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Advanced Modular and Integrated Equipment Design Trend in Waste-to-Energy Processes

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Proper processing and management of various types of waste represent an important feature of a developed society. Thermal processing followed by heat utilization of waste (or Waste-to-Energy) provides an excellent solution to reduce environmental pollution, and simultaneously to maximize the financial profit. Following the current trend of energy decentralization by small energy sources, this paper presents several novel incineration-based technologies for processing solid and gaseous wastes. In the case of solid waste processing, the micro-incineration unit, called EVECONT, is presented as a modular advanced technology enabling environmentally-friendly and energy-efficient waste management in place of its origin. Subsequently, two industrial units for waste gas treatment are introduced in an up-to-date integrated design enabling the minimization of the built-up area and heat losses. Finally, an experimental unit based on Urea hydrolysis for NO_x removal from flue gas is presented as a promising complementary technology to Waste-to-Energy processes.

1. Introduction

Society development and increasing live standard are associated with waste production, which grows at a rapid pace. Besides the solid waste from the communal area, various industrial plants produce also liquid and gaseous wastes. Proper management and disposal of waste are necessary for the sustainable development of any country and preventing land and marine pollution (Chand Malav et al., 2020). In the case of municipal solid waste, the developed countries employ alternative approaches, such as recycling or reusing, to reduce or stop landfilling, which still remains the most frequently applied waste management method. In the USA, for example, 53 $\%_{wt}$ of municipal solid waste is landfilled, while only 25 $\%_{wt}$ is recycled (Mukherjee et al., 2020). There are several drawbacks to the wider implementation of recycling, as the necessity of waste separation and removing various contaminants (food residues, etc.), which brings excessive financial and technology demands (Dogu et al., 2021).

Waste-to-Energy (WtE) processes present excellent alternative waste management methods to traditional landfilling. The energy contained in the waste is in WtE technologies recovered, which provides a suitable and sustainable substitute to fossil fuels (Murtala et al., 2012). The WtE process is based on principles of circular economy, which brings, besides pollution mitigation, also a financial profit. Waste incineration is the most frequently applied WtE method, which went through a vast development from simple waste disposal to the up-to-date WtE units, where their design combines the waste disposal and the maximum energy recovery (Tabasová et al., 2012).

Currently, the number of waste incineration plants is very low. In the Czech Republic, for example, there are only 4 municipal solid waste incineration plants. For efficient future wider use of WtE technology, one of the key points is the development of the models for waste production and tracing, forecasting, and strategy planning, such as the research published by Smejkalová et al. (2020).

The main drawback of waste incineration as the WtE technology is a high capital cost associated especially with a complex emission control technology (Dogu et al., 2021). In order to overcome this shortcoming, the incineration-based WtE technology must be improved to maximize its performance for a lower investment.

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To overcome this shortcoming, this paper presents in the first part a modular waste incineration plant called EVECONT with a capacity of 2.4 kt/y. This recently built modern integrated equipment (MIE), processing non-recyclable plastic waste, provides an environmentally friendly, energy efficient, and (with the modular arrangement) economically viable solution, which follows the 3E (Economy-Energy-Environment) strategy.
Besides solid waste management, the gaseous industrial waste, containing combustible pollutants (e.g., Volatile Organic Compounds), represents another significant potential source of pollution. These gaseous wastes are traditionally combusted in the combustion chambers with a supplemental fossil fuel to thermally decompose combustible pollutants. The supplemental energy demand, which results in very expensive operation, can be reduced by introducing the waste gas preheater to utilize the produced energy in the form of the generated flue gas (Schnelle et al., 2015). On the other hand, this WtE technology, consisting of the combustion chamber and the preheater, is associated with high investment costs, excessive built-up area, and heat losses. To overcome this shortcoming, the MIE trend, suggests integrating the devices to a single apparatus enabling the waste gas preheating and thermal processing in one body, as shown in Figure 1. This paper presents two industrial MIE units processing waste gasses from the wastewater treatment plant and from the natural gas dehumidification process.

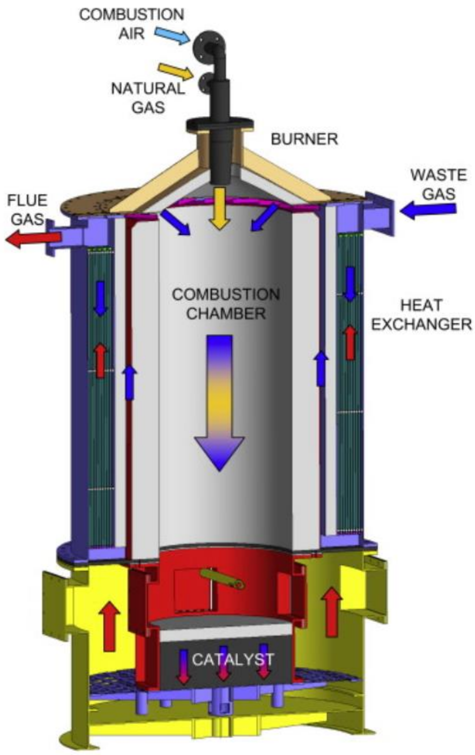

Figure 1: Modern integrated equipment for thermal processing of waste gases (Stehlik, 2012)

As Dogu et al. (2021) mentioned, waste combustion requires often very intensive flue gas cleaning. Among others, Nitrous Oxides (NO_x) represent a significant part of pollutants´ content. NO_x removal requires flue gas cleaning technology to fulfil emission limits. Selective Catalytic Reduction (SCR) in combination with Ammonia reagent reach an excellent NO_x removal efficiency up to 90 $\%_{vol}$ (Schnelle et al., 2015). On the other hand, Ammonia purchase, handling, and storage are associated with high operational costs and safety precautions. To overcome this shortcoming, the modern trend is generating ammonia onsite via Urea Hydrolysis immediately before its injection into the flue gas. Zhang et al. (2017) published results of an NO_x removal experiment in a large industrial boiler employing a pilot Urea hydrolyzer. This technology has been so far used only in large combustion processes, but its use in small-capacity waste incineration plants has not been researched yet. In order to fill this research gap, this paper presents a tailor-made experimental urea hydrolyzer, which can be used for NO_x removal in small-capacity waste incineration plants.

2. Modern integrated equipment – new trends in WtE technology and flue gas cleaning

Standard WtE technology design trend primarily offers suitable solutions for high-capacity processes. There is a lack of efficient and economically viable solutions for subregions, as industrial complexes, municipalities, hospitals, etc. Small-capacity WtE units, which are one of this paper´s topics, would enable waste disposal in place of its origin and energy utilization to cover the energy demand of adjacent complexes.
The flue gas cleaning system for NO_x removal can also be enhanced by thermal integration to the WtE process to increase operational safety and reduce operational costs.
In the paragraphs below, there are presented specific industrial cases of the Modern Integrated Equipment (MIE) reflecting a modern trend in solid and gaseous wastes´ thermal processing and in efficient NO_x removal from the flue gas.

2.1 Solid waste management and energy utilization – micro incineration unit EVECONT

EVECONT is a modern small-capacity incineration plant, which processes plastic, non-recyclable waste with a capacity 2.4 kt/y. The waste energy is utilized to produce 2 MW_{th} of heating steam for district heating in a nearby municipality. The plant is built in an industrial complex of a company C-Energy Ltd. in Czech Republic. The whole construction of the unit took place between 07/2019-02/2020 from the initial groundworks to the first operation with plastic waste. Very short construction time was achieved by the modular arrangement of the unit, which is apparent in Figure 2. The basic technological layout of the unit is illustrated in Figure 3. The key parts of the unit (boiler, control and measurement systems, sorbents´ injection technology, etc.) were assembled at suppliers´ facilities and then only transported on the construction site. This approach reduced both, the investment cost and construction time. Despite the small size of the unit, EVECONT includes all necessary technologies for efficient and green waste utilization.

Figure 2: EVECONT – micro incineration unit for thermal processing of plastic non-recyclable waste

As Masa et al. (2018) mention, the industrial partners are not willing to endanger the overall operational safety by risky projects with uncertain financial outcomes. For this reason, there is applied only verified technology, which is optimized to the modular arrangement. EVECONT unit can easily utilize mechanically untreated pressed waste as well as milled waste. According to the composition tests, the plastic waste´s average Lower Heating Value of 25 MJ/kg and high amount of combustibles (85 $\%_{wt}$) present this kind of waste as very efficient for energy utilization. Due to the relatively low amount of water contained in the waste (5 $\%_{wt}$), the undesirable flue gas condensation was not observed even at the stack temperatures around 100 °C. Finally, as the plastic waste´s ash content is around 10 $\%_{wt}$, so the combustion process generates less ash than, for example, the combustion of lignite. It is a suitable technology for processing contaminated and multilayer plastic waste from, e.g., food packaging, differing by size and composition. Flue gas cleaning system reduces the emissions bellow their regulated emission limits. In more detail, EVECONT technology is described in the magazine All for Power (2020).

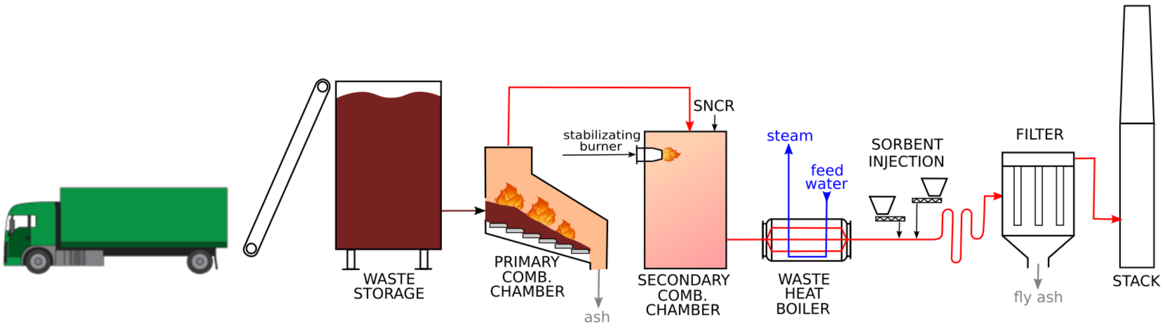

Figure 3: EVECONT – the basic process scheme

2.2 Compact technology for gaseous waste thermal treatment

Thermal oxidation is a very reliable and efficient method for processing waste gasses containing combustible pollutants, as Volatile Organic Compounds or Carbon Monoxide. On the other hand, the pollutants´ thermal decomposition requires high reaction temperatures reaching up to 1,100 °C, which is associated with very high energy demand in form of supplemental fuel. But, as Stehlik (2012) recommends, every waste treatment process should be considered from the WtE point of view instead of simple waste disposal.
In order to reduce the energy demand and simultaneously to reduce the number of apparatuses to a minimum, the concept of compact MIE technology was developed by coordination of scientific research and industrial application.
As a result, two industrial fully automatic units for thermal processing of waste gases are presented in Figure 4. According to the current waste gas composition (especially the VOC concentration), both units provide several operational modes in order to minimize the energy demand, while operational safety is maintained.

a) Processing of waste gases from waste water treatment plant

b) Processing of waste vapors from natural gas dehumidification plant

Figure 4: Industrial application of compact MIE technology for waste gas thermal treatment.

2.3 Thermally integrated flue gas cleaning technology – experimental Ammonia generator

Many combustion processes produce flue gases with the concentration of NO_x above emission limits, so some NO_x control technology has to be applied. As mentioned in the Introduction section, Selective Catalytic Reduction (SCR) provides an excellent solution in terms of NO_x reduction. The main drawback of SCR is the necessity of the use of toxic and explosive ammonia as a reducing reagent.
In practice, Anhydrous Ammonia or Ammonia solution are used, which brings excessive operational costs and risks for storage and handling.

To overcome this shortcoming, the modern trend is producing ammonia on-site directly before its injection to the flue gas from Urea solution, which is safe to store and handle. By hydrolysis reaction of Urea solution (see the chemical reaction (1) below) at elevated temperatures (above 120 °C) and pressures (around 6 bar_{abs}) (Zhang et al., 2017), the gaseous mixture of Ammonia, Carbon Dioxide, and excessive water is produced.

$$NH_2CONH_2 + H_2O \leftrightarrow 2NH_3\uparrow + CO_2\uparrow \quad (1)$$

It is an endothermic process requiring an energy input in the form of, e.g., steam or electricity. In the WtE technology, a small part of produced energy can be used for Ammonia generation, which represents an energy integrated flue gas cleaning equipment as a new trend of MIE technology for efficient NO_x removal. A simplified process layout is illustrated in Figure 5.

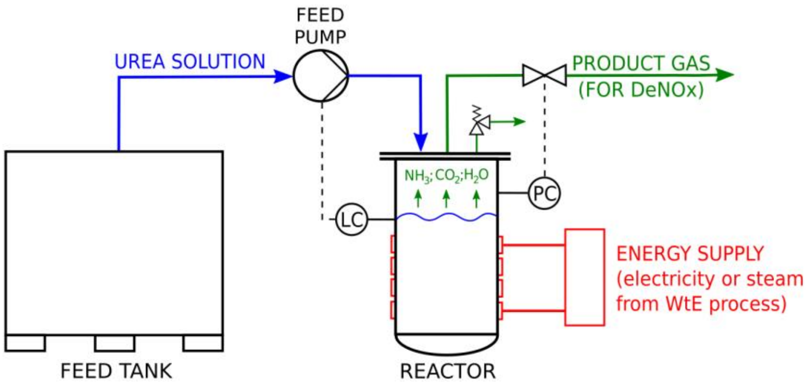

Figure 5: Process layout of MIE equipment for flue gas cleaning

Several urea hydrolysis reactors have been tested already in medium and large combustion processes, but there is no research focusing on their application in low-capacity WtE technology, which is characteristic by very rapid flue gas flowrate deviations due to the waste inhomogeneous composition and high sensitivity to sudden burnouts. For this reason the Urea hydrolysis-based Ammonia genetator for low-capacity WtE processes must, generate Ammonia product gas dynamically enough to reduce NO_x concentration and at the same time to avoid an excessive Ammonia slip.

In order to research the possibility of Urea hydrolysis application for the previously mentioned purpose, an experimental reactor is currently constructed for future tests (see Figure 6). The reactor is an electrically heated vertical cylinder pressure vessel made of stainless steel (AISI 316 Ti). The dimensions of the reactor were obtained according to the calculation of the reaction kinetics published by Zheng et al. (2013).

Figure 6: Experimental Ammonia generator (under construction).

3. Conclusion

The objective of this paper was to present several technologies for thermal processing and energy utilization of waste. At first, the micro-incineration unit EVECONT was described as a modular WtE unit for processing plastic non-recyclable waste. This technological configuration benefits from container arrangement advantages, such as easy transport of technology and short construction time. On the other hand, the investment costs are still relatively high in relation to the unit´s capacity, so every application must be considered carefully respecting key aspects, as waste availability and energy demand (district heating, etc.). This technology can be modified to any kind of combustible solid waste, so it can provide an interesting solution for waste-producing and energy consuming subregions, as municipalities and industrial complexes.
The compact incineration-based technology for gaseous waste treatment was then presented along with two operating industrial units of this type. An integrated solution, combining the combustion chamber and preheating section, reduces heat losses and consequently the supplemental fuel demand. The built-up area is also minimized, which is suitable especially in applications with strict space limitations.
In the end, the conceptual solution of heat integrated SCR system to the WtE technology is introduced as a possible technology for efficient NO_x removal from flue gas. The key device is the experimental Urea hydrolysis-based chemical reactor, where ammonia is produced as a reducing reagent for SCR.

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