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Dr. Chun-Zhu Li
Editor-in-Chief
Fuel Processing Technology

September 2, 2014

Dear Dr. Li:
I am pleased to submit an original research article entitled **"Digestate as bio-fuel in domestic furnaces"** by Simone Pedrazzi, Giulio Allesina, Tobia Bellò, Carlo Alberto Rinaldini and Paolo Tartarini for consideration for publication in the *Fuel Processing Technology Journal.*
In this manuscript, we investigate the use of a pelletized biogas power plants byproduct (digestate) as biofuel in an ordinary domestic air furnace. Three types of pure digestate and wood-digestate pellets were obtained and tested in order to optimize the higher heating value of the bio-fuel and to reduce the ash sintering in the furnace. Pellets made by 50% of wood and 50% of digestate dried at 150 °C demonstrated good performance as fuel. In addition, the exhaust analysis and the furnace efficiency evaluation were done.
We believe that this manuscript is appropriate for publication by the *Fuel Processing Technology Journal* because it analyzes the chemical and physical transformation of a byproduct of biogas power plants into a bio-fuel suitable for common pellet stoves. Furthermore this topic is poorly investigated in literature while the issues related to digestate disposal are increasing in these years.
Our manuscript suggests a way to dispose the digestate enhancing its chemical content into thermal energy. Furthermore, this process reduces problems related to digestate spread into soils. In fact this operation is limited by the European Nitrates Directives.
This manuscript has not been published and is not under consideration for publication elsewhere. We have no conflicts of interest to disclose. If you feel that the manuscript is appropriate for your journal, we suggest the following reviewers:

- Dr. Martin Kratzeisen, Institute of Agricultural Engineering (440e), Universität Hohenheim, martin.kratzeisen@uni-hohenheim.de
- Dr. Hailong Li, School of Sustainable Development of Society and Technology, Mälardalen University, lihailong@gmail.com
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Thank you for your consideration.

Sincerely,

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Highlights

- The digestate from a biogas power plant was investigated as fuel in a common air furnace.
- The digestate drying process was optimized in order to achieve the maximum higher heating value of the fuel.
- The digestate was pelletized and tested in an air furnace.
- Ash synthering issues were found using pure digestate, mixed digestate-wood pellets were creates to overcome this problem.
- The mixed pellets were suitable for combustion in the air furnace.

Response to Review Comments

I am very much thankful to the reviewers for their review. I have revised my present research paper in the light of their useful suggestions and comments, the corrections in the manuscript were made in red color. I hope my revision has improved the paper to a level of their satisfaction:

Reviewer # 1

1 the knowledge gap and the significance of this work should be further specified.
→ we add some discusison about this in the introduction, showing the major competitors to digestate combustion: composting and landfill disposal
2 what are the uncertainties for the measurements?
→ we add the uncertainties of all the measurements in the tables
3 why is SOx not included?
→ because there isn't sulphur in the biomass as shown in the chemical analysis
4 the drying temperature of 573 is too high and it is already in the torrefaction stage. the volatile is lost. this is one of the reasons for the difficulty of combustion. However, this is not clearly addressed.
→ thank you for this comment, we report this in the introduction
5 what is the size of pellet
→the size of the pellets is reported in table 1 and 4
6 both K and degree C are used at the unit of T. the authors need to use only one.
→ everything is now reported in Celsius degrees

Reviewer # 2

1) It is to much description of the study performed in the introduction. It should be moved to the method and result par. Further, the first sentences in the result part should be moves to the method. Also equations included in the results should be moved to the methodology part. The part "Sintering cases analysis", parts of chapter 3.2, 3.3 and 3.4 in the results is also description of what has been done raguer than results and should be moved to the metodology part.
→ we modify the manuscript as suggested trying to balance all the section following your and reviewer 1 suggestions.
2) Table 2 - what is the " digestate 0" . In the table values for two samples are presented. The naming is not clear- it says 100% wood, 50 % dig. and then the table text says "digestate 0" pellets and wood pellets mixture - what is what? In the text to table 5 a pellet A1 is mentioned but it is not described in the text or showed in the table?
→ we explain in details these definitions in the subsection 2.7
3) Eq. 10 The mass flow of the fuel seems to be missing in the equation. As the parameters in the equation is described the unit of the numerator is J/ s but for the denominator MJ/ kg.
→ Sorry about that, it is now corrected adding the mass flow
4) Both K and C is used as the unit for temperature- one unit should be choosen for the whole paper.
→ everything is now reported in Celsius degrees
5) Descriptions of parameters in equations/ nomenclature is missing.
→ All the parameters are now explained after each equations
6) Page 9 "figure 9 and figure 9" ?
→ sorry about that, it was a babel Latex error now corrected
7) English needs to be improved- for example "Tabella" should be "Table", " Figura" should be " Figure" etc and many language misstakes in the text.
→ sorry about that, it was a babel Latex error now corrected
8) Figure 9 very high accuracy- is it right that it can be determined with 2 decimals?

→ yes, the resolution of the instrument as high as reported in the caption of the figure 9

9) Why was the composition 50/50 chosen for digestate 2?
→The choice of 50% wood and 50% "digestate 1" was adopted in order to achieve an intermediate behavior between these two biomasses.

Thank you again for your review.
All the best,

Dr. Simone Pedrazzi. simone.pedrazzi@unimore.it

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Digestate as bio-fuel in domestic furnaces

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Abstract

This study investigates the use of the biogas power plants byproduct (digestate) as biofuel in an ordinary domestic air furnace. The digestate, disposed by a 1 MW biogas plant located in Italy, was dried out and pelletized in order to be used as fuel in a wood pellet furnace with 29 kW_{th} of nominal power, commonly installed in industrial HVAC systems. The first test was carried out starting from a heavily dried pellet called "digestate 0" characterized chemically and physically in order to obtain its composition, while its ashes were tested using an optical thermal dilatometer for the softening point evaluation. This first test outlined that the "digestate 0" pellets were not suitable for combustion applications even when mixed with an equal part of pure wood pellets. The research then focused on the raw digestate drying process through a set of physical and chemical tests. It was found that a temperature of 150 ^{o}C maximizes the higher heating value of the new "digestate 1" at 16.6 MJ/kg. However, to further avoid the ash sintering, "ultimate digestate" pellets were prepared mixing 50% of "digestate 1" and 50% of wood. The digestate obtained in such a way was experimentally tested through several runs of the air furnace. In these tests, the overall efficiency as well as the furnace emissions where measured. An optical instrument was used to estimate soot, while a gas analyzer measured the NO_x concentration in the exhausts.

Keywords: digestate, solid biofuel, pellet, domestic furnace, sintering

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1. Introduction

The anaerobic digestion of organic and/or waste matter produces a gas mixture known as "biogas" composed of about 50% of methane and 50% of CO_2. The process generates also a byproduct known as digestate [1, 2]. The biogas is used for CHP applications after a process of filtration which eliminates little amounts of sulphuric gases; it can be also upgraded to biomethane [3] for automotive fueling.

The digestate disposed by biogas power plants is composed of a liquid fraction and a solid fraction. The liquid part has a high level of nutrients while the solid fraction balances the humic equilibrium of the soil [4], for this reason Italy is one of the countries where the digestate is categorized as agricultural byproduct with fertilizing properties [5].

On the other hand liquid and solid digestate from anaerobic digestion of manure contain high levels of nitrogen in organic and inorganic form [4]. This limits its application into soils as reported in the European "Nitrates Directive" which imposes the annual maximum spreading of 170 kg of nitrogen for hectare of soil in several sensible areas of the EU union [6].

This limit reduces feasibility and profit of biogas power plants which use manure as feedstocks, because farmers are often forced to buy or rent hectares of soil to spread the digestate. For these reasons, the utilization of digestate as fuel will lead to the combined advantages of exploiting a byproduct for energy purposes together with the reduction a common issue related to biogas plants. This paper investigates the behavior and characteristics of a pelletized solid digestate used as fuel in domestic furnaces.

Digestate disposal problem has become relevant in recent years only, this is the result of the great number of biogas power plant installed. Nevertheless, literature review showed little works about using combustion as a possible solution to this issue. Other researches focus on digestate composting or its disposal in landfills [7, 8]. Contrary to these solution, the combustion of digestate pellets in small air furnaces is easy to implement in situ.

The application of pelletized digestate as fuel in heat generators is presented by Kratzeisen et al. [9] where two different digestate pellets are tested in a biomass combustion facility. The pollutant emissions and combustion behavior are there evaluated and discussed. A further study, developed by Li et al. [10], investigates the combustion of digestate in order to increase the

CHP efficiency of a biogas power plant. Reference [11] analyzes the feasibility of the combustion of manure digestate for district energy production. Further studies about digestate combustion are reported in literature [12, 13, 14].

The first attempt to exploit pure digestate into a furnace started from the solid byproduct obtained from the liquid-solid separator of the plant, dried and pelletized. During the drying process with hot air, the inorganic nitrogen (ammonia) evaporates and it can be converted into ammonia salts in an acid scrubber [4]. These salts can be used as fertilizer in agriculture.

In addition, the high temperature of drying resulted into the torrefaction of the digestate. This phenomenon stabilizes the digestate properties and increases its energy density. The digestate was subsequently transformed in pellets and burned in a furnace, however the torrefaction process consumes the volatile part of the digestate and the further combustion becomes difficult.

2. Material and methods

In this work, digestate pellets from the anaerobic digestion of a feedstock composed of manure, maize flour and straw are characterized through physical and chemical analyses. In order to evaluate the overall efficiency of the furnace, the machine performance was first evaluated using a "ENplus A1" pellets in accordance with the European regulation "EN 14961-2". Then "digestate 0" pellets were tested under two different conditions: pure digestate combustion (that failed due to sudden ash sintering) and 50% (in weight) digestate pellets and 50% certificated "ENplus A1" wood pellets combustion. In addition, the influence of the drying temperature on the properties of the digestate was evaluated by experimental analyses. Finally a new pellet, called "ultimate digestate", was produced and investigated. It is composed by a mix of an half of "digestate 1" and an half of sawdust wood obtained from the previous "ENplus A1" wood pellets. "Ultimate digestate" was characterized both chemically and physically. During its combustion test emissions were also investigated and compared with that of certified "ENplus A1" pellets.

2.1. Combustion facility

The facility used in this work is a commercial air furnace of 29 kW_{th} of nominal power. The fuel enters into the furnace through an auger connected to a hopper which is weighted during each tests in order to evaluate the fuel consumption. Before leaving the furnace, the exhausts pass through a heat exchanger increasing the temperature of an air flow. After the exchanger, the

exhausts leave the air furnace through a chimney, while the hot air is directed into a channel where an Extech HD300^{TM} anemometer is placed. This instrument measures and records the air velocity through a blade anemometer and the air temperature through a K type thermocouple. The facility described before is reported in Figure 1. A combustion test generally consists of 40 min (2400 s) at max power, data acquisition starts when furnace exhausted temperature was stabilized. The exchanger blower is activated when air raise over 37 ^{o}C. The fuel is fed into the brazier with a 10 s of auger run and 15 s of stop. The overall efficiency of the air furnace in case of "digestate 0"-"ENplus A1" pellets co-feeding was calculated by the Eq. 1.

$$\eta_{tot} = \frac{\rho_{air} c_{p,air} w A \Delta T}{\dot{m}_{bio} HHV_{dig} f_{dig} + \dot{m}_{bio} HHV_{wood} f_{wood}} \tag{1}$$

where $\rho_{air} = 1.225$ [kg m^{-3}] is the density of the ambient air, $c_{p,air} = 1.005$ [J kg $^{-1}$ K $^{-1}$] is the specific heat of the ambient air, w [m/s] in the average air flow velocity, $A = 0.0314$ [m^2] is the section of the outlet duct, ΔT [K] is the air temperature increase, $\dot{m}_{bio}$ [kg/h] is the biomass consumption, HHV_{dig} [MJ/kg] is the higher heating value of the type "digestate 0" pellets, f_{dig} is the mass fraction of the "digestate 0" pellets in the fuel, HHV_{wood} [MJ/kg] is the higher heating value of the wood pellets and f_{wood} is the mass fraction of wood pellets in the fuel. Equation 5 is adaptable in case of single feeding with pure digestate or pure wood considering equal to zero the mass fraction of wood or digestate.

2.2. Chemical analysis

In order to obtain the average dry-ash-free (daf) composition of the digestate pellets, a sample of "digestate 0" and of "ultimate digestate" pellets were tested in a EA 1110 CHNS-O analyzer. In addition, the pellets were reduced to ash by heating them in a stove at 550 ^{o}C for 4 hours [15] to estimate the ash content ASH [%]. The average "as-received" (ar) composition of the pellets was then calculated using Eqs. 1-6 [16]. The moisture of the pellets M [%] is almost zero as result of the heavy drying process.

$$C_{ar} + H_{ar} + N_{ar} + S_{ar} + O_{ar} + M + ASH = 100 \tag{2}$$

$$C_{ar} = \frac{C_{daf}\,(100 - M - ASH)}{100} \tag{3}$$

$$H_{ar} = \frac{H_{daf}\,(100 - M - ASH)}{100} \tag{4}$$

$$N_{ar} = \frac{N_{daf}\,(100 - M - ASH)}{100} \tag{5}$$

$$S_{ar} = \frac{S_{daf}\,(100 - M - ASH)}{100} \tag{6}$$

$$O_{ar} = \frac{(100 - C_{daf} - H_{daf} - N_{daf} - S_{daf})\,(100 - M - ASH)}{100} \tag{7}$$

where C_{ar}, H_{ar}, N_{ar}, S_{ar}, O_{ar}, M and ASH are the mass percentage of carbon, hydrogen, nitrogen, sulphur, oxygen, moisture and ashes in the biomass considering "as-received" conditions, C_{daf}, H_{daf}, N_{daf}, S_{daf} are the mass percentage of carbon, hydrogen, nitrogen and sulphur in the biomass considering "daf" conditions. The chemical composition of "digestate 0" pellets is reported in Table 1, instead the chemical composition of the "ultimate digestate" pellets is reported in Table 4.

2.3. Physical analysis

Average dimensions of digestate pellets were evaluated with 50 caliper measurements. The true density of the pellets ρ_{true} [kg/m^3] was estimated by a Micromeritics^{TM} helium pycnometer, model "AccuPyc 1330". While the apparent density of the pellets $\rho_{apparent}$ [kg/m^3] was evaluated using an Micrometrics^{TM} mercury intrusion porosimeter, model "AutoPore IV 9500". The void fraction of the pellets is calculated by the following formula [16]:

$$\epsilon_v = \frac{\rho_{true} - \rho_{apparent}}{\rho_{true}} \tag{8}$$

All the properties measured are reported in Table 1 and Table 4.

2.4. Combustion analysis

The higher heating value of digestate pellets was estimated using a Mahler bomb calorimeter [17]. In this device, a sample of fuel of known mass is burned into a closed vessel filled with oxygen at 20-25 atm in order to assure the complete combustion of the sample. The isochoric combustion generates

a thermal energy amount equal to the increase of the internal energy of the system ΔU [J]. The heat of combustion ΔH_{comb} is calculated by:

$$\Delta H_{comb} = \Delta U + \Delta nRT \tag{9}$$

where Δn [mol] is the moles variation of the gas inside the "bomb", R [J mol^{-1} K^{-1}] is the universal gas constant and T [K] is the temperature. The difference between ΔH_{comb} and ΔU is small for solid fuel such as biomass (about 0.1 %), so the ΔH_{comb} is considered equal to ΔU. The method to evaluate ΔU is to soak the "bomb" into a quasi-adiabatic vessel filled with a known amount of water. The combustion increases the water temperature with a specific trend and a graphical method discussed in Reference [17] allows us to calculate the average ΔT of the water. The ΔU of water is assumed equal to the ΔH_{comb} and it is evaluated using the following equation:

$$\Delta H_{comb} = \Delta U_{water} = k\Delta T \tag{10}$$

where the calorimeter constant k [J/K] was previously calculated through a calibration process described in Reference [17].

2.5. Ashes analysis

The high amount of low-melting-point ash into the digestate pellets create some agglomerations during the combustion. In order to understand this phenomenon of agglomeration, some biomass pellets were heated in a kiln for 4 hours at 550 ^{o}C to reduce it to ash. The ash sintering behavior was then investigated testing a parallelepiped of pressed ash into an optical vertical dilatometer. The dilatometer was heated up to 500 ^{o}C before the ash sample was added (flash test mode as suggested by [18]). The temperature in the instrument rose to 850 ^{o}C at a rate of 80 ^{o}C/minute and then the heaters were turned off, letting the sample cool down.

2.6. Emissions analysis

During the tests with "ENplus A1" wood pellets and "ultimate digestate" pellets, emissions were investigated: soot level and NO_x concentration were recorded and elaborated by an "AVL emissions tester 4000". The instrument sampling tube was placed in the exhausts duct, four diameters far from the furnace body. All the fuels were tested in the same way: 20 min of acquisition at 0.5 Hz for both the measurements (NO_x and soot). The SO_x are not

considered because the chemical analysis reveals the absence of sulfur in the digestate.

2.7. Digestate pellet description

The digestate "0" pellets were obtained from the solid part of the digestate dried in a rotational drier at a air peak temperature of 300 ^{o}C and then pelletized. The biogas power plant which disposed the digestate is fed with 50x10^{3} kg of pig slurry, 11x10^{3} kg of maize flour and 6x10^{3} kg of milled straw. Table 1 resumes the thermo-chemical properties of these pellets.

In order to define the best condition for "digestate 1" pellet production, several samples of solid digestate were fully dried in a muffle furnace at 105, 150 and 200 ^{o}C for 5 hours in order to find the temperature able to maximize the higher heating value of the fuel. Each sample was also chemically characterized and Table 3 resumes the results of these analyses.

The drying process at 150 ^{o}C guarantees the higher HHV of the digestate. This is the optimum temperature, in fact at lower and higher temperatures of drying, the digestate HHVs decrease following a parabolic trend as shown in Figure 6 where at 300 ^{o}C the HHV of the "digestate 0" pellets is reported.

The digestate dried at 150 ^{o}C, known as "digestate 1", was mixed with sawdust of "ENplus A1" wood pellets and further HHV and ash content analyses were done. Results of these mixtures are reported in Figure 8. However, even if the ash content of "digestate 1" is higher than the type "0", it will be better to mix it with pure wood before pelletizing. This procedure will further increase the HHV and reduce the ash sintering due to the addition of matter with high-softening-point ashes in between the pellets.

Finally, it was produced a pellet, known as "ultimate digestate", composed 50% solid digestate treated at 150 ^{o}C ("digestate 1") and 50% wood, the characteristics of this pellets are reported in Table 4. The choice of 50% wood and 50% "digestate 1" was adopted in order to achieve an intermediate behavior between these biomasses.

3. Results

3.1. "Digestate 0" combustion tests

Figure 2 reports the results of the ashes analysis of "digestate 0" pellets. There are two different lines: 1) the "blue" one represents the sintering percentage that was evaluated measuring the geometry variations of the sample

and 2) the "red" line is the temperature of the sample since the moment it was inserted in the heated part of the instrument. The most important trend is the sintering percentage one. A reduction under 95% range is symptomatic of ash sintering and therefore "slagging" is imminent. The test outlined a temperature of 300 ^{o}C that was much lower than 800 ^{o}C typical of hard wood ashes [19].

The combustion of "digestate 0" pellets in the air furnace is difficult to maintain in periods longer than an hour because the true density of the pellets is high and the surface of the pellets is covered by a thin layer of torrefied lignin which is hard and compact. This feature complicates the pellets ignition. In addition, during the combustion, the ash creates several agglomerates known as "klinker" which obstruct the brazier holes and partially choke the combustion after few minutes. Figure 3 shows a big agglomerate found in the combustion chamber after an hour of test.

Figure 4 illustrates the velocity and the temperature of the hot air flow (in the exchanger) which is generated by the air furnace when it is fueled by type "digestate 0" pellets. The air flow is variable and unstable as result of the intermittent combustion behavior.

These results suggest that these digestate pellets are not suitable as fuel for combustion. One possible reason of that is the drying temperature of 300 ^{o}C too high and already in the torrefaction stage. In such a way, the volatile is lost the combustion becomes difficulty.

The first method to overcome this issue is to mix the digestate pellets with wood pellets certified as "ENplus A1". These wood pellets have a measured higher heating value of 19 MJ/kg and a measured ash content lower than 1 %. The air furnace behavior fed with wood pellets only is illustrated in Fig. 5, where is interesting to note that the temperature and velocity of the hot air flow are almost constant during the whole combustion test.

A mixture composed of 50% of digestate pellets and 50% wood pellets was tested. The temperature trends of the hot air flow are depicted in Figure7. Table 2 resumes and compares the results of the combustion tests using wood pellets as fuel (100% wood) and using a mixture of 50% wood pellets and 50 % "digestate 0" pellets as fuel. The test with 50 % of digestate is more stable, even thought during this test the formation of klinker persisted. This phenomenon reduces the reliability and the performance of the device.

3.2. " Ultimate Digestate" combustion pellets

Several tests were done using "ultimate digestate" pellets as fuel in order to investigate the combustion behavior of this bio-fuel. The tests were conducted under the same conditions reported for other pellets: the air exchanger blower starts to operate at the hot air temperature of 37 ^{o}C, while the only changed parameter is the auger run time. It has increased to 11 s, because of the different dimension of this pellet. With this settings the furnace feeding rate was always between 5.3 and 5.9 kg/h in each case of study. Weather was sunny and the average air temperature was around 19 ^{o}C. The results of combustion tests underline a significant increase of temperature of hot air from the exchanger compared to the test with "digestate 0" as fuel. Despite all, even with this new pellet the problem of sintering is not completely defeated. Agglomerates persists but now are not as hard as the ones generated during "digestate 0" combustion. Under these conditions, an ash removing system would significantly reduce the problem. The new pellet has a higher combustion efficiency because the HHV is higher as well as the exhaust temperature. These features resulted into a better kinetic exchange conditions of the hot air flow as reported in Table 5.

3.3. Emissions

During the test with the "ultimate digestate" pellets the furnace exhausts where monitored acquiring data about the soot level as well as NO_x concentration. Results of the tests are reported in Figure 9. The soot analysis should be considered only in a qualitative way: the instrument of analysis is an opacimeter, this kind of soot-meter are commonly used in automotive engines but it gives little information about soot concentration and and dimension of particulate matter which composed it. In Figure 9 it could be noted how the "ultimate digestate" emissions are threefold compared to the certified "ENplus A1" one. Contrary to the soot measure, the NO_x one is more precise because the sensor used identifies the exact amount of nitrogen oxides in the exhausts as reported in Figure 9. The NO_x average emission value of the "ultimate digestate" is significantly bigger that the certified wood pellet value: 347 mg/m^3 Vs. 50 mg/m^3 as reported in Table 6. These values were obtained from the measured one after converting ppm to mg/m^3 and scaling the values to 13% Oxygen content in the gas in order to be compared with the limits suggested by [20].

In each case, results respect theoretical previsions in consequence of the high content of ashes and nitrogen content in "ultimate digestate" pellets. It was demonstrated that the more ashes residues in the brazier, the higher

soot would be emitted [21]. Moreover, literature suggest that the majority of NO_x emissions is strictly related with nitrogen amount in the fuel [21].

CONCLUSIONS

In this work, the digestate derived from an anaerobic digestion power plant was used as fuel in an air furnace. The initial feedstock (type "digestate 0" pellets) is not suitable as fuel because of its ashes as a low temperature melting point, they built up creating big agglomerates in the combustion chamber which compromise a proper combustion. Also a test where "digestate 0" and "ENplus A1" wood pellets were mixed failed. The fuel obtained had better performance in terms of HHV and ash sintering but all the tests ended with the brazier bottom covered by sintered ashes. This issue slightly decreased the thermal performance of the air furnace. To overcome the problem, the raw digestate drying temperature was varied and it was found that the temperature which maximizes the HHV of the digestate is 150 ^{o}C. However, even if the ash content of "digestate 1" is lower than the type "0", it was decided to mix it with pure wood before pelletizing. This new pellet was called "ultimate digestate". The combustion of the "ultimate digestate" pellets shown an easier disaggregation of the agglomerates. Emissions evaluations of exhausts show a significant gap: the "ultimate digestate" pellet emissions are higher than the one produced by certified "ENplus A1" pellets with quite threefold contribute registered.

In addition, economical consideration will be done in order to compare this method to conventional methods of digestate disposal and/or utilization. On the other hand, environmental consideration about the convenience of this use could be done considering the bio-fuel Life Cycle Assessment (LCA) compared to the traditional use as fertilizer of this byproduct.

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4. FIGURES CAPTIONS AND TABLES

Figure 1: Combustion facility

Figure 2: Flash test analysis of "digestate 0" pellets

Figure 3: Klinker created by "digestate 0" pellets combustion

Figure 4: Velocity and temperature of the hot air flow with "digestate 0" pellets as fuel

Figure 5: Velocity and temperature of the hot air flow with wood pellets as fuel

Figure 6: HHV of the dried digestate varying the drying temperature

Figure 7: Temperature of the hot air flow with wood pellets as fuel

Figure 8: HHV of the dried digestate varying the drying temperature

Figure 9: Comparison between wood pellet "ENplus A1" and "ultimate digestate" pellet. AVL declare a resolution of 0.01 m^{-1} for the opacimeter K-value evaluation

5. TABLE OF FOOTNOTES

A) Tab.6 Combustion tests results. Pag 16

Text: Mean values represent what sensor has registered, the normalized ones were calculate whit an oxygen amount of 13% in the exhausted as indicated by normative.

Parameter	Symbol	Value
True density	ρ_{true}	1.510±0.002g/cm^3
Apparent density	$\rho_{apparent}$	1.260±0.002g/cm^3
Void fraction	ϵ_v	16.1 %
Diameter	D	6±0.01mm
Length	L	24.6±0.01mm
Carbon amount	C_{ar}	32.2±1%
Nitrogen amount	N_{ar}	1.3±1%
Hydrogen amount	H_{ar}	4.8±1%
Sulfur amount	S_{ar}	$\simeq$ 0 %
Moisture	M_{ar}	$\simeq$ 0 %
Ash amount	ASH	13.0±0.1%
Higher heating value	HHV_{ar}	14.0±0.1 MJ/kg

Table 1: "Digestate 0" pellets properties

	100% wood	50% dig.
Time of the test	30 min	20 min
Fuel mass	2.7±0.1 kg	1.8±0.1 kg
Feeding rate	5.4 ±0.1 kg/h	5.4 ±0.1 kg/h
Average ash content in the fuel	0.7±0.1%	7±0.1%
Average HHV_{ar} of the fuel	19.0±0.1MJ/kg	16.5±0.1MJ/kg
Average ambient air temperature	17.8±0.1^{o}C	15.9±0.1^{o}C
Average hot air temperature	58.9±0.1^{o}C	40.1±0.1^{o}C
Average hot air velocity	12.6±0.1m/s	12.3±0.1m/s
Average thermal power	15.8 kW	11.5 kW
Average overall efficiency	55.4 %	46.5 %

Table 2: Results of the combustion tests using wood pellets and a mixture of 50% wood pellets 50% "digestate 0" as fuel.

Parameter	T=105^{o}C	T=150^{o}C	T=200^{o}C
C [%wt.]	36.1±1	34.0±1	34.2±1
N [%wt.]	1.6±1	1.7±1	1.8±1
H [%wt.]	6.0±1	5.2±1	4.9±1
S [%wt.]	0.2±1	0.2±1	0.3±1
ASH [%wt.]	11.4±0.1	18.6±0.1	20.7±0.1
HHV [MJ/kg]	13.0±0.1	16.6±0.1	16.5±0.1

Table 3: Chemical characterization of the solid digestate varying the temperature of the muffle furnace

Parameter	Symbol	Value
Diameter	D	8±0.01mm
Length	L	32±0.01mm
Carbon amount	C_{ar}	33.32±1%
Nitrogen amount	N_{ar}	1.66 ±1%
Hydrogen amount	H_{ar}	5.32 ±1%
Sulfur amount	S_{ar}	$\simeq$ 0 %
Moisture	M_{ar}	$\simeq$ 0 %
Ash amount	ASH	13.8 ±0.1%
Higher heating value	HHV_{ar}	15.50±0.1 MJ/kg

Table 4: "Ultimate digestate" pellets properties

	100% wood	dig. "2"
Time of the test	19 min	21 min
Fuel mass	1.88±0.1 kg	1.85±0.1 kg
Feeding rate	5.9 ±0.1 kg/h	5.3 ±0.1 kg/h
Average ash content in the fuel	0.7±0.1%	13.77±0.1%
Average HHV_{ar} of the fuel	19.0±0.1 MJ/kg	15.5±0.1 MJ/kg
Average ambient air temperature	19.6±0.1 ^{o}C	19.4±0.1 ^{o}C
Average hot air temperature	54.2±0.1 ^{o}C	41.1±0.1 ^{o}C
Average hot air velocity	12.5 ±0.4 m/s	12.3 ±0.4 m/s
Average thermal power	35.62 kW	28.63 kW
Average overall efficiency	53 %	45 %

Table 5: Combustion tests result: wood pellet vs "ultimate digestate" pellet

	NO_x	O_2	NO_x [with 13% O_2]
Pellet "ENplus A1"	28.07 $\pm$1 [ppm]	16.55 $\pm$0.01 [%]	50.47[mg/Nm^3]
Pellet "Ultimate digestate"	149.97 $\pm$1 [ppm]	17.55 $\pm$0.01[%]	347.47[mg/Nm^3]

Table 6: Combustion tests results [A]

Figure

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Figure

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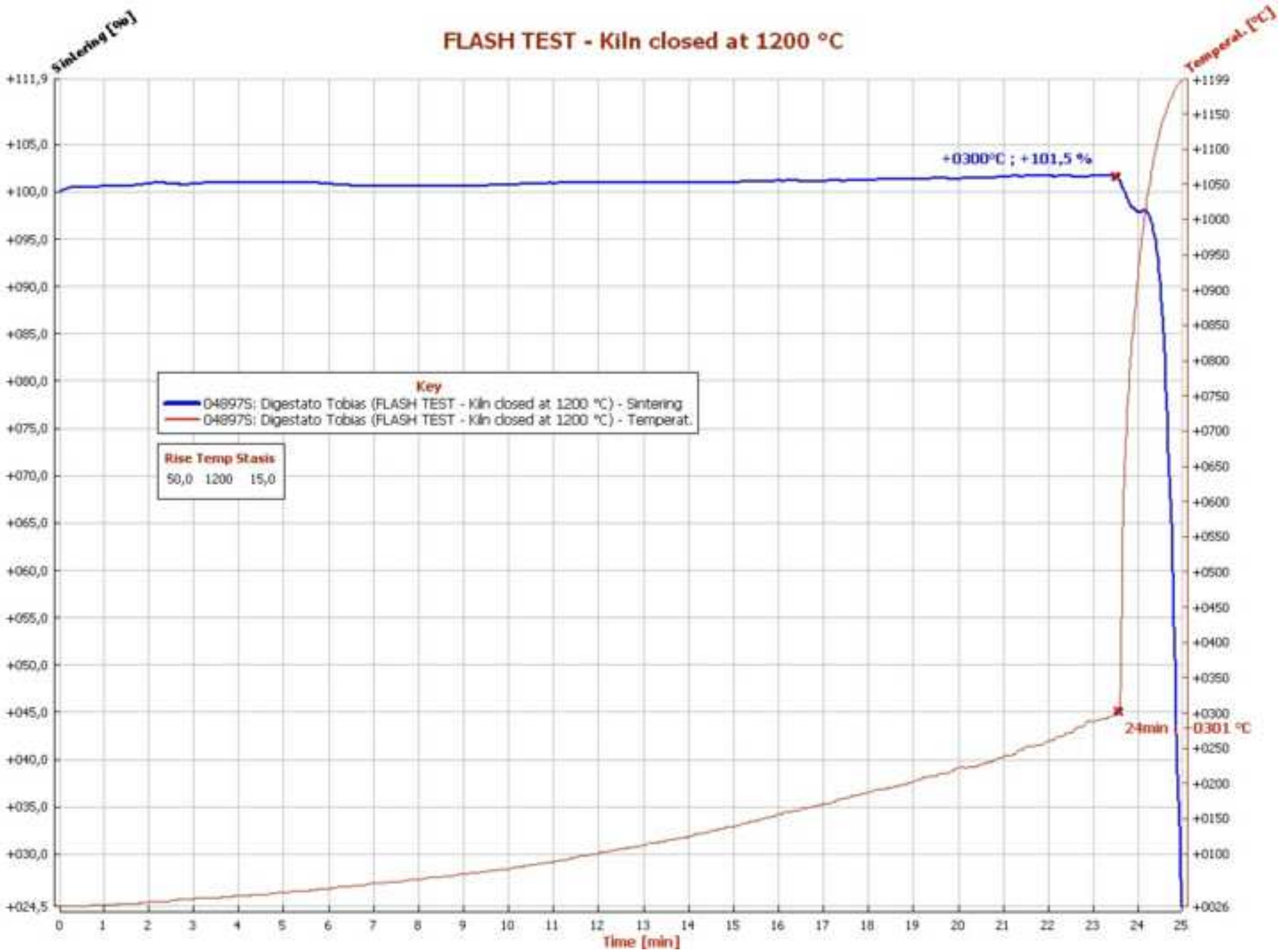

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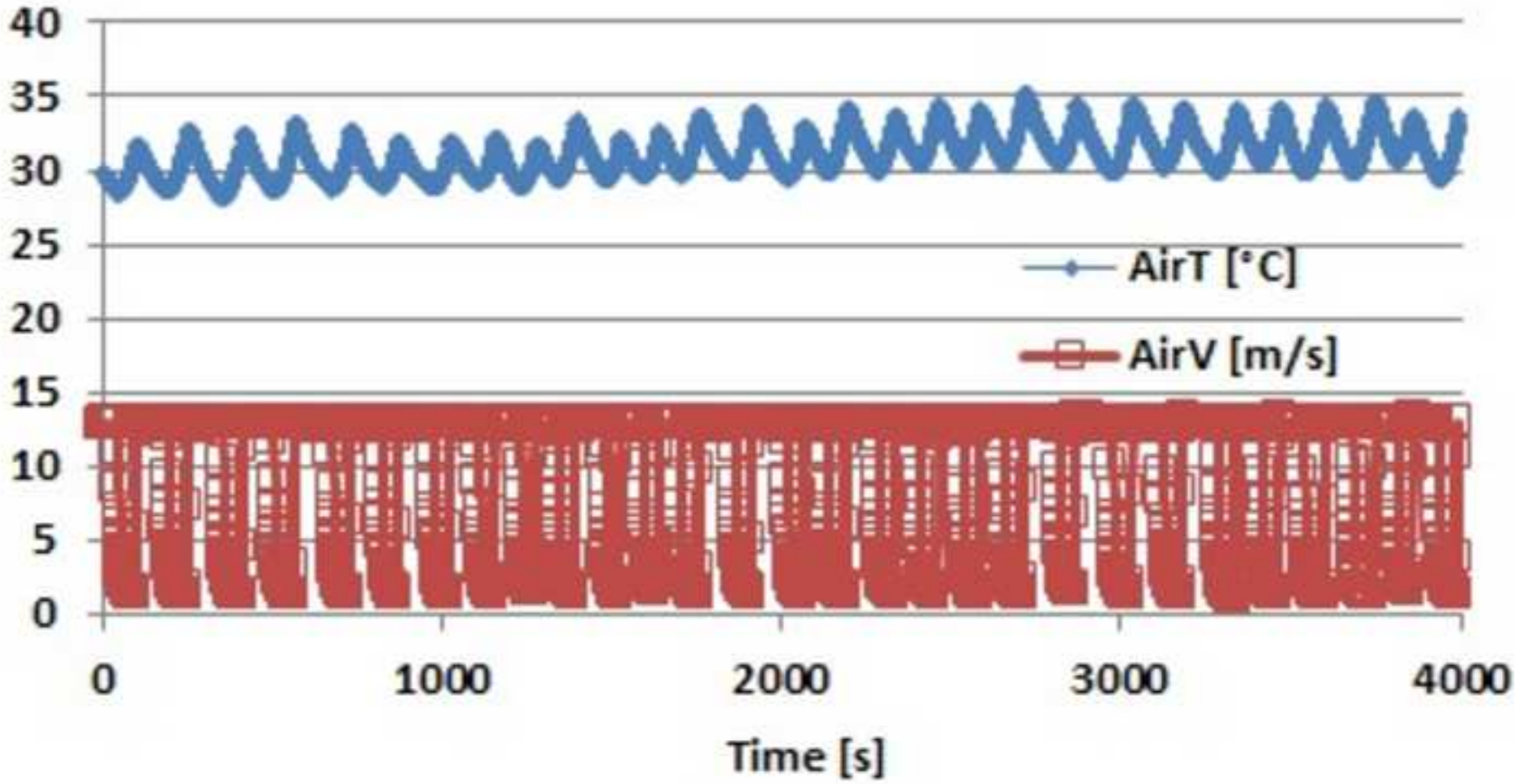

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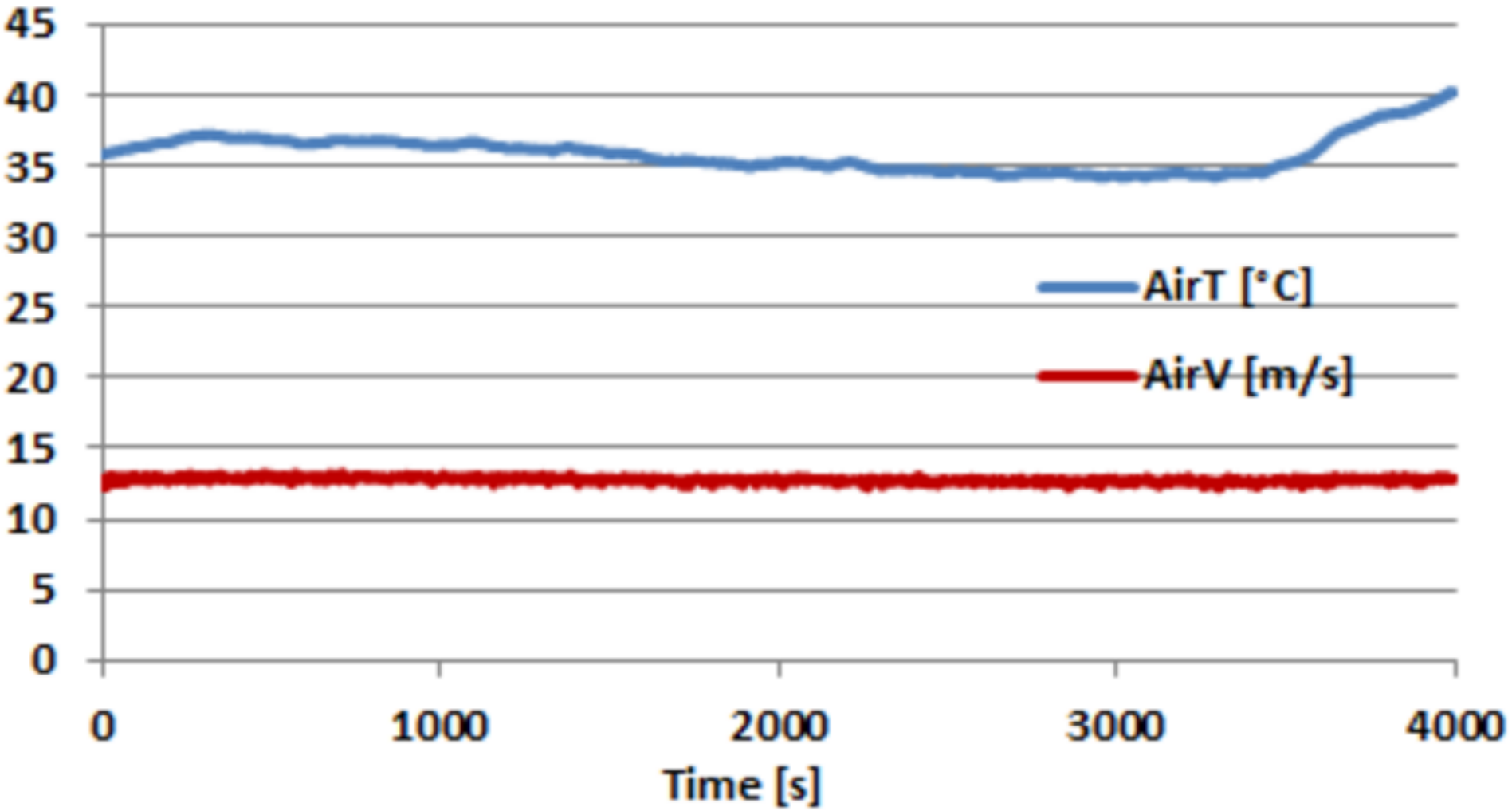

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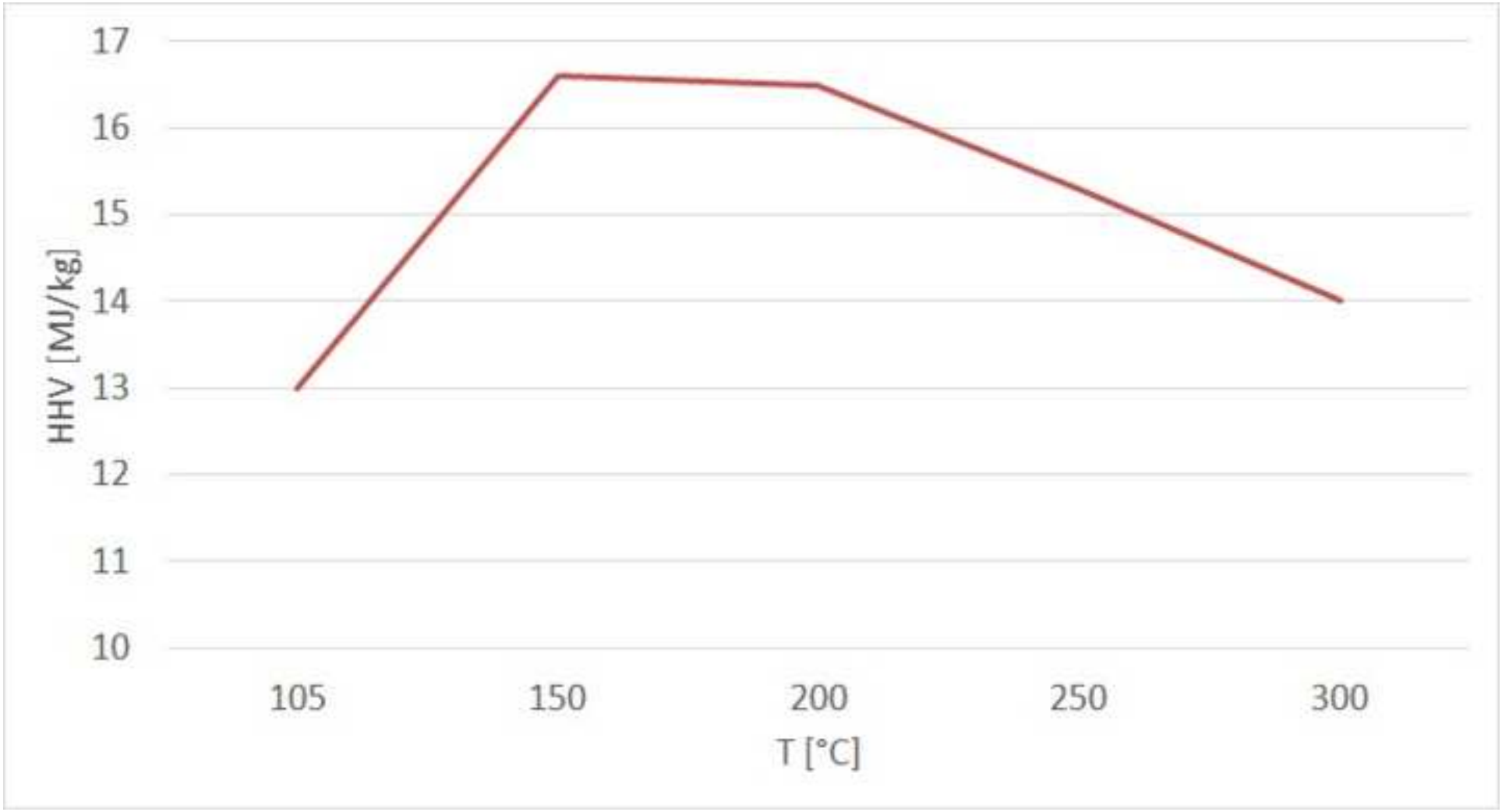

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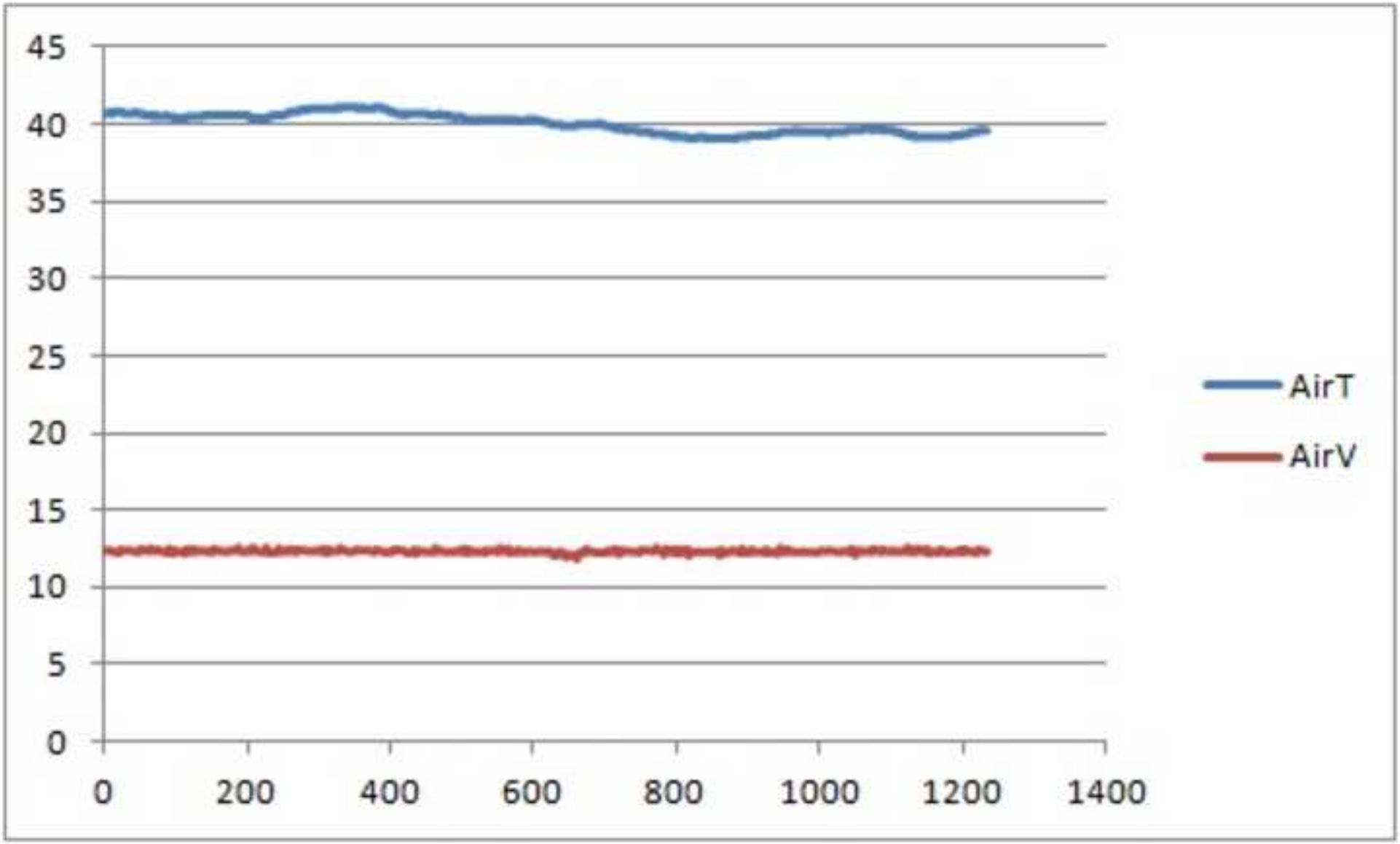

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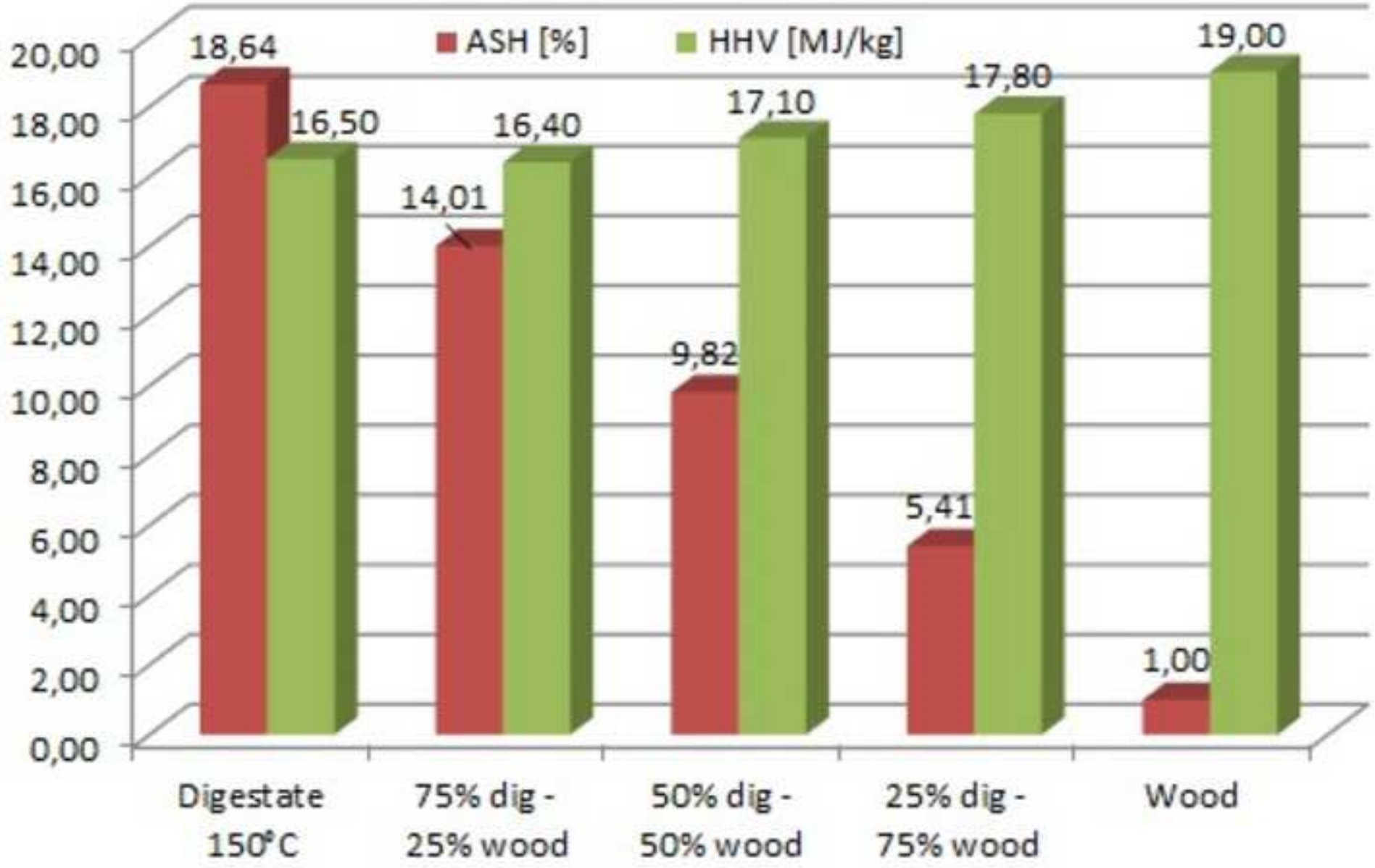

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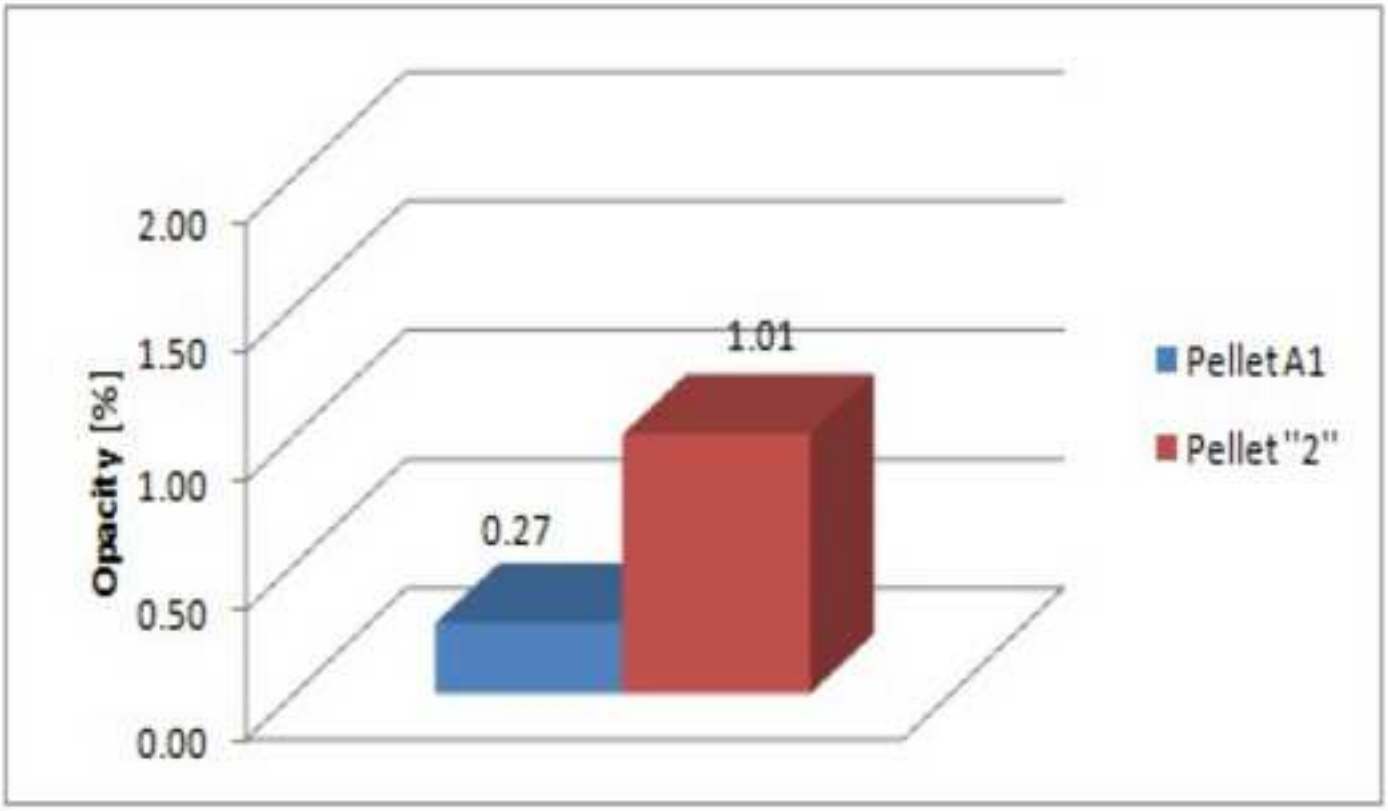
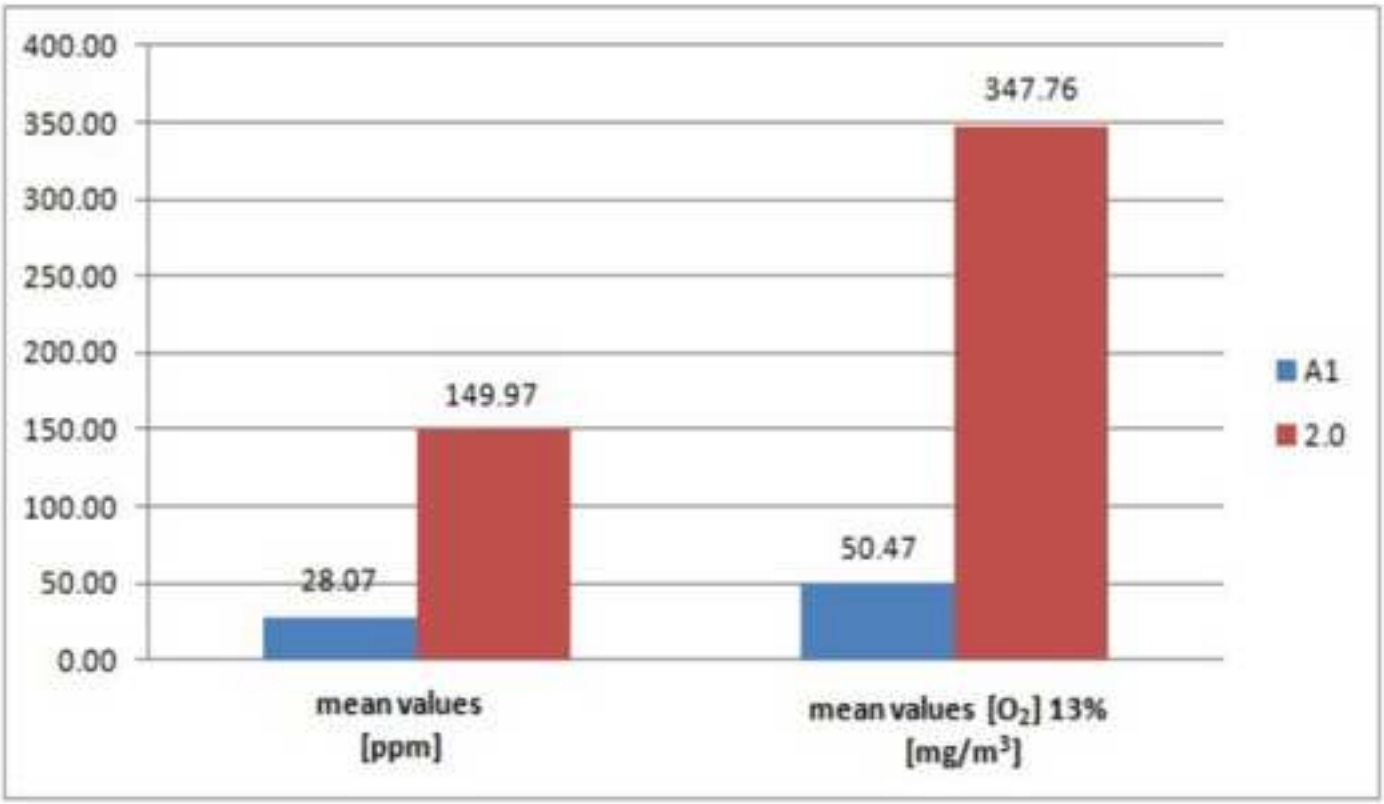


(a) Opacity mean values comparison



(b) NO_x comparison

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