

MODULAR BOILER HOUSE FOR DISTRIBUTED BIOMASS AND RDF CO-INCINERATION

Dmitrijs Rusovs¹, Sandis Gromovs², Janis Meikulans²

¹Riga Technical University, Latvia; ²SIA “EcoHeat Technologies”, Latvia
dmitrijs.rusovs@rtu.lv, info@ecoheatholdings.lv, janis.meikulans@ecoheatholdings.lv

Abstract. Technology of Waste-to-Energy (WtE) for regeneration of Municipal Solid Waste (MSW) is already used in more than 499 incineration plants across Europe. Mostly used are grate firing steam boilers with power input of few tens of Megawatt. In this case boiler furnace has sufficient volume to provide flue gas residence time which ensures dioxin decontamination. Subsequent flue gas cleaning methods use wet or dry technology for harmful component removal. However, big scale of considered WtE plants request sufficient MSW flow. Another approach to waste regeneration presents combustion of mixed fuel (with some portion of waste with convenient fuel) in small scale boilers which are not able to regenerate untreated waste. However, the demand for distributed waste regeneration can be coupled with available heating plants using biomass as fuel. This paper deals with integration of an existing moving grate 2.5 MW furnace into a modular plant able to ensure Refuse Derived Fuel (RDF) co-incineration with wood chips. Additional part of the modular design will include a fuel handling module where RDF will be mixed with wood chip flow, a unit for flue gas treatment, like a post combustion chamber and flue gas cleaning system with an advanced monitoring system. Since waste combustion generates harmful emissions like dioxin, the environmental regulation requests to retain flue gas after combustion at high temperature at least 2 seconds before it enters the heat exchanger (boiler). Therefore, the focus of the paper is devoted to estimation of the flue gas flowrate in the furnace and estimation of the post combustion chamber volume. The case study describes redesigning and rebuilding the existing modular co-incineration biomass and RDF heating plant developed by SIA “EcoHeat Technologies”. The plant is integrated with a semidry flue cleaning system, temperature and emission control, fuel feeding system and air flow management.

Keywords: regeneration; waste; flue gas; modular design.

Introduction

Within the framework of the Directive 2000/76/EC [1], municipal solid waste (MSW) incineration has become a widely adopted solution to address challenges in waste management [2; 3].

In 2023, MSW treatment in the European Union was distributed among several methods, with incineration accounting for 25.6% and landfill disposal for 23.4% [4].

By 2015, approximately 1,179 MSW incineration plants with energy recovery were operating worldwide, with a combined treatment capacity exceeding 700,000 Mg per day. This corresponds to an average capacity of approximately 600 tonnes per day for each facility [2]. On an annual basis, such a plant requires roughly 216,000 tonnes of MSW for continuous operation.

According to the Confederation of European Waste-to Energy (WtE) Plants (CEWEP) 2023, over 499 WtE facilities were operational in Europe, collectively incinerating around 101 million tonnes of residual waste annually [5].

Waste incineration is primarily driven by two key factors: energy recovery and landfill diversion. First, the process enables the regeneration of energy through the conversion of waste materials into heat and electricity. Secondly, WtE processes contribute to reducing reliance on landfills by significantly decreasing the volume of waste requiring final disposal. Residual waste treated in such facilities is combusted under controlled conditions, resulting in an approximate 90% reduction in volume.

For example, the waste disposal challenge in the Stockholm region has been effectively addressed through the implementation of waste incineration at the Högdalen facility. This plant processes approximately 700,000 tonnes of waste annually and operates as a combined heat and power (CHP) system, generating about 3.6 TWh of heat and 0.3 TWh of electricity [6].

Integrated waste management systems enhance the efficiency of regeneration processes. A comparative analysis of energy flows for the treatment of 8,500 tonnes of municipal solid waste (MSW) indicates that the total energy input required for processing and transportation is 383 GJ. In contrast, energy recovery achieved through waste regeneration amounts to 18,884 GJ [7]. These results demonstrate that the energy generated from MSW recycling exceeds the energy consumed by approximately a factor of fifty, highlighting the significant net energy benefit of such systems.

A major limitation of waste incineration lies in the public and scientific concern regarding its potential contribution to air pollution, particularly due to emissions of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDDsPCDFs), and mercury (Hg) [8].

Raw flue gas generated from waste incineration may contain concentrations of PCDDsPCDFs up to $200,000 \text{ ng}\cdot\text{Nm}^{-3}$, while mercury levels can reach as high as $1,000 \text{ }\mu\text{g}\cdot\text{Nm}^{-3}$ [8]. A comparison with established environmental standards clearly indicates that effective flue gas cleaning is an essential requirement for waste incineration processes.

Recent measurements of stack gas emissions from a small-scale waste incinerator indicate concentrations of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F) of approximately $38.9 \pm 0.88 \text{ ng}\cdot\text{Nm}^{-3}$ [9].

The adoption of appropriate combustion practices, in conjunction with effective flue gas decontamination, is essential for ensuring safe waste co-incineration. A broad range of established cleaning technologies, supported by the application of various chemical reagents, enables the implementation of efficient flue gas treatment systems, including dry and semi-dry processes, in compliance with stringent environmental standards [10].

One of the key factors limiting the wider adoption of incineration is the spatial distribution of population across Europe. In Northern European countries, population density is relatively low – for example, approximately 30 inhabitants per km^2 in Latvia, 32 in Estonia, 18 in Finland, and 15 in Norway [11]. This low density, combined with the concentration of population in major urban areas, creates logistical and economic challenges for large-scale centralized waste incineration.

The selection of the purification agent was based on recommendations reported in [12].

Table 1

Pollutant and chemical for treatment

Pollution	Cleaner (purification agent)	Environment norm [13; 14]
NO, NO ₂	Ammonia Water	$400 \text{ mg}\cdot\text{Nm}^{-3}$
HF	Calcium hydroxide Ca(OH) ₂	$1 \text{ mg}\cdot\text{Nm}^{-3}$
HCl	Calcium hydroxide Ca(OH) ₂	$10 \text{ mg}\cdot\text{Nm}^{-3}$
SO ₂	Calcium hydroxide Ca(OH) ₂	$50 \text{ mg}\cdot\text{Nm}^{-3}$
Hg	Activated carbon	$0.05 \text{ mg}\cdot\text{Nm}^{-3}$
Dioxin	Activated carbon	$0.1 \text{ mg}\cdot\text{Nm}^{-3}$
Furan	Activated carbon	$0.1 \text{ mg}\cdot\text{Nm}^{-3}$
Cd + Ti	Activated carbon	$0.05 \text{ mg}\cdot\text{Nm}^{-3}$
Sb + As + Pb + Cr + C0 + Cu + Mn + Ni + V	Activated carbon	$0.05 \text{ mg}\cdot\text{Nm}^{-3}$
TOC (total organic Carbon)	Activated carbon	$10 \text{ mg}\cdot\text{Nm}^{-3}$

Volume definition Nm^{-3} in Table 1 is given for temperature 273 K, pressure 101.3 kPa, oxygen content in dry gas 11% according to p.52 in [14].

The distributed nature of waste generation creates opportunities to couple local community energy demand with decentralized waste treatment systems. In this context, the integration of widely used biomass combustion technologies – such as wood-fired grate furnaces – with waste co-incineration represents a promising approach for regional waste recovery.

Between large-scale MSW incinerators and small waste incineration units, there exists a range of intermediate facilities employing diverse technologies and treatment capacities. Approximately thirty WtE plants, with waste processing range from 1 to $28 \text{ t}\cdot\text{h}^{-1}$, are described in the review [15].

For communities with populations of up to 10,000 inhabitants, the generated waste stream corresponds to an incineration capacity of approximately 1,000 tonnes per year, which is equivalent to an hourly waste flow on the order of $100 \text{ kg}\cdot\text{h}^{-1}$. Such a processing rate is characteristic of small-scale

waste incinerators [16] and is often insufficient to support adequately advanced flue gas cleaning systems.

Therefore, this paper proposes an alternative approach in which waste is utilized as a supplementary fuel. Co-incineration of waste with biomass in existing boiler facilities can ensure more stable combustion conditions and enable the application of effective flue gas treatment, thereby enhancing the environmental safety of the process. In the context of MSW management, incineration processes are ineffective for the recovery of valuable materials such as plastics and metals. Transitioning from MSW to refuse-derived fuel (RDF) is posited to enhance waste management practices. This shift has the potential to decrease the quantity of harmful components subjected to incineration, thereby rendering the combustion products more environmentally acceptable [17].

The core of the presented paper focuses on the endeavour to upgrade an existing woodchip boiler house into a safe co-incinerator. This transformation involves the incorporation of additional modules to ensure comprehensive flue gas treatment.

The objective of the modular design presented in this paper is to develop an economically viable and environmentally friendly concept that can be widely implemented within local communities.

Materials and methods

Emission control is of critical importance for the societal acceptance of waste co-incineration processes. Consequently, the characteristics of the fuel and RDF mixture, together with the prevailing combustion conditions, become key factors influencing both the volume of flue gas produced and its chemical composition.

Fuel mixture definition

$$M_{RDF} = X \cdot (M_{RDF} + M_B) = X \cdot M_f, \quad (1)$$

where M_{RDF} – waste mass kg;
 X – share of RDF in mixture;
 M_B – biomass (wood chips) mass, kg;
 M_f – mixture (fuel) mass, kg.

It is possible to calculate the ratio of waste to biomass as

$$M_{RDF} = M_B \cdot (1.7974 \cdot X^2 + 0.8513 \cdot X + 0.0081), \quad (2)$$

Thus, for $X = 0.1$, the required addition of RDF is 1.112 kg per 10 kg of biomass. Given approximation is valid in range $0.1 < X < 0.25$. Equation (2) was determined using the least squares method applied to the function $X/(1 - X)$, yielding a coefficient of determination $R^2 = 1$. RDF and biomass chemical composition according laboratory reports can be used for mixture properties definition as follows

$$C_M = C_B \cdot (1 - X) + C_{RDF} \cdot X, \quad (3)$$

where C – carbon share in given component by mass %.

Similarly it is possible to estimate all other mixture elements: H – hydrogen, O – oxygen, S – sulphur, W – fuel moisture as mass fraction in percent and Q net calorific value.

As an example, Table 2 presents possible fuel mixture with $X = 0.1$.

Table 2

Fuel and mixture chemical composition in mass percent and Net Calorific Heat Q as received

	$C, \%$	$H, \%$	$S, \%$	$O, \%$	$W, \%$	$N, \%$	$Q, \text{kJ} \cdot \text{kg}^{-1}$
Biomass	25.9	3.11	0.052	20.72	48	0.5	8382
RDF	35.7	4.42	0.08	20.4	32	0.8	13070
Mixture	26.88	3.241	0.0548	20.688	46.4	0.53	8850.8
Standardized instrumental method ISO	16948:2015	16948:2015	16994:2016	16993:2016	18134-1:2022	16948:2015	18125:2017
Uncertainty%	± 0.70	± 0.70	± 0.02	± 1.00	± 1.00	± 0.04	± 1.50

Flue gas amount depends on fuel composition and α - excess air coefficient. When oxygen O_2 volumetric composition (on dry basis) in flue gas is available, it is possible to estimate as

$$\alpha = \frac{(100 \cdot C + 237 \cdot H + 37.5 \cdot S + 9 \cdot N - 29.6 \cdot O)}{C + 3 \cdot H + 0.375 \cdot (S - O)} \cdot \frac{O_2}{21 - O_2}, \quad (4)$$

where C, H, N, S, O – composition of fuel by weight fraction in percent [18].

The equation used to calculate the excess air coefficient was selected based on recommendations provided by Ganapathy Veerappan in Steam Generators and Waste Heat Boilers [18].

The design of the plant developed by SIA “EcoHeat Technologies” [19] anticipates oxygen in flue gas $O_2 = 8\%$, then the calculated value becomes $\alpha = 1.6$ or excess air is 60% from the theoretical air amount.

Volume of flue gas in normal condition depends on fuel composition and excess air amount

$$V_{FG0} = (V_{RDF} + V_B) = M_f(V_{CO_2} + V_{N_2} + V_{H_2O} + V^0 \cdot (\alpha - 1)), \quad (5)$$

where V_{RDF} – flue gas from RDF per kilogram of fuel, $Nm^3 \cdot kg^{-1}$;
 V_B – flue gas from biomass per kilogram of fuel, $Nm^3 \cdot kg^{-1}$.

Air consumption stoichiometric for one kilogram of fuel, $Nm^3 \cdot kg^{-1}$

$$V^0 = 0.0889 \cdot (C + 0.375S) + 0.265 \cdot H - 0.033 \cdot O. \quad (6)$$

Carbon dioxide volume, $Nm^3 \cdot kg^{-1}$

$$V_{CO_2} = 0.01866 \cdot C. \quad (7)$$

Nitrogen in flue gas, $Nm^3 \cdot kg^{-1}$

$$V_{N_2} = 0.79 \cdot V^0. \quad (8)$$

Water steam amount, $Nm^3 \cdot kg^{-1}$

$$V_{H_2O} = 0.00111 \cdot H + 0.0124 \cdot W + 1.6 \cdot 0.013 \cdot V^0. \quad (9)$$

The given above relation can be absorbed by below equation derived for $\alpha = 1.6$, $Nm^3 \cdot kg^{-1}$

$$V_{FG0} = 0.14456 \cdot C + 0.48759 \cdot H + 0.00293 \cdot S + 0.0124 \cdot W - 0.96655 \cdot O. \quad (10)$$

Fuel consumption calculated as a function of boiler power output N , kW and efficiency η

$$M_f = \frac{N \cdot 100}{Q \cdot \eta}, \quad (11)$$

where N – boiler power output, kW;

η – boiler efficiency, used to be around 90% [19].

When flue gas is at elevated temperature $T_{exit} = 1173$ K in comparison with normal one 273 K, then flue gas volume should be recalculated

$$V_{FG900} = \frac{T_{exit}}{273} \cdot V_{FG0}. \quad (12)$$

The given above estimation was used to calculate flue gas flow at the post combustion chamber exit. According to environmental regulations [13; 14], flue gas should retain the temperature 850 °C at least 2 seconds if chlorine amount in fuel is less than 1%. Therefore, the below presented diagram (Fig. 1) can be used to estimate how fuel properties and moisture W (as received) can influence the post combustion chamber requested volume. Fuel moisture content reduces the effective heat of combustion and increases the proportion of water vapour in the flue gas; consequently, the quantity of the flue gas is strongly dependent on the fuel moisture content and fuel consumption.

For fuel with moisture $W = 50\%$ and $C = 26\%$, $O = 20.7\%$, $H = 3.3\%$ and $S = 0.08\%$, net calorific value $Q = 8850$ $kJ \cdot kg^{-1}$ at power output of 2500 kW the requested volume of the post combustion chamber will be around 15 m^3 . An increase in the fuel moisture content leads to a corresponding rise in the flue gas volume and necessitates a larger post-combustion chamber size.

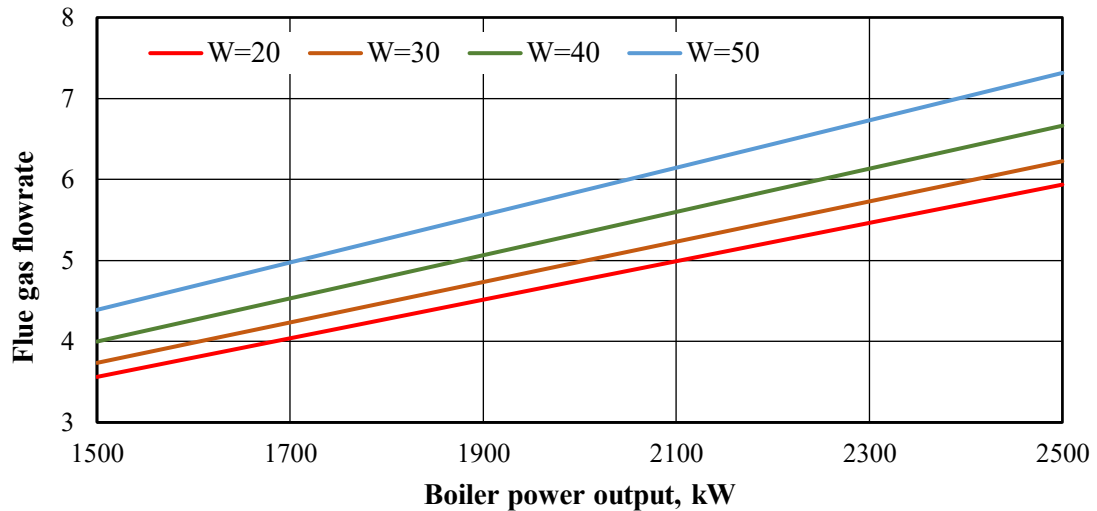


Fig. 1. Biomass and RDF flue gas flowrate in m^3s^{-1} at $O_2=8\%$ and temperature $900\text{ }^\circ\text{C}$

When actual oxygen O_m in flue gas is different from the standard, E_m emission concentration should be corrected in following way

$$E_s = \frac{21 - O_s}{21 - O_m} \cdot E_m, \quad (12)$$

where the oxygen concentration in the flue gas, O_s , is 11%, in accordance with the incineration requirements [14].

Case study

The company “EcoHeat Technologies” has developed an extensive portfolio encompassing the design and manufacturing of modular boiler houses intended for biofuel heating plants for power range from 50 to 3000 kW [19]. Using its own experience and technology, the company developed the concept and design of a modular plant for co-incineration of waste and biomass with subsequent cleaning of flue gases. Preliminary investigation for RDF co-incineration was done in two boiler plants: GRANDEG 300 kW (pellet burner) and Binder VRRK 6 MW (fire grate moving, wood chip combustion), Fig. 2.

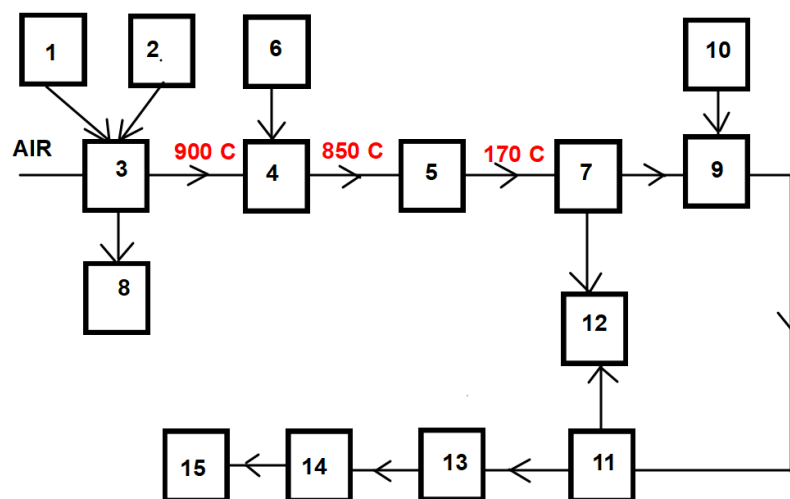


Fig. 2. Modular design of co-incineration plant (RDF + wood chips): 1 – wood chips tank; 2 – RDF tank; 3 – furnace with moving grid; 4 – post combustion chamber; 5 – boiler for flue gas heat recovery; 6 – ammonia water tank; 7 – multicyclone (dust separation); 8 – ash container; 9 – reactor, where flue gas undergoes semi-dry chemical treatment; 10 – mixture of calcium hydroxide $\text{Ca}(\text{OH})_2$ with activated carbon; 11 – bag filter; 12 – flue gas solid residual container; 13 – Continuous Emission Monitoring System (CEMS); 14 – flue gas fan; 15 – chimney.

The novelty of this paper lies in the presentation of a modular co-incineration plant design supported by a definition of its main components. This approach considers the principal material flows, including fuel, RDF, ash, and chemicals required for flue gas treatment. Such framework enables a preliminary feasibility assessment of RDF and biomass co-incineration at an early stage of project development.

A cleaner agent like Sorbalit [20] based calcium hydroxide, containing 10% of activated carbon can be used as chemical for flue gas treatment.

Table 3

Main components of modular boiler house (produced by SIA “EcoHeat Technologies”)

Name	Model	Performance
Wood chips warehouse	FM34	$V(\text{min}) = 180 \text{ m}^3$
RDF warehouse	FM18	$V(\text{min}) = 90 \text{ m}^3$
Furnace	T4.A	2500 MW, $TS = 130 \text{ }^\circ\text{C}$
Post-combustion	T4.I	850°C 2s
Boiler	T4.J	max 2500 MW, $TS = 130 \text{ }^\circ\text{C}$
Multicyclone	MC3	$Q = 10000 \text{ m}^3 \cdot \text{h}^{-1}$
Reactor	R100	$H = 9.5 \text{ m}$, $D = 1 \text{ m}$
Bag-filter	FP130	191 m^2 ; $1.0\text{-}2.5 \text{ m}^3 \cdot \text{min}^{-1} \cdot \text{m}^{-2}$
Continuous Emission Monitoring System (CEMS)	MCA100	acc. to Reg. No. 401[8]
Chemical silo for sorbent	SBB-HFF	1 m^3

Results and discussion

The described modular boiler plant, with a thermal power output of 2500 kW, is capable of processing approximately 800-1200 tons of RDF per year, for fuel moisture in range 40-55% and 8000 hours of annual operation. This capacity would enable the replacement of a comparable amount of wood chips as a primary fuel and contribute to reducing the proportion of waste disposed of in landfills.

For flue gas treatment, approximately 120 tons per year of Sorbalit 15% or a similar reagent are required for the removal of acidic pollutants and other contaminants. In addition, the process is expected to generate approximately 100-200 tons of ash annually, a portion of which may be classified as hazardous waste due to the potential presence of heavy metals and other harmful compounds. Even though the plant is currently under construction and will undergo commissioning at a later stage, sufficient background information is already available to provide a preliminary estimation of the capital expenditure (CAPEX) associated with the co-incineration process. Once the plant becomes operational, the collection of real-time operational data will be essential. The analysis of material flow datasets will enable a more accurate evaluation of the operational expenditure (OPEX) required for plant operation.

Conclusions

1. The concept of modular design for waste co-incineration, presented in this paper and supported by its implementation in a real project, can be considered a viable approach for enabling distributed waste recovery. This approach is particularly relevant for countries with low population density, such as certain regions of Latvia, where centralized waste treatment facilities may be less efficient or economically feasible.
2. The approximation derived in this paper can be applied to estimate flue gas flow rates for various fuel and RDF compositions. This estimation is important for ensuring adequate flue gas residence time in the post-combustion chamber, which is required for the safe decomposition and removal of dioxins and furans during flue gas treatment.
3. The novelty of this paper consists in a project-supported attempt to develop a solution for a medium-scale co-incineration system (power output range as few MW). While numerous waste-to-energy plants with electrical power generation capacity exist at large scales, and many designs of small-scale incinerators (e.g., for hospital waste) are also available, there is a noticeable gap between these two categories. Bridging this gap through the development of medium-scale incineration solutions could contribute to more sustainable and resilient waste recovery systems.

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Author contributions

Conceptualization, S.G.; methodology, D.R.; formal analysis, J.M and D.R.; investigation, S.G., D.R. and J.M.; data curation, J.M. and D.R.; writing – original draft preparation, D.R.; writing – review and editing, D.R. and J.M.; visualization, J.M.; project administration, S.G.; funding acquisition, S.G. All authors have read and agreed to the published version of the manuscript.

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