Demonstration of the thermal valorisation of dried sludge through combustion over a flat moving grate

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Abstract: Thanks to the EU-funded “PerFORM Water 2030” project, a pilot plant for the thermal valorisation of sewage sludge has been developed and installed in the premises of an Italian wastewater treatment plant. The plant, based on innovative technologies for both sludge combustion and flue gas cleaning, has been tested during 2020 and 2021. The experimentation has provided relevant results on the performance and reliability of the technologies employed for pollutants capture, as well as some insightful information served as input for a Computational Fluid Dynamics analysis of the combustion process. Moreover, the analysis on the collected ash has shown the convenience of the proposed incineration technology for both reaching high combustion efficiency and easily concentrating the ashes for further recovery of precious material like phosphorus.

Keywords: thermal valorisation; dried sludge; phosphorus recovery; pollutants removal; flat moving grate

Introduction

Large amounts of sewage sludge are annually produced in every industrialized country by WasteWater Treatment Plants (WWTPs). The management of such a waste comprises agricultural use, landfill disposal, and incineration. On the one hand, the use as soil improvers and as basis for fertilizers is often problematic, because of the contents of organic and inorganic pollutants. Therefore, various legislations are setting more and more stringent limits, which are significantly reducing the room for these practices. On the other hand, the landfill disposal of a waste with appreciable contents of valuable elements (e.g., phosphorus) and energy is not compliant with the waste management hierarchy, as defined by the waste framework directive (EU, 2008). Incineration is, thus, emerging as the most promising way to manage this type of waste.

VOMM has been recently developing and demonstrating an innovative grate-based technology for the combustion of dried sludge and the recovery of its energy content, in the framework of “PerFORM Water 2030”, a Research and Demonstration Project funded by the Lombardy Region (Italy) through the EU ROP ERDF 2014-2020 fund, under the scientific supervision of Politecnico di Milano.

VOMM pilot plant for sludge incineration and thermal recovery

Figure 1 depicts the schematic layout of the pilot plant that has been built in the premises of a WWTP located in the south-east area of the Metropolitan City of Milan. The plant features a grate-based combustor of about 480 kW (LHV basis) thermal input, a heat recovery section to recover about 410 kW, and a flue gas treatment system.

This plant represents the first one in Italy employing the technology of flat moving grate applied to sludge combustion.

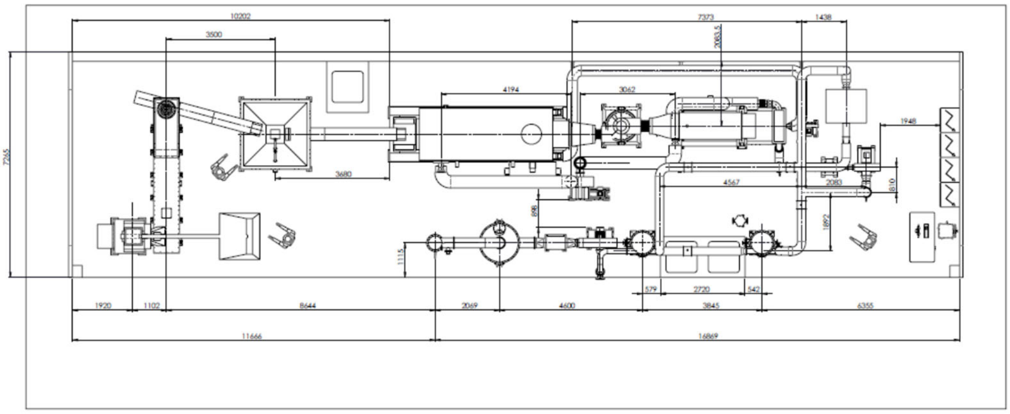

Figure 1 Schematic layout of the pilot plants that has been built in the premises of a North-Italian WWTP.

Sludge combustion takes place inside an adiabatic chamber, where pellets of dried sludge are fed onto a flat moving grate, leading to flue gas and ash production. Ash is mostly extracted from the bottom of the grate. Flue gas goes through the thermal recovery section, which allows supplying thermal power to district heating, WWTP facilities, etc., then through the flue gas treatment line, which comprises five stages, of which two are innovative systems developed by VOMM. The consecution of the equipments is the following:

1. Dried sludge pelletizer
2. Incineration oven with flat moving grate
3. Adiabatic chamber
4. Adiabatic cyclone (VOMM patent)
5. Heat recovery system
6. Air pre-heater
7. Fabric filter
8. Venturi scrubber n.1, operating with water solution (VOMM patent)
9. Venturi scrubber n.2, operating with sodium hydroxide
10. Activated carbon filter

Aims of the project

First objective of the operating campaigns is to demonstrate the performances and the reliability of the developed technologies for incineration and thermal recovery from dried sludge, and to verify the effectiveness of the different gas cleaning stages.

Secondly, the desire is to investigate, thanks to experimental activities, a number of aspects:

1. Breakdown of ash and pollutants among the various collection points
2. Utility of installing VOMM high temperature cyclone
3. Possible introduction of a Selective Non-Catalytic Reduction (SNCR) system instead of Selective Catalytic Reduction (SCR) system for the abatement of nitrous oxides
4. Validation of a model able to reproduce the combustion process and its multi-physics, to predict and optimize the yield of the incineration oven

Experimental results

The experimental activity has been carried out by means of four campaigns of one or two consecutive weeks of operation during 2020 and 2021, in order to demonstrate the performance and the reliability of the developed technologies.

An all-encompassing plan for the sampling and analysis of solid residues, liquid effluents, and gas emissions was implemented during the experimentation, and has originated many analytical results, which made possible to fulfil the aims presented above.

First of all, the experimentation has proved the sustainability and the correct functioning of the whole process of incineration, as well as of the flue gas cleaning process in its multiple stages. In particular, feeding 100 kg/h of dried sludge with 88% of dry matter, is sufficient:

a) to make the plant autothermal with no auxiliary fuel needed

b) to obtain 950°C – 1.000°C in the combustion chamber

c) to keep flue gas for more than 2 seconds at a temperature above 850°C, thermally destroying PCDD/F

d) to recover a thermal power of 250 kW or more, depending on the PCI of the processed sludge

e) to yield ashes with low carbon residual content (TOC < 3%)

Figure 2 reports the trend, during 12 hours of operation, of temperature transmitter TT03, which is placed on the exit of flue gas from the adiabatic chamber, proving the former statements: the temperature trend is nearly a horizontal line corresponding to a constant sludge flow imposed, whereas the burner intervention would result in a rising curve from 850°C up to the set point of the temperature required (890°C).

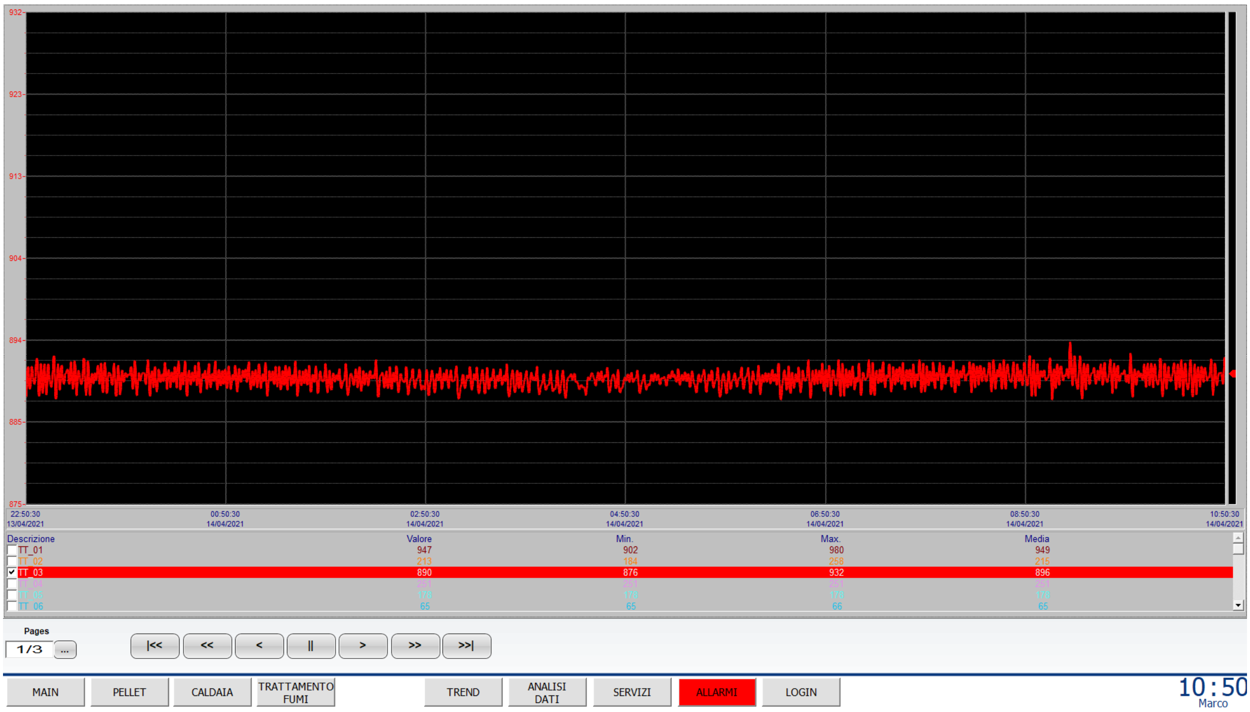

Figure 2 Trend of flue gas temperature exiting from adiabatic chamber, during 12 hours of operation. Temperature (y-axis) versus time (x-axis).

Here are resumed a few data regarding the amount of sludge processed by the plant, the energy recovered through its combustion, and operating hours of experimental activities accumulated:

- Dried sludge incinerated: about 63.000 kg
- Hours of operation: about 700 hours
- Average dried sludge flow: about 110 kg/h
- Ashes generated: about 24.000 kg
- Thermal energy produced: about 151 MWh

A first main result is that employing pelletized sludge on the flat moving grate leads to 92-96% of the total amount of ashes as bottom ashes from the grate. Moreover, it has been observed (as figure 3 shows) that they keep a perfect cylindrical structure as the one that pellets originally owned. This represents a great advantage linked to the choice of employing flat grate with pelletized sludge since:

1. It facilitates storage and removal of the ashes, as they are almost collected from one point only, i.e., at the end of the grate
2. Ashes are not dusty thanks to their compact structure
3. The recovery of phosphorus and other precious metals leads to major extraction efficiency because ashes are not contaminated from other materials (for example the sand of fluidized bed reactors), and their concentration of precious elements is the highest
4. The following systems, as the boiler, the pre-heater, etc., are preserved from erosion and fouling since the quantity of flying ashes is the lowest (4-8% only).

Figure 3 Bottom ashes from the grate represent 92-96% of total amount of ashes.

Secondly, the efficiency of the high temperature adiabatic cyclone introduced by VOMM has been investigated. Weight analysis show that the cyclone is able to capture from 4% to 7% of total ashes coming from sludge combustion, leaving only 1% or less of total ashes going through the following systems as fly ashes. Thus, it is possible to conclude that employing the adiabatic cyclone is very useful because:

1. boiler and following heat exchangers lifetime would be longer since the erosion is drastically reduced

2. fabric filter have to bear much less of fly ashes deposit so their availability is improved
3. it will be necessary a lower quantity of compressed air to clean fabric filter

Regarding the introduction of SNCR system for NOx removal, it has been foreseen an urea injection system inside adiabatic chamber, to evaluate during the different campaigns its effectiveness. In fact, nitrogen is contained in high quantity inside all sludges, of civil as well as of industrial origin, and, therefore, it may lead to high production of fuel-NO_x.

Thanks to analytical data collected on flue gas exiting from the stack, it has been possible to compare NO_x emissions before and after the activation of SNCR; the results are shown in the following table and demonstrate the efficiency of the system employed. If the combustion process is well conducted, it is not necessary to adopt an expensive SCR system to meet emission limit relative to NO_x imposed by IED directive, since it is sufficient employing SNCR technology, taken for granted a proper installation of injection nozzles inside the chamber, maybe with the contribution of a Computational Fluid Dynamics (CFD) study.

Period of analysis:	**SNCR operation:**	**NO_x concentration at stack:**
2nd campaign (October 2020)	OFF	585 mg/Nm^3
3rd campaign (April 2021)	ON	44,8 mg/Nm^3

Table 1 Efficiency of SNCR system for NO_x removal. NO_x concentrations are referred to dry gas at 11%O_2 as NO_2

Computational Fluid Dynamics models of combustion on the grate

Concerning the simulation of combustion process, two CFD studies of the bed of burning sludge over the grate has been conducted (Sanchez, 2019; Rossi, 2020). The activity aims to create a theoretical model that supports the practical use of sludge waste-to-energy technology in a grate combustor.

Figure 4 reports the preliminary results that show the almost complete consumption of the solid carbon in the sludge during the process along the grate, as it was expected.

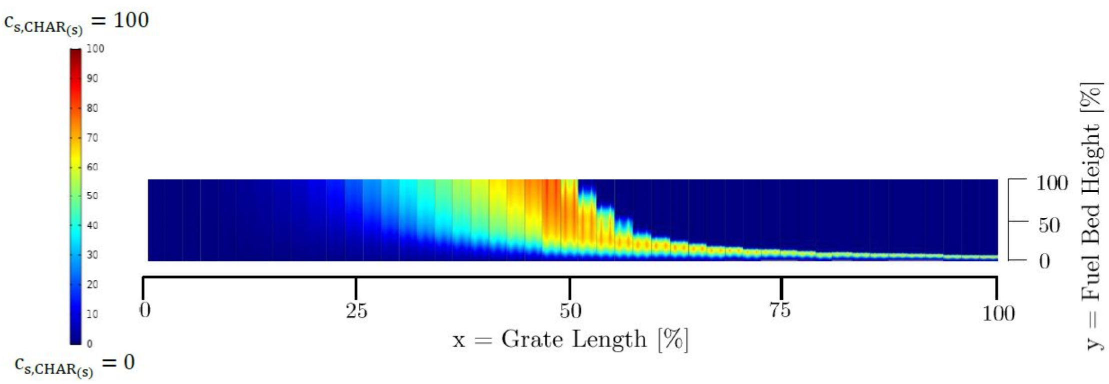

Figure 4 First results (Sanchez, 2019) of the CFD analysis of the bed of burning sludge on the grate of the combustor. Different colours represent the concentration of solid carbon and show its almost complete consumption during the process.

The first CFD model, however, needed further refinement and tuning, which has been carried out (Rossi, 2020) starting from the data collected during the experimentation on the pilot plant. The theoretical simulation, conducted in parallel with the experimentation during the campaigns, produced mutual benefits both in terms of model refinement and optimization of the plant operation.

The refined and updated CFD model shows a physically correct description of the complex set of combustion phenomena that occur inside the mobile grate combustor of the pilot plant. The moisture evaporation is the first phenomenon that occurs, with a kind of "reaction front" that moves from the grate to the upper surface of the fuel bed thanks to the flow of preheated air provided under the grate. Only when evaporation is over, the devolatilization or pyrolysis process begins.

Pyrolysis reaction penetrates the fuel bed from the top surface down to the level of the grate. The radiation heat that diffuses from the free-board region of the combustor onto the surface of the fuel bed is the key parameter driving the penetration of the pyrolysis process. The developed model considers a constant temperature of 1300 K for the radiation that affects the bed of pellets. The coupling with a free-board region model is a possible improvement of the developed CFD model.

Until the pyrolysis is completed, there is no oxygen available for the oxidation of the char, since this reagent is consumed by the combustion of the volatile gases (modelled as a mixture of mainly methane and carbon monoxide) released by the pyrolysis. Volatiles that are not fully oxidized in the bed, due to insufficient oxygen availability (as shown in figure 5), end up in the free-board region, where they develop flames in gaseous phase, encountering oxygen from the other sections of the grate.

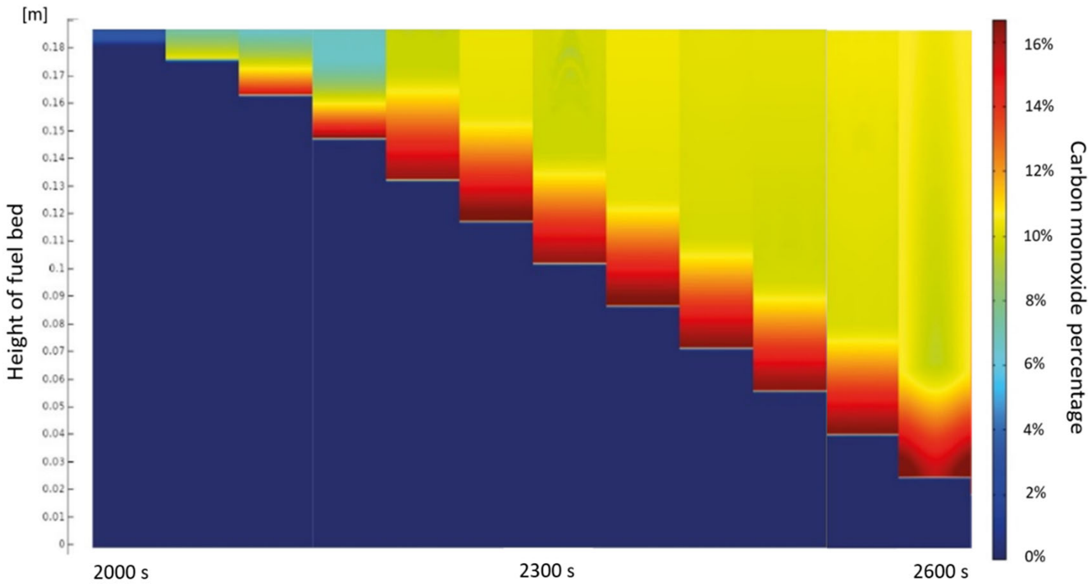

Figure 5 Carbon monoxide concentration in some assembled bed slices, during the pyrolysis process. Note the presence of CO above the reaction front due to the limited oxygen availability.

Eventually, when the pyrolysis is almost completed, the availability of oxygen triggers the combustion of the char, which moves from the bottom part, i.e., from the level of the grate, to the top surface of the fuel bed (see Figure 6). The CFD model made possible to understand that the key process of the entire sludge combustion is pyrolysis. Its speed is strongly influenced by the penetration of heat from the top surface of the combustion bed into the solid domain.

The last phase of the whole process, i.e., the char combustion, is the slowest and continues as long as some char is still present on the grate combustor. The CFD results show that the char conversion cannot be completed, due to the “quenching” effect of the relatively cold grate on the thin layer of fuel bed in contact with it. The relatively cold air, entering the combustion bed through the air inlet holes, cools down not only the grate but also the thin layer of char on the grate that remains after the devolatilization reaction. In the CFD model this char layer does not undergo mixing due to the peculiar dynamics of the flat moving grate. Therefore, the layer near the grate has no possibility of being heated enough to allow the combustion reaction to develop. Overall, given the ash content of the fuel, unburned carbon represents less than 1% of the bottom ash produced on weight basis, thus respecting the legislative limit of 3% fixed by European Directive 2010/75/EU.

This scenario returned by the CFD model was confirmed by the results of the experimental campaigns conducted on the pilot plant, proving a certain adequacy and the correctness of the hypothesis assumed.

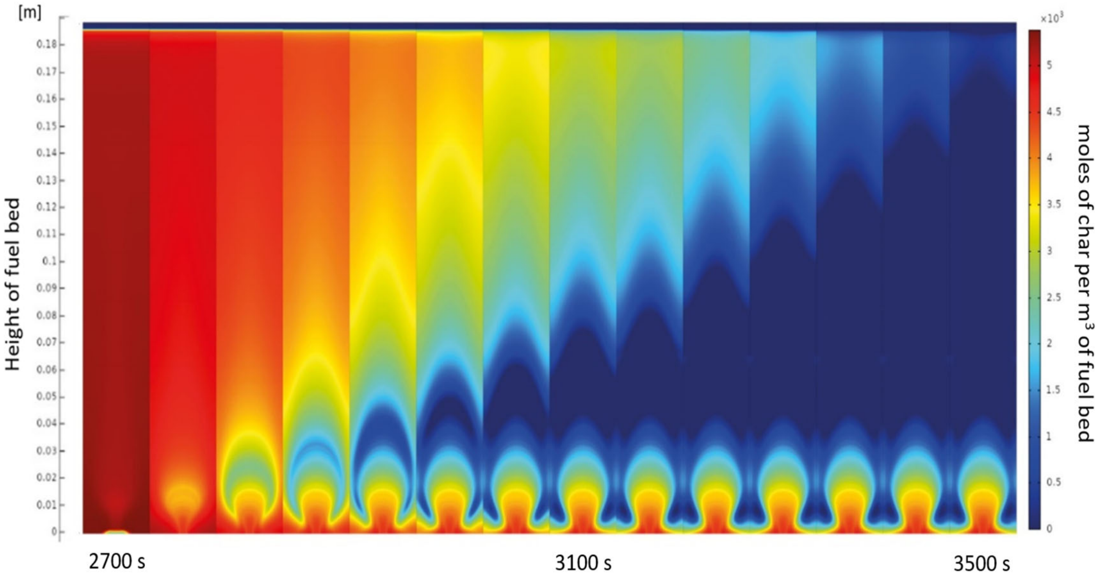

Figure 6 Concentration of char in some bed slices assembled together, during the main part of the char combustion process. Note that a small region of unconverted char remains at the grid level.

Conclusions

The experimental activities conducted on the pilot plant have demonstrated the environmental sustainability of the proposed thermal valorisation process applied to dried sludge and the convenience of employing a grate combustor to obtain the highest quantity of bottom ashes suitable for phosphorus recovery. The analytical results collected made possible to verify the effectiveness of gas cleaning stages, in particular of the SNCR system and of the high temperature cyclone. Finally, the CFD studies of the combustion process along the grate helped to better understand the role and the mechanism of the physics involved and have given the way to predict the combustion efficiency as regards the total organic carbon unburned.

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