocity is reported in Fig. 4. The simulation results show a good match with experimental data [8].

3.2. Model application

Once the model has been validated against experimental data, it has been used to simulate the system, assuming the values for model parameters reported in Table 3. A typical particulate concentration of 5 g/m³ for syngas from a downdraft gasifier has been assumed [14]. Examples of simulation results in cases of diagnostic interest are presented.

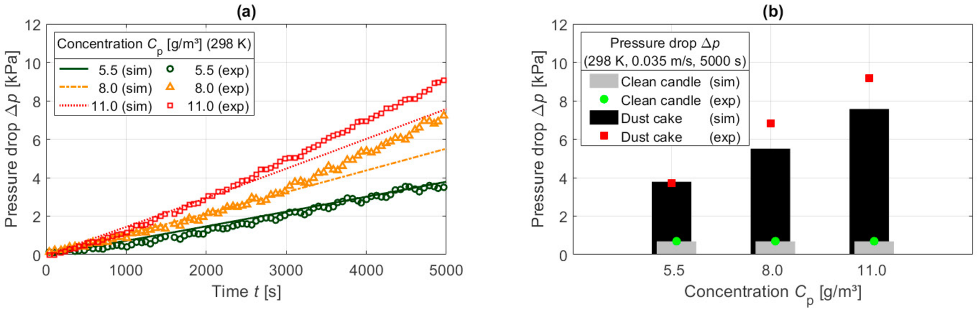

Fig. 3. Dust cake pressure drop with varying particle concentrations: (a) comparison of simulated and experimental [8] time evolution (for F-40 filter); (b) comparison of simulated pressure drops and experimental dust cake pressure drop [8] at $t = 5000$ s .

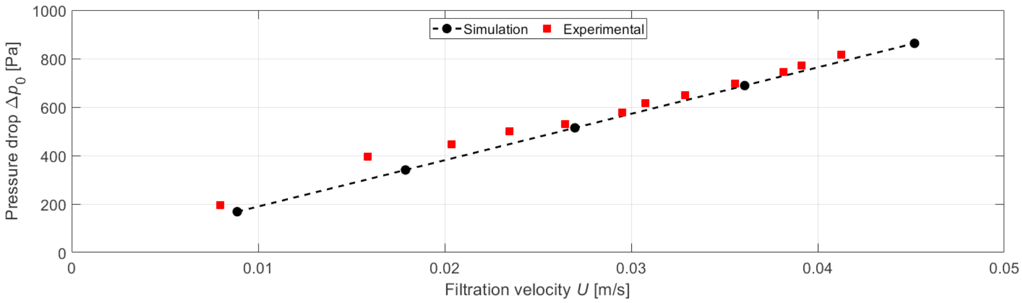

Fig. 4. Clean ceramic candle pressure drop against gas velocity: simulation results vs experimental data (for F-40 filter, at $T = 298$ K) [8].

Table 3. Simulation parameters for model application

Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
N_{cc}	14	H_{cc}	1.000 m, 1.400 m	C_p	5 g/m³	$T_{cc,0}$	600 K
$D_{i,cc}$	0.160 m	$A_{i,cc}$	9.236 m²	G	0.5 kg/s	U	0.11 m/s
$D_{o,cc}$	0.200 m	$A_{cc\text{-}g}$	2.676 km²	$T_{g,0}$	600 K	V_{pl}	2.782 m³

The time evolution of pressures is reported in Fig. 5a. A sudden 10 % decrease of the incoming gas mass flow rate is assumed (e.g., due to changes in gasification operating conditions) at $t = 60$ s.

This causes a steep pressure reduction. Once the incoming mass flow rate is restored, the plenum pressure becomes constant again; the outlet pressure steadily slowly declines because of pressure drops across the ceramic candles.

The time evolution of ceramic candles and outgoing gas temperatures is reported in Fig. 5b, when the incoming gas temperature varies at $t = 120$ s (e.g., due to varying gasification conditions). For a sudden variation of the incoming gas temperature, the ceramic candle temperature closely follows the outgoing gas temperature and they both vary relatively slowly. This is due to the large exchange surface area and to the heat capacity of the medium.

Steady state values of filter pressures and pressure drops across the ceramic candles, for varying incoming gas temperatures, are reported in Fig. 6a and b, respectively. The filter plenum pressure increases with temperature; filter outlet pressure varies, with respect to plenum pressure, as a consequence of pressure drops varying with temperature. The clean ceramic candle pressure drop Δp_0 is maximum at approximately $T = 700$ K: this is the combined effect of velocity $U(T)$ increasing and resistance $K_0(T)$ decreasing with temperature, as reported in Eq. (3). The dust cake pressure drop Δp_{dc} is also maximum at approximately $T = 700$ K: this is the effect of velocity $U^2(T)$ and viscosity $\mu(T)$ increase, combined with resistance decrease $\alpha_{dc}(T)$, as reported in Eq. (5).

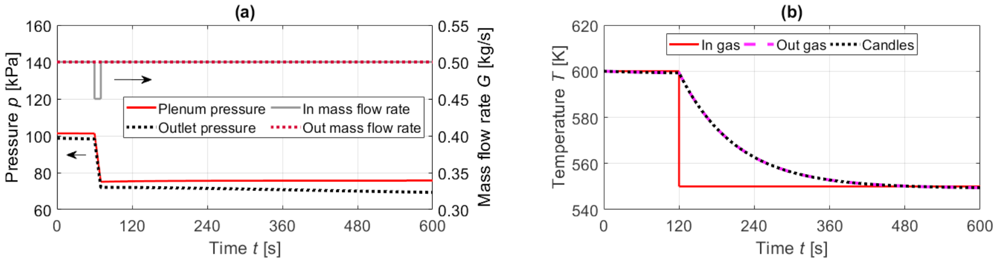

Fig. 5. (a) Time evolution of pressures with a sudden reduction of incoming mass flow rate; (b) time evolution of temperatures in the case of a sudden reduction of incoming gas temperature.

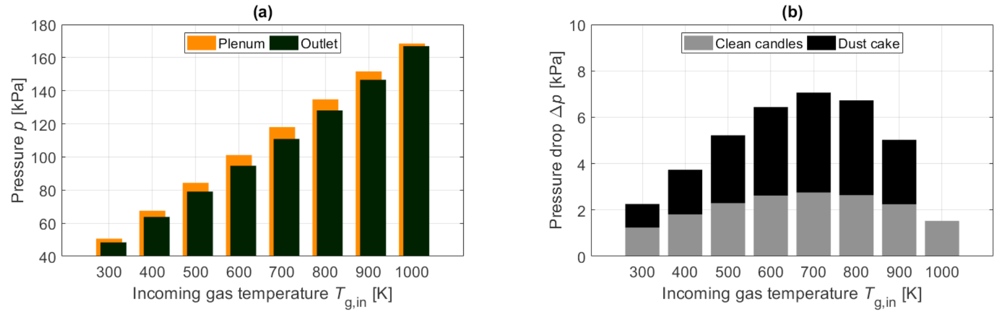

Fig. 6. (a) Steady-state filter pressures at varying incoming gas temperature; (b) steady-state pressure drops at varying incoming gas temperatures, at $t = 1800$ s.

4. Conclusions

To promote the implementation of biomass power plants, especially small-scale CHP systems, it is essential to improve the systems reliability, and the use of diagnostic models is a promising solution. In this context, project SYNBIOSE aims at developing a diagnostic simulation model, supported by experimental activity, based on an existing commercial-grade system.

In the present work, a comprehensive model for the simulation of the filter in a biomass syngas CHP system is developed, by combining separate existing models developed for individual phenomena and different applications. Firstly, the model is validated against experimental data available in literature. Then, the model is analyzed considering the configuration of an existing plant. The sensitivity to syngas properties and operating conditions is analyzed. The diagnostic ability of the model is assessed, as shown from the most significant results presented in the paper.

The achieved results show that the model is a valuable tool for component diagnostics. Once proven for a single component, this approach can be used for the other components. The development will be supported by experimental data from the system under investigation. The developed models can be integrated in an overall model for the diagnosis of the whole plant for similar systems.

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References

[1] Formica M, Frigo S, Gabbrielli R. "Development of a new steady state zero-dimensional simulation model for woody biomass gasification in a full scale plant." *Energy Conversions and Management* 2016;120:358-369.

[2] Francois J, Abdelouahed L, Mauviel G, Patisson F, Mirgaux O, Rogaume C, et al. "Detailed process modeling of a wood gasification combined heat and power plant." *Biomass and Bioenergy* 2013;51:68-82.

[3] Vera D, de Mena B, Jurado F, Schories G. "Study of a downdraft gasifier and gas engine fueled with olive oil industry wastes." *Applied Thermal Engineering* 2013;51(1):119-29.

[4] Prando D, Patuzzi F, Pernigotto G, Gasparella A, Baratieri M. "Biomass gasification systems for residential application: An integrated simulation approach." *Applied Thermal Engineering* 2014;71(1):152-60.

[5] Elsner W, Wysocki M, Niegodajew P, Borecki R. "Experimental and economic study of small-scale CHP installation equipped with downdraft gasifier and internal combustion engine." *Applied Energy* 2017;202:213-27.

[6] Rokni M. "Thermodynamic and thermoeconomic analysis of a system with biomass gasification, solid oxide fuel cell (SOFC) and Stirling engine." *Energy* 2014;76:19-31.

[7] Elmegaard B, Houbak N. "DNA–a general energy system simulation tool." *Proceedings of SIMS.* Citeseer; 2005:43-52.

[8] Lin JC-T, Hsiao T-C, Hsiau S-S, Chen D-R, Chen Y-K, Huang S-H, et al. "Effects of temperature, dust concentration, and filtration superficial velocity on the loading behavior and dust cakes of ceramic candle filters during hot gas filtration." *Separation and Purification Technology* 2018;198:146-54.

[9] Lupion M, Alonso-Fariñas B, Rodriguez-Galan M, Navarrete B. "Modelling pressure drop evolution on high temperature filters." *Chemical Engineering and Processing: Process Intensification* 2013;66:12-9.

[10] Amhalhel GA, Furmanski P. "Problems of modeling flow and heat transfer in porous media." *Biuletyn Instytutu Techniki Cieplnej Politechniki Warszawskiej* 1997(85):34.

[11] Schumann TEW. "Heat transfer: A liquid flowing through a porous prism." *Journal of the Franklin Institute* 1929;208(3):12.

[12] Borutzky W. "Bond graph modelling and simulation of multidisciplinary systems – An introduction." *Simulation Modelling Practice and Theory* 2009;17(1):3-21.

[13] Lee K-S, Sohn J-R, Park Y-O. "Filtration performance characteristics of ceramic candle filter based on inlet structure of high-temperature and high-pressure dust collectors." *Journal of Industrial and Engineering Chemistry* 2015;21:101-10.

[14] O. Akudo C, S. Theegala C. "Quantification of Tars, Particulates, and Higher Heating Values in Gases Produced from a Biomass Gasifier." *BioResources* 2014;9(3):5627-5635.