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Coal-plastic waste blendings. Experimental research and prediction of the thermal process

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Abstract

The topic of waste incineration/co-incineration is critical, given the increasingly stringent regulations on environmental aspects. The widespread use of polymeric materials generates significant waste, posing an ecological problem. Current regulations mandate a reduction in the landfilling of plastic waste, which should be replaced by recycling, with the possibility of exploiting the energy potential due to its high calorific value. The electricity generation in Poland is mainly based on coal, so using polymers as alternative fuels is an important research issue. The research results presented in this paper make it possible to compare the properties of selected waste plastics and coal and their behavior during thermal processes, considering the quality of the gases released. Based on the thermal analyses, a FuzzyTherm model was introduced based on one of the fuzzy logic methods, one of the main artificial intelligence modeling approaches. The model predicts the temperatures corresponding to endothermic and exothermic reactions. The model achieved good accuracy. The maximum relative error between measured and calculated data is lower than 11%. These aspects constitute an innovative element of this paper.

Keywords: Polymer waste; Coal; Thermal analysis; TG/DTG/DSC/EGA; Artificial intelligence

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1. Introduction

The issue of fuel combustion is a current topic of scientific work [1]. Still, due to increasingly stringent environmental conditions, the use of renewable energy sources [2] and the thermal disposal of various types of waste, including coal waste [3,4] and polymer waste [5–24], with the possibility of energy recovery, are of great interest. For example, in 2020 (in the EU27+3), about 1/3

of plastic waste was sent for recycling, 40% – for energy recovery, and more than 23% went to landfills [6].

Polymeric materials manufacturing technologies increasingly use modern engineering polymers with a wide range of applications at much higher temperatures of continuous use than typical thermoplastic polymers. This is due to the limited possibility of recycling waste plastics, which cannot be repeatedly processed technologically and in terms of achieved strength parameters.

Nomenclature

FC	– fixed carbon
I	– ionic current
LHV	– low heating value
m	– mass number
m/z	– mass spectrum
o	– crisp, real output value after defuzzification
T_{melt}	– temperature corresponding to endothermic (melting) of exothermic reactions, K
T_{max}	– temperatures corresponding to maximum temperature of exothermic reactions, K
z	– charge number of the ion

Greek symbols

μ	– membership value (between 0 and 1)
\bar{o}	– centroid of each membership function

Subscripts and Superscripts

exp – measure

Abbreviations and Acronyms

AI	– artificial intelligence
DSC	– differential scanning calorimetry
DTG	– derivative thermogravimetry
EGA	– evolved gas analysis
FL	– fuzzy logic
FTIR	– Fourier transform infrared spectroscopy
GPC	– gel permeation chromatography
MS	– mass spectrometry
PEEK	– polyether ether ketone
POM	– polyoxymethylene
PTFE	– polytetrafluoroethylene
QMS	– quadrupole mass spectrometer
TG	– thermogravimetry

There is a problem with the disposal of such materials. Thermal analysis of waste materials and the possibility of utilization in the form of mixtures is essential in energy recovery processes. According to the literature, thermal processes associated with modifying polymeric waste indicate its possible energy recovery.

Thermal analysis (thermogravimetry/differential scanning calorimetry – TG/DSC) with simultaneous detection of released gases (evolved gas analysis – EGA) makes it possible to record the mass change of a sample and obtain information on which temperature ranges these changes occur and which compounds are released into the atmosphere during high-temperature processes. According to the literature, the energy properties of polymer wastes make it possible to recover energy from them. Using fillers such as carbon black, fly ash, and carbon-based materials in polymer composites, on the other hand, improves the thermomechanical properties, and energy recovery of such materials is economically justified, considering the ecological aspects of waste reduction.

In the paper [7], the author presented numerical results of polyoxymethylene combustion in a reactor. Several combustion reactor configurations were introduced to obtain optimal parameters for the polymer combustion process. The mathematical model developed by the author solves the basic features of the combustion process, such as multicomponent reaction gas flow, heat and mass transfer, radiation heat transfer, polymer combustion, and pyrolysis. The paper presents the distribution of hydrodynamic and thermal parameters in the combustion chamber, characterized by a distinct two-dimensional combustion process. It is shown that the combustion of the polymer in the reactor proceeds in a diffusion mode. The paper [8] addresses the recovery of energy and chemical compounds formed during POM combustion. Measurements were carried out using a specially designed burner. The solid fuel's combustion surface temperature and mass burning rates were determined. The chemical structure of the flame was studied by mass spectrometry using a microprobe. The composition of the gas sample was analyzed by spectrometry. The following gas components: CH₂O, CO,

CO₂, H₂O, O₂, and N₂ were identified, and their concentration profiles were measured. Mass spectrometry and thermogravimetric analysis determined POM thermal degradation's product composition and kinetic parameters. The authors in [9] presented the effect of reprocessing and thermo-oxidative aging on the degradation behavior of polyoxymethylene. The study used thermogravimetric analysis (TG) in a nitrogen and air atmosphere. Tests were carried out with a five-fold heating process to evaluate the activation energy at several conversion steps. TG measurements were carried out with simultaneous monitoring of the evolved gases using a mass spectrometer (MS) connected to the outlet of the TG furnace. The mass spectra showed that the main decomposition product was formaldehyde and that further water formation could be detected in the air. In nitrogen, samples aged in the atmosphere emitted small amounts of carbon dioxide at the onset of mass loss. The activation energy for low conversion rates (5%) increased in air and nitrogen as a function of conversion. A difference appeared for higher conversions as degradation progressed: the activation energy decreased continuously in air, while no significant changes were obtained in the nitrogen atmosphere. The paper [10] presents a process for energy recycling of polyoxymethylene in a fluidized bed formed from cenospheres (hollow, spherical particles). Air, N₂, and CO₂ were used in the combustion process. The composition of the process products in the flue gases as a function of fluidized bed temperature for each fluidization gas is presented and discussed. Fourier transform infrared spectroscopy FTIR analysis of the flue gases and spectra of multicomponent gas samples were used to quantitatively monitor POM thermal degradation products. POM was thermally recycled at 400°C in an air or CO₂ atmosphere to recover the monomer, and nearly 90% formaldehyde formation efficiency was achieved. At temperatures above 600°C, the air or N₂ use led to energy or CO-rich gas recovery, respectively. CO-rich gas was obtained during POM pyrolysis when CO₂ was the liquefying agent. The amount of CO in the flue gas was almost twice as much as the amount of carbon introduced into the process in the polymer material. This means

that carbon was converted to CO from the fluidization environment, thus recycling POM into a CO-rich feedstock with negative CO₂. The authors of papers [11,12] investigated the effects of processing and physical aging on the degradation behavior of thermally stabilized polyoxymethylene homo- and copolymers using thermogravimetric analysis. To this end, the samples were processed by injection molding, followed by six reprocessings, temperature aging in an oven for up to eight weeks, and ultraviolet (UV) light exposure in a xenon tester. TG points to the accidental rupture of the main chain as the initiating mechanism for degradation. The subsequent process depends on the condition of the material and the degradation treatment – thermal, loading, or UV radiation. As observed by gel permeation chromatography (GPC), repeated processing did not affect the molecular weight distribution of the materials. TG/MS (thermogravimetry /mass spectrometry) studies showed the formation of formaldehyde and stabilizer wear as the main processes during aging procedures, which in some cases result in a strong reduction of POM thermal stability.

The authors of the paper [13], while conducting thermal degradation studies of polyoxymethylene using thermogravimetry-Fourier transform infrared spectroscopy (TG-FTIR), also found that POM tends to separate formaldehyde, starting from the unstable ends of the chain, random chain rupture occurs at elevated temperatures, and several related reactions probably take place during the degradation process. The results show that formaldehyde is the dominant product during degradation. Among engineering plastics used at much higher service temperatures, PEEK and PTFE plastics and their composites are important. The paper [14] points out the possibilities of using and modifying PEEK plastic but considering the material's thermal stability. According to the author, PEEK derivatives have significant commercial applications as plastics, especially molded products, and as composites with glass, carbon, and Kevlar fibers with various structural applications, including but not limited to aerospace and engineering. In [15], the authors performed thermogravimetric analyses for three different modes of non-isothermal heating in an inert atmosphere and observed the reactions for carbon-PEEK at 500–700°C and for carbon-phenol, whose pyrolysis begins at around 200°C. The activation energy was determined using the integral (Starink) and differential (Friedman) isoconversion methods as a function of the degree of conversion responsible for the identified reaction compartments. For carbon- polyether ether ketone under inert conditions for Starink, the average value was estimated at 207.71 kJ/mol, while for Friedman, it was 213.88 kJ/mol. The difficulty of estimating the activation energy of polymeric materials favors using different methods, allowing the identification of a range of activation energies for materials for which no data exists in the literature. The so-called compensation effect method was used to evaluate the decomposition model and the one-step approach proposed by Friedman. An evaluation of possible decomposition was obtained for carbon- polyether ether ketone under inert conditions. Investigations during combustion and thermogravimetric analysis for PEEK are presented in the paper [16], indicating the products of combustion and the reactions taking place. Polyether

ether ketone carbon-fiber filled (CA) and glass-fiber filled (GL) samples at 30% were used for the study. TG tests were conducted, and it was determined that the decomposition process of PEEK in an oxidizing environment took place in two separate stages. The first stage of decomposition is attributed to the randomness of the disruption of the ether and ketone bond chain, while the second stage is attributed to the oxidation and carbon charring resulting from the first stage of decomposition [17]. Based on the analysis of the phenomena taking place, the paper [18] proposed mechanisms that attempt to explain the products formed at each stage of PEEK decomposition and identify the intermediates that should be formed at each stage. The authors conducted studies of the thermal and fire properties of the high-temperature polymer material polyether ether ketone using advanced measurement methods [19]. The paper analyzed TG plots of PEEK at different oxygen concentrations, showing that the initial thermal decomposition stage does not depend much on the oxygen level. Several methods were used to understand the mechanism of thermal decomposition of PEEK, including pyrolysis - gas chromatography - mass spectrometry (Py-GC-MS), thermogravimetric analysis (TG) combined with Fourier transform infrared spectrometer.

It was observed that the initial stage of material decomposition could lead to the release of non-flammable gases and the formation of a material with a highly cross-linked carbon structure resembling graphite. During the calorimetric test, PEEK showed excellent char and fire resistance with a heat flux of 50 kW/m². Based on the identification of pyrolytic gases formed during PEEK decomposition, the enhanced fire resistance of PEEK was attributed to the dilution of combustible decomposition gases and the formation of a protective carbonized graphite-like structure during decomposition. The paper [20] addresses the study of energy recovery from PTFE polymer and thermal degradation. Thermal degradation of PTFE was carried out in a horizontal tubular reactor [20]. The effects of temperature and atmosphere on the reaction and the degradation products formed were studied. Various processes were carried out, including pyrolysis. The studies were conducted in the range of 750–1050°C. In pyrolysis cycles, C₂F₄ and C₃F₆ were found as perfluorocarbon compounds. Under oxidizing conditions, C₂F₄, C₃F₆ and CF₄ were found. In the paper [21], thermal characterization of PTFE material was carried out using thermal analysis methods and thermophysical property testing techniques, including differential scanning calorimetry to determine the transformation energy and specific heat. The comparison of different physical properties allowed analysis of thermal property changes during phase transitions. Studies related to the thermal processes of modified PTFE were conducted by the authors of the paper [22], analyzing the thermal pyrolysis process of mold-pressed Al/PTFE composites. XRD (X-ray diffraction) studied the composites' energy properties and the composition of the pyrolysis residue. The authors showed that the PTFE content of the composites determined the energy release from the material and the composition of their combustion residue. Analysis of the composition of the combustion residue indicated the formation of AlF₃, Al₂O₃, Al₄C₃, and amorphous carbon.

Analysis of the thermal processes of engineering polymers such as POM, high-temperature PEEK, and PTFE and their modification with fillers indicates the possibility of utilization and energy recovery of this type of material, taking into account the energy values of the fillers. It also shows the potential of thermal utilization of carbon in this material. In [23], the authors studied the combustion characteristics of various coal samples using differential scanning calorimetry (DSC) and thermogravimetry (TG-DTG) at different heating rates (5, 10 and 15°C/min). The thermographic and thermogravimetry (TG-DTG) curves indicated two main reaction areas at each heating rate tested. The reaction areas, maximum temperatures, mass loss, and heat of the reaction of the samples were determined. The kinetic parameters of the coal samples were also determined using various methods, and it was found that the activation energy values of the coal samples were in the range of 27.2–76.2 kJ/mol. The paper [24] pointed out the properties of polymer-carbon composites and the possibilities of applications, which also involve thermal processes and the utilization of such materials.

The purpose of this paper is to comparatively analyze selected waste plastics (POM, PTFE, PEEK) and bituminous coal in terms of the potential use of their wastes in thermal research, blending of waste plastics, and energy recovery from them. The authors compared the thermal testing results of polymer waste in mixtures with coal. TG/DTG/DSC/EGA thermal analysis methods made it possible to identify the energy properties of the studied engineering polymers, including high-temperature ones, both in the environmental aspect of waste utilization and in combination with coal blends. Thermal analysis of the base materials (polymer waste, carbon) will allow future clarification of the behavior of the materials, also in the form of composites under high-temperature conditions. Base materials differ in composition and calorific value, which significantly impacts waste plastics' process, conditions, and possibilities for energy recovery.

Finally, since predicting the thermal properties of fuels and fuels/plastic wastes, covering endothermic, with melting processes and maximum exothermic mechanisms, is essential from a practical point of view when considering, e.g., smooth transport in feeding installations of energy objects, we developed a fuzzy logic based FuzzyTherm model to predict the thermal behavior of the considered waste fuels. The model used Fuzzy Logic methods, constituting one of the main artificial intelligence (AI) methods, besides artificial neural networks [25–28] and other modelling techniques [29–31].

2. Methodology

Technical and ultimate analysis of the fuels/wastes under consideration was carried out using apparatus of Czestochowa University of Technology, Poland: CHNS elemental analyzer of the FlashSmart series [32], LECO AC600 calorimeter [33], a laboratory dryer (determination of moisture content), according to Polish standard PN-80/G-04511, a muffle furnace (determination of ash content), according to Polish standard PN-80/G-

04512, a muffle furnace (determination of volatiles content), according to Polish standard PN-81/G-04516.

Thermal analysis (TG/DSC) of the samples was performed using the STA 449 F3 Jupiter (Netzsch) coupled to the quadrupole mass spectrometer QMS Aëolos [34]. The measurements were carried out on samples weighing 7 mg in platinum crucibles in an atmosphere of synthetic air and argon (flow 20 ml/min of each gas). Samples were heated from ambient temperature up to 700°C at a heating rate of 10°C/min.

An interesting element of the work was determining the changes in the shapes of samples of the tested polymers during heating using a Misura HSM (hot stage microscopy) high-temperature microscope [35]. For this purpose, cylinder-shaped test specimens ($\phi = 2$ mm, $h = 3$ mm) were manually pressed and heated at 10°C/min. The thermal testing apparatus used in the study is located at the AGH University of Krakow, Faculty of Materials Science and Ceramic, Poland.

Since the temperature of endothermic reactions, expressing plastic-based waste melting processes T_{melt} , as well as the temperature of the maximum energy yield during the exothermic reactions in the fuels T_{max} , are the two critical characteristic effects recorded during thermal DSC tests, their accurate prediction is beneficial when choosing the proper operating parameters of the auxiliary equipment of industrial boiler, including, e.g., feed and fuel belt conveyors and fuel hoppers. A FuzzyTherm system, based on the fuzzy logic (FL) methods, is developed in this paper, allowing us to determine both T_{melt} and T_{max} for coal and plastic wastes.

The fuzzy logic-based modelling approach belongs to the so-called soft-computing methods introduced by Lofti Zadeh, which defined it as a precise logic of imprecision and approximate reasoning. This approach allows the development of knowledge-based systems for solving complex problems. The method uses fuzzy sets and linguistic variables to deal with imprecise, vague, and uncertain information and employs qualitative judgment to parameters quantitative in nature to describe the behavior of processes or objects. An essential feature of the method is that it allows an empirical problem to be formalized using experience rather than the process's strict knowledge. Therefore, due to complex mechanisms corresponding to the studied processes, applying a fuzzy logic-based approach is justified because it allows the building of a model in cases where the experience of an expert is more easily accessible than a strict knowledge of the system's behavior. Owing to the intricate mechanisms inherent in the investigated processes, the employment of methods grounded in fuzzy logic is warranted by the capacity of these methods to facilitate the construction of a model in scenarios where expert experiential knowledge is more readily available than a precise understanding of the system's dynamics [36,37]. Bituminous coal as a parent fuel and PTFE, PEEK, and POM as plastic wastes are considered in the study. Moreover, the mixtures of coal and plastic wastes as additives with a mass fraction of each additive equal to 20% are included in the developed model.

Table 1. Proximate and ultimate analyses of the considered fuels.

Fuel/waste	Nitrogen content N ^a	Carbon content C ^a	Hydrogen content H ^a	Sulfur content S ^a	Moisture content M ^a	Ash content A ^a	Volatile matter content V ^a	FC ^{calc}	FR ^{calc}	LHV
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[-]	[%]
PTFE	0.34	27.01	0.00	0.00	0.06	0.00	97.68	2.26	0.02	4272
PEEK	0.13	72.47	4.64	0.00	0.32	0.00	49.82	49.86	1.00	24402
POM	0.18	42.60	6.90	0.11	0.23	0.00	99.36	0.41	0.01	12960
Bituminous coal	0.85	59.00	4.12	0.92	5.67	17.23	27.74	49.36	1.78	18245

FC = 100-(M^a + V^a + A^a), FR = FC/V^a, (a – analytical state), calc – calculated.

3. Results

Table 1 shows the results of the proximate and ultimate analysis of the considered wastes of plastics and hard coal. In the case of plastics, it should be noted that they contain a high content of volatile parts, practically zero sulfur and ash, and varying nitrogen, carbon, and calorific values. A high proportion of nitrogen, carbon, sulfur, ash, and high calorific value characterizes hard coal.

The melting temperature of the polymer (329°C – PTFE, 279°C – PEEK, 162°C – POM) plays a crucial role in the subsequent stages of the thermal process. This information, detailed in Table 2, provides valuable insights for practical applications.

Table 2. The shape of the sample (HSM microscope) at the melting temperature determined by thermal analysis.




Polymer/ melting temperature	PTFE (329°C)	PEEK (279°C)	POM (162°C)
			

Figure 1 shows the methodology for recording the maximum DSC and DTG peaks, corresponding to the maximum heat release and the maximum fuel mass loss rate, during the considered thermal process for a hard coal sample. The figure shows the coincidence of the temperatures of the mentioned peaks.

Figures 2–7 illustrate sample TG/DTG/DSC/EGA thermal test results of the fuels/wastes considered, along with the analysis (the type of gas emitted was determined according to the *m/z* value [38]).

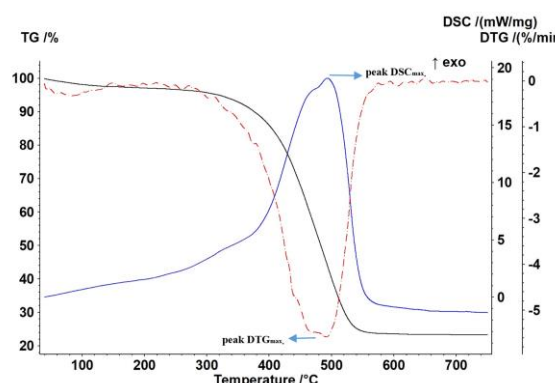


Fig. 1. TG/DTG and DSC profiles for bituminous coal.

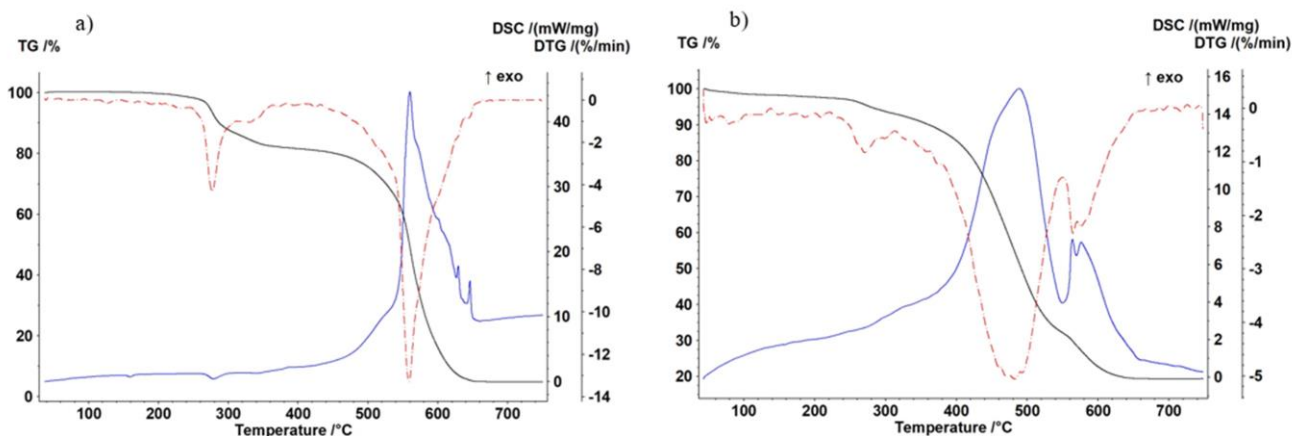


Fig. 2. TG/DTG and DSC profiles of samples: a) PEEK, b) bituminous coal 80%/PEEK 20%.

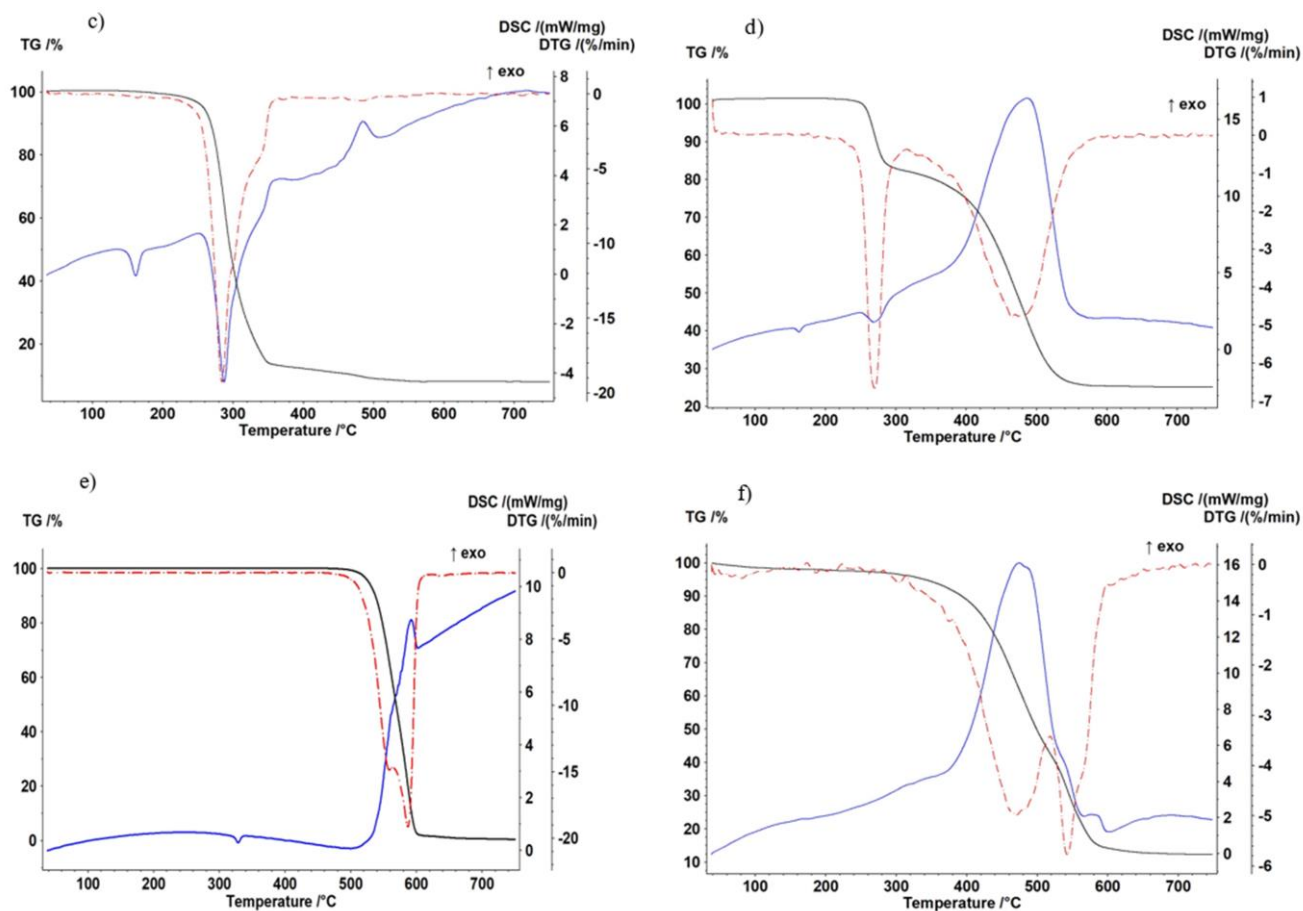


Fig. 2. TG/DTG and DSC profiles of samples: c) POM, d) bituminous coal 80%/POM 20%, e) PTFE f) bituminous coal 80%/PTFE 20%.

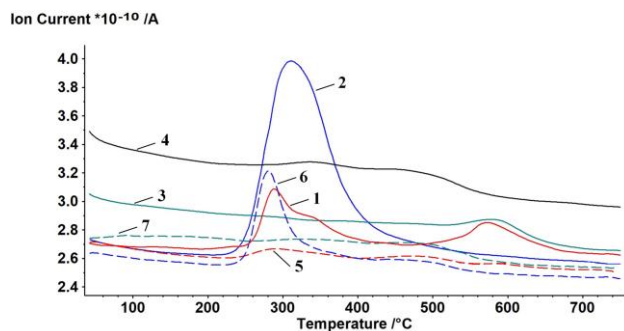


Fig. 3. Results of profiles of evolved gases of $m/z = 2$ (H_2) samples: 1 – PEEK, 2 – POM, 3 – PTFE, 4 – bituminous coal, 5 – bituminous coal 80%/PEEK 20%, 6 – bituminous coal 80%/POM 20%, 7 – bituminous coal.

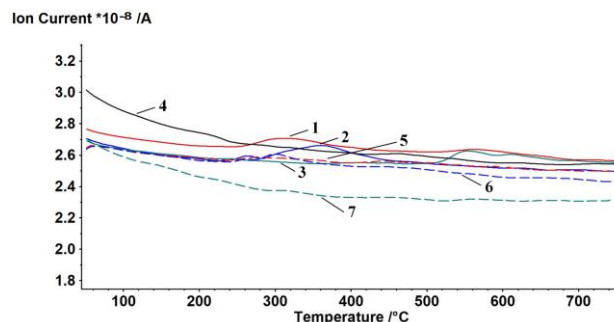


Fig. 4. Results of profiles of evolved gases of $m/z = 28$ (CO) samples: 1 – PEEK, 2 – POM, 3 – PTFE, 4 – bituminous coal, 5 – bituminous coal 80%/PEEK 20%, 6 – bituminous coal 80%/POM 20%, 7 – bituminous coal 80%/PTFE 20%.

In the EGA method, recording ionic currents I , as a function of temperature, allows qualitative determination of gases emitted during thermal processes. The composition of fuels/wastes significantly affects their behavior during thermal processes and the emission of gases into the atmosphere. The values of FC and FR, and the elemental content of carbon and volatile matter in the fuel, as well as nitrogen, hydrogen, and sulfur, are reflected in the values $m/z = 44$, $m/z = 28$, $m/z = 46$, $m/z = 2$ and $m/z = 64$,

respectively, which correspond to the emissions of carbon dioxide, carbon monoxide, nitrogen oxides, hydrogen, and sulfur dioxide. The addition of plastic waste to hard coal adequately changes the value of the I_{total} ionic current for these compounds (lowering emissions of CO_2 , NO_x , SO_2 , and H_2 except for POM, which has a high hydrogen content among plastic waste, and an increase in CO), relative to coal alone (Table 3).

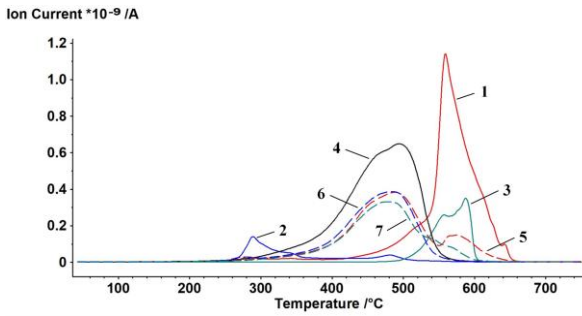


Fig. 5. Results of profiles of evolved gases of $m/z = 44$ (CO_2) samples: 1 – PEEK, 2 – POM, 3 – PTFE, 4 – bituminous coal, 5 – bituminous coal 80%/PEEK 20%, 6 – bituminous coal 80%/POM 20%, 7 – bituminous coal 80%/PTFE 20%.

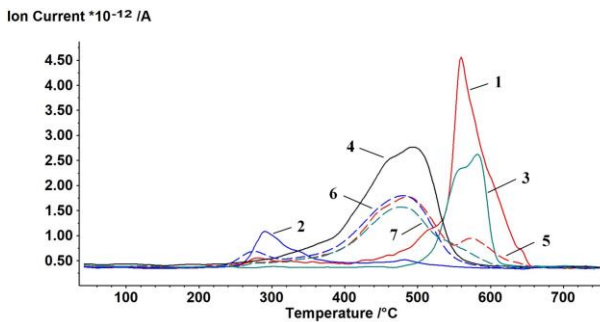


Fig. 6. Results of profiles of evolved gases of $m/z = 46$ (NO_x) samples: 1 – PEEK, 2 – POM, 3 – PTFE, 4 – bituminous coal, 5 – bituminous coal 80%/PEEK 20%, 6 – bituminous coal 80%/POM 20%, 7 – bituminous coal 80%/PTFE 20%.

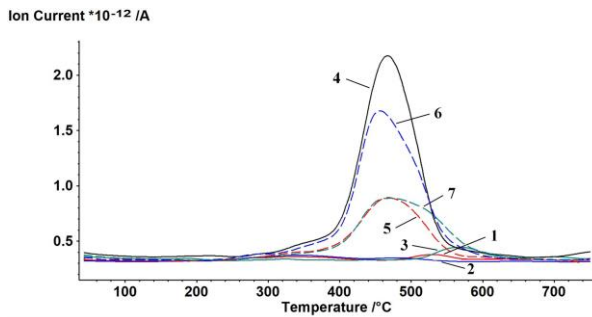


Fig. 7. Results of profiles of evolved gases of $m/z = 64$ (SO_2) samples: 1 – PEEK, 2 – POM, 3 – PTFE, 4 – bituminous coal, 5 – bituminous coal 80%/PEEK 20%, 6 – bituminous coal 80%/POM 20%, 7 – bituminous coal 80%/PTFE 20%.

Predicting the thermal properties of fuels and fuels/plastic wastes, covering endothermic, with melting processes and maximum exothermic peaks, which are essential from a practical point of view when considering, e.g., smooth transport in feeding installations of energy objects. Therefore, for this paper, we developed a FuzzyTherm model based on fuzzy-logic methods, allowing to predict:

- T_{melt} for PTFE, PEEK, POM, and mixtures of coal with plastic wastes

- T_{max} for bituminous coal, PTFE, PEEK, POM, and mixtures of coal with plastic wastes, and T_{melt} and T_{max} are the model outputs.

The input section of the FuzzyTherm model has two inputs, i.e.:

- Coal/PlasticWaste/Mixture, as the type of material, including bituminous coal, plastic waste, or their mixture,
- D32 as the particles Sauter mean diameter of the considered materials.

The inputs and outputs are described in Table 4.

The fuzzifier, i.e., the first of the main blocks in the data processing procedure of a typical fuzzy model, maps crisp inputs to fuzzy functions and employs triangular fuzzy sets, assigning each crisp value of an input to a membership value μ of a fuzzy set [39] (see Fig. 8). The selection of triangular fuzzy sets results from simplifying the model, as they belong to the essential fuzzy functions [40].

A knowledge base of the IF-THEN fuzzy rule base allows the transfer of expert knowledge into the developed FuzzyTherm system [41]. The fuzzy rule base for the model is given in Table 5.

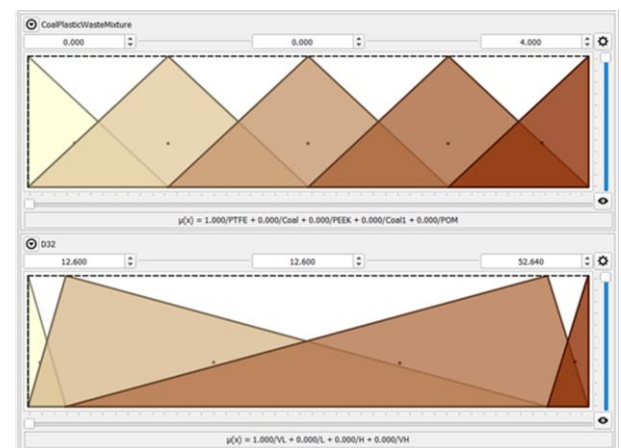


Fig. 8. Inputs of the FuzzyTherm system.

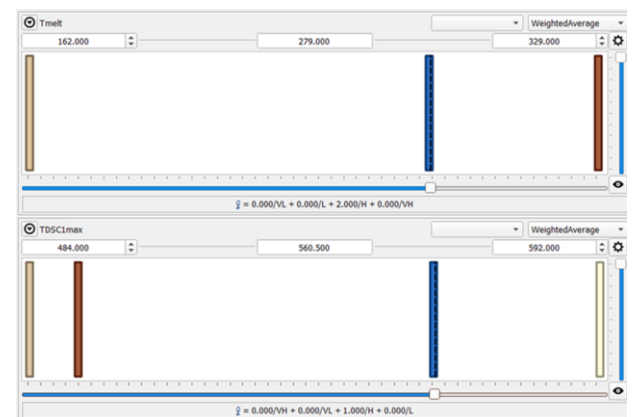


Fig. 9. Outputs of the FuzzyTherm system.

Table 3. Analysis of experimental research results.

Fuel	Characteristic peak DSC	Characteristic peak DTG	Max change in fuel weight	Ionic current I for given m/z (temperature of the characteristic peak of I _{peak} , the total emission of a given gas I _{total} , I _{total} – area under curve of I)	
				I _{max. peak m/z=2} t=587°C I _{max. peak m/z=28} t=550°C I _{peak m/z=28} t=607°C I _{max. peak m/z=44} t=587°C I _{max. peak m/z=46} t=585°C I _{peak m/z=64} t=567°C	I _{total m/z=2} = 4.49 · 10 ⁻⁹ A·s I _{total m/z=28} = 133.91 · 10 ⁻⁹ A·s I _{total m/z=28} = 50.33 · 10 ⁻⁹ A·s I _{total m/z=44} = 109.63 · 10 ⁻⁹ A·s I _{total m/z=46} = 0.77 · 10 ⁻⁹ A·s I _{total m/z=64} = 0.07 · 10 ⁻⁹ A·s
PTFE	0.29 mW/mg (329°C) endothermic peak – melting 8.74 mW/mg (592°C) maximum exothermic peak	19.13%/min	97.19% (400–600°C)	I _{max. peak m/z=2} t=587°C I _{max. peak m/z=28} t=550°C I _{peak m/z=28} t=607°C I _{max. peak m/z=44} t=587°C I _{max. peak m/z=46} t=585°C I _{peak m/z=64} t=567°C	I _{total m/z=2} = 4.49 · 10 ⁻⁹ A·s I _{total m/z=28} = 133.91 · 10 ⁻⁹ A·s I _{total m/z=28} = 50.33 · 10 ⁻⁹ A·s I _{total m/z=44} = 109.63 · 10 ⁻⁹ A·s I _{total m/z=46} = 0.77 · 10 ⁻⁹ A·s I _{total m/z=64} = 0.07 · 10 ⁻⁹ A·s
PEEK	.49 mW/mg (279°C) endothermic peak – melting 20.25 mW/mg (561°C) maximum exothermic peak	13.30%/min	65.27% (400–600°C)	I _{max. peak m/z=2} t=287°C I _{peak m/z=2} t=572°C I _{max. peak m/z=28} t=283°C I _{peak m/z=28} t=558°C I _{max. peak m/z=44} t=557°C I _{max. peak m/z=46} t=559°C I _{peak m/z=46} t=282°C I _{max. peak m/z=64} t=524°C I _{peak m/z=64} t=325°C I _{peak m/z=64} t=795°C	I _{total m/z=2} = 16.03 · 10 ⁻⁹ A·s I _{total m/z=2} = 7.80 · 10 ⁻⁹ A·s I _{total m/z=28} = 302.28 · 10 ⁻⁹ A·s I _{total m/z=28} = 149.15 · 10 ⁻⁹ A·s I _{total m/z=44} = 368.69 · 10 ⁻⁹ A·s I _{total m/z=46} = 1.33 · 10 ⁻⁹ A·s I _{total m/z=46} = 0.03 · 10 ⁻⁹ A·s I _{total m/z=64} = 0.01 · 10 ⁻⁹ A·s I _{total m/z=64} = 0.01 · 10 ⁻⁹ A·s I _{total m/z=64} = 0.01 · 10 ⁻⁹ A·s
POM	0.85 mW/mg (162°C) endothermic peak – melting 5.52 mW/mg (284°C) maximum endothermic peak 2.78 mW/mg (484°C) maximum exothermic peak	19.24%/min.	87.20% (200–400 C)	I _{max. peak m/z=2} t=307°C I _{max. peak m/z=28} t=360°C I _{peak m/z=28} t=264°C I _{max. peak m/z=44} t= 288°C I _{peak m/z=44} t=481°C I _{max. peak m/z=46} t=291°C I _{peak m/z=46} t=482°C I _{peak m/z=46} t=668°C I _{max. peak m/z=64} t=343°C I _{peak m/z=64} t=479°C	I _{total m/z=2} = 76.65 · 10 ⁻⁹ A·s I _{total m/z=28} = 48.94 · 10 ⁻⁹ A·s I _{total m/z=28} = 471.97 · 10 ⁻⁹ A·s I _{total m/z=44} = 34.19 · 10 ⁻⁹ A·s I _{total m/z=44} = 4.41 · 10 ⁻⁹ A·s I _{total m/z=46} = 0.22 · 10 ⁻⁹ A·s I _{total m/z=46} = 0.02 · 10 ⁻⁹ A·s I _{total m/z=46} = 0.006 · 10 ⁻⁹ A·s I _{total m/z=64} = 0.02 · 10 ⁻⁹ A·s I _{total m/z=64} = 0.008 · 10 ⁻⁹ A·s
Bituminous coal	19.08 mW/mg (493°C) maximum exothermic peak	5.58%/min	62.35% (400–600°C)	I _{max. peak m/z=2} t= 336°C I _{peak m/z=2} t=460°C I _{max. peak m/z=28} t= 466°C I _{max. peak m/z=44} t=493°C I _{max. peak m/z=46} t=493°C I _{peak m/z=46} t=468°C I _{max. peak m/z=64} t=468°C	I _{total m/z=2} = 1.72 · 10 ⁻⁹ A·s I _{total m/z=2} = 1.61 · 10 ⁻⁹ A·s I _{total m/z=28} = 20.02 · 10 ⁻⁹ A·s I _{total m/z=44} = 470.55 · 10 ⁻⁹ A·s I _{total m/z=46} = 1.85 · 10 ⁻⁹ A·s I _{total m/z=46} = 1.85 · 10 ⁻⁹ A·s I _{total m/z=64} = 0.99 · 10 ⁻⁹ A·s
Bituminous coal 80%/PTFE 20%	3.92 mW/mg (311°C) endothermic peak – melting 16.08 mW/mg (475°C) maximum exothermic peak	4.88%/min	74.39% (400–600°C)	I _{max. peak m/z=2} t=329°C I _{peak m/z=2} t=465°C I _{max. peak m/z=28} t=435°C I _{peak m/z=28} t=567°C I _{max. peak m/z=44} t=478°C I _{max. peak m/z=46} t=47°C I _{max. peak m/z=64} t=470°C	I _{total m/z=2} = 0.67 · 10 ⁻⁹ A·s I _{total m/z=2} = 0.27 · 10 ⁻⁹ A·s I _{total m/z=28} = 25.81 · 10 ⁻⁹ A·s I _{total m/z=28} = 15.20 · 10 ⁻⁹ A·s I _{total m/z=44} = 228.44 · 10 ⁻⁹ A·s I _{total m/z=46} = 0.82 · 10 ⁻⁹ A·s I _{total m/z=64} = 0.41 · 10 ⁻⁹ A·s
Bituminous coal 80%/PEEK 20%	3.09 mW/mg (294°C) endothermic peak – melting 15.1 mW/mg (485°C) maximum exothermic peak	2.70%/min.	63.18% (400–600°C)	I _{max. peak m/z=2} t=288°C I _{peak m/z=2} t=472°C I _{peak m/z=2} t=588°C I _{max. peak m/z=28} t=297°C I _{max. peak m/z=44} t=487°C I _{max. peak m/z=44} t=575°C I _{max. peak m/z=46} t= 85°C I _{peak m/z=46} t=572°C I _{max. peak m/z=64} t=467°C	I _{total m/z=2} = 3.01 · 10 ⁻⁹ A·s I _{total m/z=2} = 1.58 · 10 ⁻⁹ A·s I _{total m/z=2} = 0.25 · 10 ⁻⁹ A·s I _{total m/z=28} = 32.50 · 10 ⁻⁹ A·s I _{total m/z=44} = 168.11 · 10 ⁻⁹ A·s I _{total m/z=44} = 9.92 · 10 ⁻⁹ A·s I _{total m/z=46} = 0.54 · 10 ⁻⁹ A·s I _{total m/z=46} = 0.02 · 10 ⁻⁹ A·s I _{total m/z=64} = 0.30 · 10 ⁻⁹ A·s
Bituminous coal 80%/POM 20%	1.97 mW/mg (268°C) endothermic peak – melting 16.23 mW/mg (484°C) maximum exothermic peak	4.78%/min	49.71% (400–600°C)	I _{max. peak m/z=2} t=281°C I _{max. peak m/z=28} t=301°C I _{max. peak m/z=44} t=485°C I _{peak m/z=44} t=275°C I _{max. peak m/z=46} t=486°C I _{peak m/z=46} t=274°C I _{max. peak m/z=64} t=456°C I _{peak m/z=64} t=892°C	I _{total m/z=2} = 17.54 · 10 ⁻⁹ A·s I _{total m/z=28} = 195.49 · 10 ⁻⁹ A·s I _{total m/z=44} = 231.09 · 10 ⁻⁹ A·s I _{total m/z=44} = 1.85 · 10 ⁻⁹ A·s I _{total m/z=46} = 0.91 · 10 ⁻⁹ A·s I _{total m/z=46} = 0.05 · 10 ⁻⁹ A·s I _{total m/z=64} = 0.78 · 10 ⁻⁹ A·s I _{total m/z=64} = 0.05 · 10 ⁻⁹ A·s

Table 4. Parameters of the FuzzyTherm of the model.

Parameter	Values
Inputs	
Coal/PlasticWaste/Mixture, - D32, μm	PTFE, PEEK, POM, Coal 15.3, 52.6
Outputs	
T_{melt} , $^{\circ}\text{C}$	162–329
T_{max} , $^{\circ}\text{C}$	484–592

During the inference step, the fuzzy output is generated. Due to its flexibility, the developed FuzzyTherm model uses the Takagi-Sugeno engine (TSK or Takagi, Sugeno, and Kang model) [42,43]. According to the TSK approach, outputs are polynomial functions of the inputs. In the case considered in this paper, we employed constant functions to define outputs, as shown in Fig. 9.

Finally, the weighted average inference method was applied to determine a crisp value of each output o , generated by the FuzzyTherm model, according to the following formula [44,45]:

$$o = \frac{\sum \mu(\bar{o}) \cdot \bar{o}}{\sum \mu(\bar{o})}, \quad (3)$$

where o is the crisp, real output value after defuzzification, μ is the membership value (between 0 and 1), and \bar{o} is the centroid of each membership function. Such a performed FuzzyTerm knowledge-based system allows the simulation of the thermal DSC processes and predicts temperatures T_{melt} and T_{max} , i.e.,

Table 5. The knowledge base of the FuzzyTherm model.

ID	Fuzzy rule
1.	If Coal/PlasticWaste/Mixture is PTFE then T_{melt} is VH*
2.	If Coal/PlasticWaste/Mixture is PEEK then T_{melt} is H
3.	If Coal/PlasticWaste/Mixture is POM then T_{melt} is L
4.	If D32 is VH then T_{melt} is L
5.	If D32 is H then T_{melt} is VH
6.	If D32 is VL then T_{melt} is H
7.	If Coal/PlasticWaste/Mixture is PTFE then T_{max} is VH
8.	If Coal/PlasticWaste/Mixture is PEEK then T_{max} is H
9.	If Coal/PlasticWaste/Mixture is POM then T_{max} is L
10.	If Coal/PlasticWaste/Mixture is Coal then T_{max} is L
11.	If D32 is H then T_{max} is VH
12.	If D32 is H then T_{max} is VH

H – high, L – low, VH – very high.

temperatures corresponding to the endothermic (melting) maximum temperature of exothermic reactions.

The model was built upon data corresponding to pure materials, i.e., coal, PTFE, PEEK, and POM. Its validation was carried out based on coal and plastic waste mixture data. Figure 10 compares trained and validation data calculated and obtained from the experiment.

The FuzzyTherm model achieves good accuracy, close to 99%, for trained data (Fig. 10a). The model's accuracy for the validation data corresponding to mixtures is worse but still acceptable. The maximum relative error between calculated and

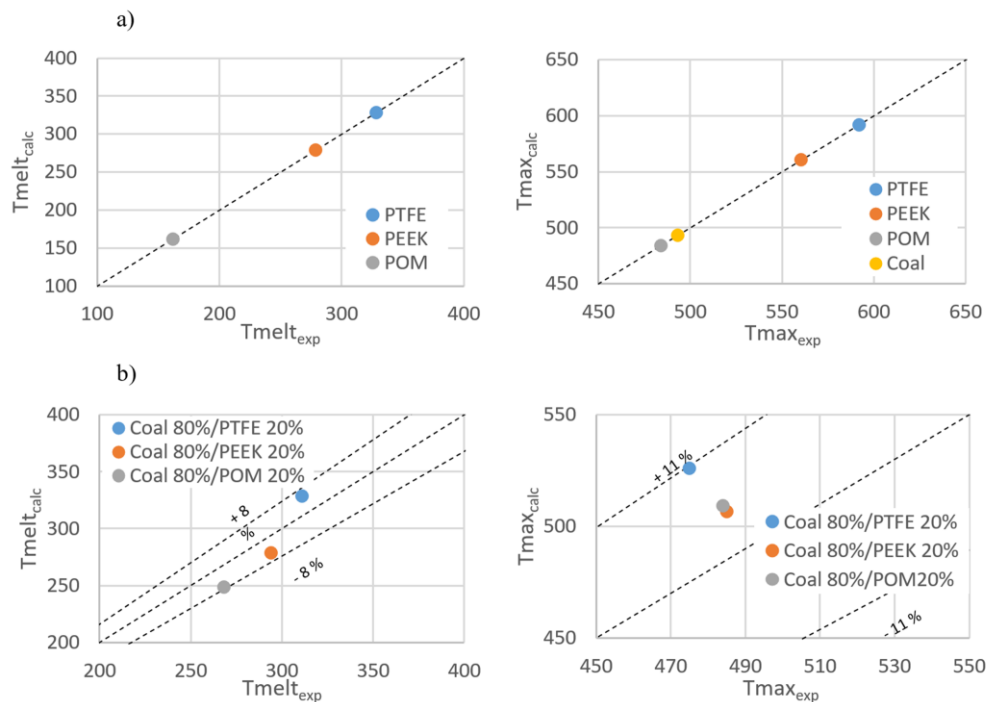


Fig. 10. The comparison of trained a) and validation data b) calculated and obtained from DSC the experiments.

measured data was lower than 11% (Fig. 10b). Based on the reported metrics, the developed FuzzyTherm model can predict T_{melt} and T_{max} . The presented approach can also be applied to predicting other peaks in TG/DTG/DSC or MS profiles of the evolved gases, which will be the objective of the subsequent papers.

The initial analysis of waste behavior, as outlined in the presented results, marks a significant step in understanding the dynamics of waste management. For a more comprehensive understanding, future studies should delve into the valuation of polymer waste. This should focus on pioneering methods for either repurposing or recycling polymer materials. The emergence of new technologies in managing polymer waste is expected to have far-reaching implications, particularly in sectors such as biofuel production. These advancements are pivotal in enhancing the efficiency and sustainability of waste-to-energy conversion processes [46].

The broader context of energy strategies integrated within the circular economy principles warrants further discussion. This comprehensive framework encompasses energy efficiency and sustainability and emphasizes resource reutilization and recycling to create a more sustainable and resilient energy ecosystem [47,48].

It is imperative to underscore the importance of environmental considerations in waste management and energy engineering. This emphasis is due to the intricate interplay between ecological impacts and economic factors. Furthermore, the profitability of sustainable technologies should not be overlooked. From an investor's perspective, comprehending the motivations behind and trends in funding sustainable technologies is essential. The financial viability of these technologies is a crucial determinant of their long-term sustainability and success [49,50].

The industrial perspective and advanced technologies in modern manufacturing are crucial, especially process optimization and automation in decision-making [51–53]. It is also essential to acknowledge that energy self-sufficiency frequently plays a significant role in national sovereignty. This aspect underscores the strategic importance of a country's ability to independently meet its energy needs, thereby enhancing its autonomy and security on the global stage [54,55].

5. Conclusions

The authors have drawn several key conclusions:

1. The calorific value and composition of the materials directly influence the peak heat generation and emissions of pollutants.
2. Compared to coal, plastic waste has a high content of volatile parts and a negligible share of sulfur.
3. Polyether ether ketone has the highest energy potential of the polymers due to its highest calorific value.
4. The temperatures of maximum gas emissions (I_{peak}) and accompanying thermal processes coincide with DSC and DTG peaks for a given fuel/waste.
5. The developed model, based on fuzzy logic, can predict the maximum heat output from the tested waste materials during the specified thermal processes.

6. Given the environmental considerations, particularly concerning pollutant emissions, the results serve as a foundational benchmark for further refinement of the fuzzy logic-based model beyond just thermal process analysis.

In the context of the discussed study, the authors established two primary research hypotheses: The calorific value and composition of materials are directly correlated with the peak values of heat generation and pollutant emissions.

The model developed utilizing fuzzy logic can predict the maximum heat release from the studied waste materials during the thermal processes under analysis.

The findings shown in the article represent the initial research stages. They offer a comparative analysis of the combustion process of various waste types, employing thermal analysis techniques. The authors plan to extend this research to include co-incineration and energy recovery from these wastes. The exploration into thermal analysis of waste materials as potential fuel sources marks a significant step towards implementing net-zero emission strategies, adhering to sustainable development policies, and enhancing energy efficiency.

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