Retrofit of Integrated Waste Gas-to-Energy Units by Conceptual Design Method

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ABSTRACT

Thermal oxidation represents an efficient and reliable technology for processing industrial waste gases containing combustible pollutants, for example, Volatile Organic Compounds. Thermal oxidation units (or waste gas-to-energy units) enable the heat utilization of the waste gases, which thus become a promising energy source. This is, however, very energy-intensive process requiring a huge amount of primary fuel, which is dependent on the heat recovery efficiency. This paper presents a straightforward and fairly accurate graphic-numerical method for Energy Retrofit of waste gas-to-energy units providing formulas for estimation of maximum reachable fuel savings and tools for the design of specific technological modifications, which results in the increase of the heat recovery efficiency, energy demand reduction, operational costs savings and environmental pollution mitigation. The method is further applied to Energy Retrofit of a standard industrial unit and a modern compact unit for thermal processing of waste gases. Finally, the developed method´s accuracy was successfully verified by the comparison with non-linear simulation of both studied industrial units.

KEYWORDS

Waste Gas-to-Energy Unit, Energy Retrofit, Conceptual Design Method, Heat Recovery Shifting Diagram, primary fuel saving, Modern Integrated Equipment.

INTRODUCTION

Human activity is associated with huge energy demand, which is mostly covered by fossil fuels as traditional energy sources. Their amount is, however, limited, so the research of energy savings in industrial and municipal sector is currently very discussed topic. Since the oil crisis in the 1970s, the energy, chemical, and process industry have undergone great technological development, which led to a significant improvement of industrial plants in terms of energy efficiency. Among other inventions, the Pinch Analysis discovery, which was in the late 1970s published by, e.g., Linnhoff and Flower [1], improved the heat utilization in heat exchanger networks. Since then, Pinch Analysis has been significantly improved in order to reach the savings of resources, such as energy, water, etc., by integrating the process

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equipment into the complex operations. The summary of the up-to-date Process Integration (PI) methodologies based on Pinch Analysis was published by Klemeš et al. [2]. These approaches were applied to design the new industrial plants as, for example, Bandyopadhyay et al. [3], who performed the design of a new diesel hydrotreating unit. Further, the Process Integration methodologies were applied to the retrofit of the existing industrial units to reach the energy savings, as, e.g., Marton et al. [4] on a case study of an oil refinery. However, despite the above achievements, according to Forman et al. [5], 72% of the primary energy consumption is lost after the conversion. Thus, besides the energy efficiency increase of various industrial processes, alternative energy sources must be utilized in order to cover a part of total energy demand.

Energy utilization of industrial and municipal waste for heat and power production represents a promising solution for reduction of the fossil fuel demand. It is also an eco-friendly way to mitigate the environmental pollution caused, e.g., by landfilling or open dumping of solid wastes, as discussed by Chand Malav et al. [6].

Several industry sectors (as refineries, wastewater treatment plants, paint shops, etc.) generate considerable amounts of waste gases (WGs) containing combustible pollutants, as Volatile Organic Compounds (VOC), or Carbon Monoxide (CO). Thermal oxidation represents a commonly applied technology for the simultaneous thermal decomposition of the pollutants and the energy utilization of WGs containing VOC or CO in small concentrations. A thorough review of the techniques for air pollution control including thermal oxidation and other methods for VOC and CO abatement was published by Schnelle et al. [7]. The principle of heat utilization of WGs in a standard industrial unit based on thermal oxidation, or the Waste Gas-to-Energy (WGtE) unit, is illustrated in Figure 1.

The processed WG is brought to the combustion chamber (CC), where the contained pollutants decompose at high temperatures commonly ranging between 520-950 °C, while the flue gas (FG) is produced [7]. The high temperatures in the CC are maintained by the primary fuel (commonly natural gas). The FG heat is then utilized in the WGtE unit´s Heat Recovery System (HRS), which consists of heat exchangers (HEs) for energy media production (e.g., steam) and for WGs´ preheating in order to reduce the primary fuel demand. FG cleaning technology might be also applied to remove remaining pollutants, if necessary.

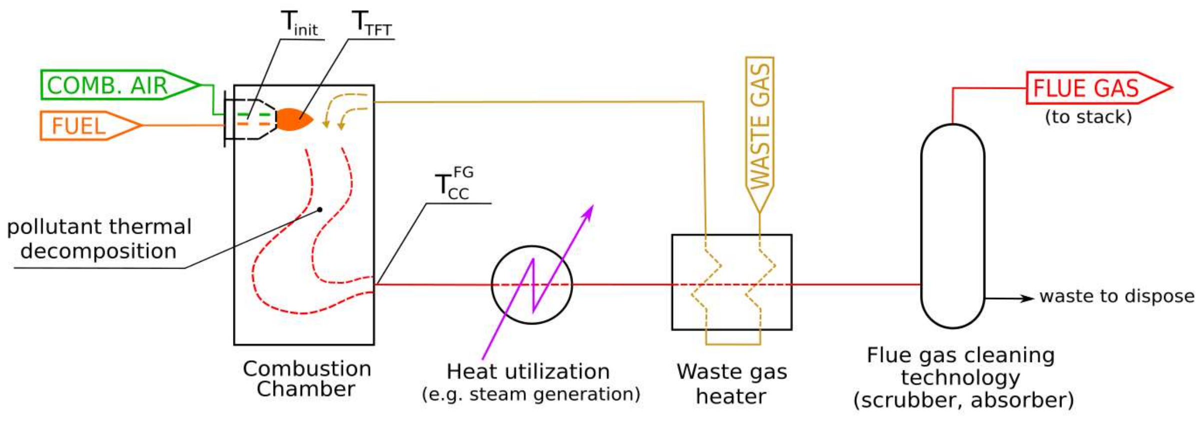

Figure 1 – Standard waste gas-to-energy unit

The presented arrangement of the WGtE unit requires a number of equipment covering relatively high built-up area. This technological arrangement is suitable for processing the high volumes of the WGs. The up-to-date approach is, however, to reduce the number of apparatuses merging them into a single piece of equipment, as proposed by Jegla et al. [8]. This modern integrated equipment (MIE) for the WGtE process provides savings in terms of built-up area and energy loss. An example of the MIE technology for the WG thermal processing integrating the CC and the HRS into a single body is illustrated in Figure 2. In order to reduce the WGtE unit´s primary fuel consumption, the thermal oxidation of the pollutants in the CC may be replaced by catalytic oxidation as demonstrated by Leštinský et al. [9].

Figure 2 – Compact MIE for thermal processing of WG [10]

The described WGtE technology is a part of many industrial plants in order to process WGs and to utilize the generated heat. Many of them, however, do not use fully the energy contained in the WG, which leads to unnecessarily high primary fuel consumption. The WG is then considered as a poor alternative energy source requiring high operational costs. Considerable primary fuel savings could be, however, reached by the modification of the existing WGtE unit´s HRS, i.e. by the Energy Retrofit (ER). Even though there has been done extensive research in the area of the retrofit of heat exchanger networks, the WGtE technology represents a special case, which excludes an application of available PI methods on the HRS of the WGtE unit. The first reason is the absence of Utility Path as illustrated in Figure 1. Further, there is a direct dependence between the heat transfer within the HRS and the mass balance of selected streams. A common procedure to perform the ER design of some specific WGtE unit is to apply advanced modelling requiring some commercial software, which brings excessive costs.

This paper presents a tailor-made Conceptual Design Method (CDM) in order to provide a reliable tool for a simple and fairly accurate ER of MIE and WGtE units, which does not require an application of any commercial software and it could be done even by simple desk calculation.

The developed CDM covers the results published in several recent papers. First, the CDM includes a relationship between the heat and mass balance in the studied unit, which was published by Freisleben and Jegla [11]. The CDM then provides a calculation procedure for the determination of maximum achievable fuel saving of a specific unit representing the ER target. Further, the CDM is designed as a graphic-numerical method, which introduces a special tool called the Heat Recovery Shifting Diagram (HRSD). The HRSD is used to illustrate the heat transfer in the studied unit, as well as flowrate changes of selected streams during the ER. The HRSD is based on principles of the Shifting Flue Gas Line (SFGL)

method, which was published by Freisleben and Jegla [12]. The HRSD can be effectively used to design appropriate technological modifications in the HRS of the studied WGtE unit in order to reach the ER target.
In summary, the developed CDM enables an evaluation of maximum achievable primary fuel savings, and further the conceptual design of the studied unit´s modification in order to reach the desired fuel savings. Such ER considerably increases the WGtE unit´s performance in terms of operational cost reduction and the mitigation of environmental impact associated with Carbon Dioxide emissions.
The developed CDM is in the paper described in detail and its applicability to the wide range of WGtE units is then verified by its application to the ER of two case studies representing the standard high-capacity WGtE unit and low-capacity MIE technology. The CDM´s accuracy is finally verified by the comparison of the obtained results from both case studies to the results of an advanced non-linear simulation performed in software CHEMCAD 7 from Chemstations Inc. [13].

METHODS

The developed method follows a procedure illustrated in Figure 3, which is further in this paper described on the model unit illustrated in Figure 1.

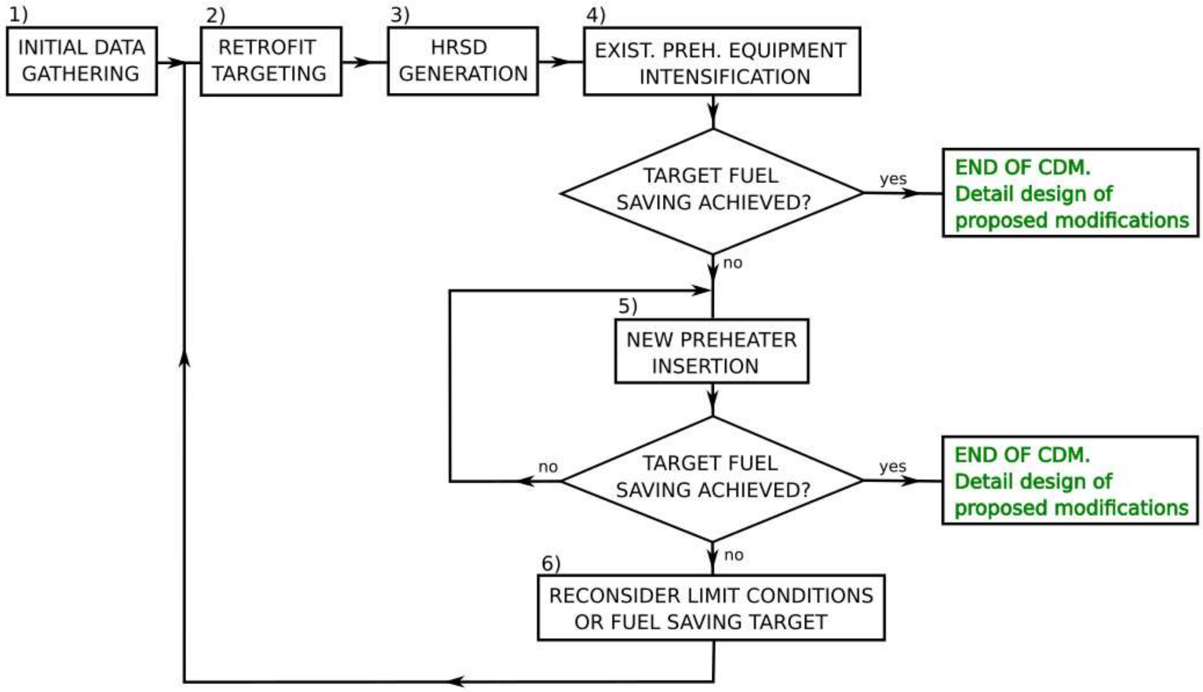

Figure 3 – The ER procedure of the WGtE unit according to the CDM

Initial data gathering

The procedure starts with the determination of key parameters of the studied unit, which consist of several points:

- **Defining the process streams and their key characteristics,** as temperatures, flowrates, and average specific heat capacities. Especially important temperature for the CDM is the FG temperature at the outlet of the CC (T_{CC}^{FG}), and the FG temperature at the outlet of the WGtE unit (T_{stack}^{FG}). Further, the streams in the existing unit are divided into fixed-flow streams and variable-flow streams. The fixed-flow streams´ flowrates are assumed to be constant during the ER, as, for example, waste gases and energy media. The flowrate of the variable-flow streams is according to the unit´s mass balance connected with primary fuel consumption (as fuel, combustion air, and flue gas). As the ER of the WGtE unit results in the fuel flowrate reduction, the flowrate of the variable-flow streams must be during the ER recalculated.

- **Determination of limit temperatures.** For further ER purposes, the FG limit temperature (T_{min}^{FG}) is specified as a safe minimum FG temperature at the outlet of the WGtE unit´s HRS in order to avoid, e.g., risk of FG condensation, increased equipment corrosion, etc.
  Furthermore, the maximum allowed temperatures of all processed WGs (T_{max}^{WG}) are determined. These maximum temperature limits are important from the operational safety point of view. The concentration of combustible substances in the WGs is generally at room temperatures well below the Lower Explosive Limit (LEL). However, the LEL concentration is decreased with the WGs´ increasing temperature [14]. The WGs´ heating must be therefore limited in order to avoid the risk of explosion.
  If the combustion air (CA) preheating is considered, then its maximum temperature T_{max}^{CA} must be also determined to avoid excessive Nitrogen Oxides (NO_x) formation.
- **The current HRS determination.** The heat loads of the existing heat exchangers (HEs) are calculated by the heat balance equation (1). Further, their FUA values are obtained by eq. (2) and (3) [14].

$$\dot{Q}_{balance}^{HE} = \dot{m}^h \cdot \bar{c}_p^h \cdot \left(T^{h,in} - T^{h,out}\right) = \dot{m}^c \cdot \bar{c}_p^c \cdot \left(T^{c,out} - T^{c,in}\right) \quad (1)$$

$$FUA^{HE} = \frac{\dot{Q}_{balance}^{HE}}{LMTD^{HE}} \quad (2)$$

$$LMTD^{HE} = \frac{\left(T^{h,in} - T^{c,out}\right) - \left(T^{h,out} - T^{c,in}\right)}{\ln\left(\frac{T^{h,in} - T^{c,out}}{T^{h,out} - T^{c,in}}\right)} \quad (3)$$

  $\dot{Q}_{balance}^{HE}$ defines the HE´s heat load, $\dot{m}$ is a stream mass flowrate, $\bar{c}_p$ is a mean specific heat capacity, T denotes the temperature, and $LMTD^{HE}$ is a HE´s logarithmic mean temperature difference. FUA^{HE} is composed of a correction factor F, overall heat transfer coefficient U, and the HE´s heat transfer area A. The hot stream (upper index h) is in WGtE units mostly the FG, and the cold stream (upper index c) is often the WG stream, or energy medium.
- **Supplemental fuel/oxidizer characteristics** are specified, as a Lower Heating Value (*LHV*) of the primary fuel, Theoretical Flame Temperature (T_{TFT}), an oxidizer/fuel initial temperature (T_{init}), and their mass ratio (*K*). The Fuel Heating Value utilizable to keep the high temperature inside the CC is then calculated according to the eq. (4), where n_{cor} is a correction factor ranging between 1.07-1.09 [11].

$$FHV_{CC} = n_{cor} \cdot LHV \cdot \frac{T_{TFT} - T_{CC}^{FG}}{T_{TFT} - T_{init}} \quad (4)$$

- **Heat loss and limit thermal efficiency in the current WGtE** are then calculated according to eq. (5) and (6) [12]. The FG average specific heat capacity $\bar{c}_p^{FG}$ is determined for the temperature interval between T_{CC}^{FG} and T_{stack}^{FG}. The calculated heat loss is, therefore, only approximate value providing an initial estimation of the waste heat in the current unit.

$$\dot{Q}_{loss}^{FG} = \dot{m}^{FG} \cdot \bar{c}_p^{FG} \cdot (T_{stack}^{FG} - T_{limit}^{FG}) \quad (5)$$

$$\eta_{limit} = \frac{T_{CC}^{FG} - T_{stack}^{FG}}{T_{CC}^{FG} - T_{min}^{FG}} \quad (6)$$

Retrofit targeting

The primary fuel saving achievement is the main goal of the ER of the WGtE unit. This can be done by enhancing the heating of the streams entering the CC. These streams are preheated by the FG as shown in Figure 1. The achievable supplemental fuel saving faces, however, two limit operating conditions.

The first limit condition is associated with minimum FG temperature at the outlet of the WGtE unit (T_{min}^{FG}). As a result of the FG heat utilization improvement, the FG outlet temperature (T_{stack}^{FG}) is reduced in comparison to the current operation. T_{stack}^{FG} shouldn´t, however, drop below the determined minimum temperature T_{min}^{FG}. The amount of available heat is, therefore, limited.

The achievable fuel saving related to maximum utilization of the FG waste heat ($\Delta\dot{f}_s^{\dot{Q}_{loss}}$) is calculated by eq. (7), which takes into account the FG reduced flowrate as a result of the ER. Achievable fuel saving according to eq. (7), however, does not take into account the decrease of the current HRS heat load due to the FG flowrate reduction, therefore it provides only approximate results.

$$\Delta\dot{f}_s^{\dot{Q}_{loss}} = \frac{\dot{Q}_{loss}^{FG}}{FHV_{CC} + (T_{CC}^{FG} - T_{min}^{FG}) \cdot \bar{c}_p^{FG} \cdot (K+1)} \quad (7)$$

The second limit condition is determined by the maximum allowed temperatures of the streams entering the combustion chamber T_{max}^{WG} and T_{max}^{CA}, when the maximum heating of the WGs and the CA is reached. This condition implies that higher fuel saving is not possible in order to ensure the WGtE unit´s operational safety. To evaluate the achievable fuel saving related to reaching the maximum temperatures $\Delta\dot{f}_s^{T_{max}}$, equations (8), (9), and (10) are used.

$\Delta\dot{Q}_{pr}^{WG}$ denotes a maximum increase of the WGs preheating, $T_{out}^{WG,i}$ and T_{out}^{CA} are the outlet temperatures of the individual WGs and the CA from HEs in the existing HRS, $\dot{m}_{ExUn}^{FG}$ is the FG flowrate in the existing unit, and θ is used to include the CA flowrate reduction to the fuel saving calculation.

$$\Delta\dot{f}_s^{T_{max}} = \frac{\Delta\dot{Q}_{prh}^{WG} + \dot{m}_{ExUn}^{FG} \cdot \theta}{FHV_{CC} + \theta} \quad (8)$$

$$\Delta\dot{Q}_{pr}^{WG} = \sum_i \left(\dot{m}^{WG,i} \cdot \bar{c}_{p,i}^{WG,i} \cdot \left(T_{max}^{WG,i} - T_{out}^{WG,i}\right)\right) \quad (9)$$

$$\theta = K \cdot \bar{c}_p^{CA} \cdot (T_{max}^{CA} - T_{out}^{CA}) \quad (10)$$

The smaller value of the above calculated limit fuel savings represents the final ER target of the studied WGtE unit, see eq. (11).

$$\Delta\dot{f}_s^{target} = min \left\{\Delta\dot{f}_s^{\dot{Q}_{loss}}; \Delta\dot{f}_s^{T_{max}}\right\} \quad (11)$$

Heat Recovery Shifting Diagram generation

After the target fuel saving is obtained, the conceptual design of the studied WGtE unit can be performed. The first step is generating the Heat Recovery Shifting Diagram (HRSD). The HRSD is a tool of the CDM for visualization of the heat transfer in the existing unit containing temperature-enthalpy profiles of all (hot and cold) streams (hereafter referred to as just streams´ lines).

Further, the variable-flow streams are reassessed. The fuel, CA, and FG flowrates are reduced according to the result of the ER targeting by eq. (12), (13), and (14).

$$\dot{f}_{ER} = \dot{f}_{ExUn} - \Delta\dot{f}_s^{target} \tag{12}$$

$$\dot{m}_{ER}^{CA} = \dot{m}_{ExUn}^{CA} - K \cdot \Delta\dot{f}_s^{target} \tag{13}$$

$$\dot{m}_{ER}^{FG} = \dot{m}_{ExUn}^{FG} - (K+1) \cdot \Delta\dot{f}_s^{target} \tag{14}$$

The FG flowrate reduction results in the FG line rotation, creating the Shifting Flue Gas Line (SFGL) [12]. Consequently, the driving forces for the heat exchange in the existing HEs are slightly reduced due to the FG rotation, therefore the HEs heat loads´ reassessment is recommended. Within the CDM, the FUA^{HE} value of any HE is assumed as constant, which is a common simplifying assumption for the HE heat load recalculation under modified operating conditions with the same, hot and cold, fluids. Then the modified heat load of each HE can be calculated by equations (15), (16), and (17), which were derived from eq. (1), (2), and (3). If the re-evaluated heat loads considerably differ from the heat loads in the existing unit, they can be introduced to the HRSD.

The maximum allowed temperatures of the CA (T_{max}^{CA}) and all processed WGs (T_{max}^{WG}) are introduced to HRSD as well. The HRSD of the unit illustrated in Figure 1 is shown in Figure 4. The value $\dot{Q}_a$ calculated according to eq. (18) denotes the amount of the available waste heat in the FG, which must be recovered to reach the ER target.

$$\dot{Q}_{ER}^{HE} = \dot{m}_{ER}^{FG} \cdot \bar{c}_p^{FG} \cdot \left(T_{ER}^{FG,in} - T_{ER}^{FG,out}\right) \tag{15}$$

$$T_{ER}^{FG,out} = \frac{(e^{\psi}-1)\cdot\dot{m}_{ER}^{c}\cdot\bar{c}_p^{c}\cdot T_{ER}^{c,in} + T_{ER}^{FG,in}\cdot(\dot{m}_{ER}^{c}\cdot\bar{c}_p^{c} - \dot{m}_{ER}^{FG}\cdot\bar{c}_p^{FG})}{e^{\psi}\cdot\dot{m}_{ER}^{c}\cdot\bar{c}_p^{c} - \dot{m}_{ER}^{FG}\cdot\bar{c}_p^{FG}} \tag{16}$$

$$\psi = \frac{FUA^{HE}\cdot(\dot{m}_{ER}^{c}\cdot\bar{c}_p^{c} - \dot{m}_{ER}^{FG}\cdot\bar{c}_p^{FG})}{\dot{m}_{ER}^{c}\cdot\bar{c}_p^{c}\cdot\dot{m}_{ER}^{FG}\cdot\bar{c}_p^{FG}} \tag{17}$$

$$\dot{Q}_a = \Delta\dot{f}_s^{target} \cdot FHV_{CC} \tag{18}$$

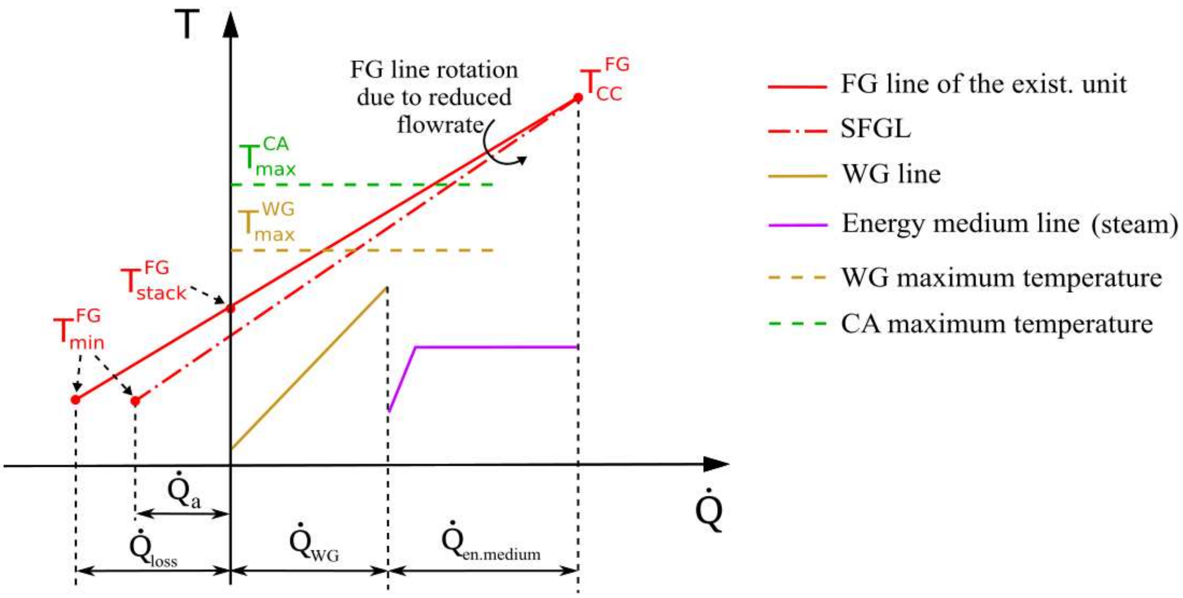

Figure 4 – Initial HRSD of WGtE unit

If the fuel saving target requires the maximum WG (CA) preheating (i.e., $\Delta\dot{f}_s^{target} = \Delta\dot{f}_s^{T_{max}}$), then the goal of the CDM is to propose technological modifications enabling to heat the subject streams up to their maximum temperatures.
Otherwise, if the fuel saving target requires the maximum FG waste heat utilization (i.e., $\Delta\dot{f}_s^{target} = \Delta\dot{f}_s^{\dot{Q}_{loss}}$), then the FG stack temperature must be minimized (i.e. $T_{ER,stack}^{FG} = T_{min}^{FG}$) by preheating the streams entering the CC to meet the ER target. To demonstrate the CDM, the paragraphs below are based on the assumption of full waste heat utilization necessity.

Enhancement of existing heaters

During the ER of the WGtE unit it is necessary to look for economically viable solutions to reach the desired fuel savings. In general, minor technological modifications are preferred due to lower investment costs. As a result, cheap and efficient solutions improving the heat transfer in the unit´s HRS are considered first during the ER. Within the CDM, the enhancement of existing heaters is summarized by the following suggestions:

- **Repiping of the non-preheated minor WGs to the existing WG heater** is a simple modification applicable for WGtE units processing several WGs. The heater´s heat load is then enhanced as the heat transfer coefficient on the HE´s WG side is increased.
- **Heat transfer enhancement technology** might be also applied to the controlling side of the heat exchanger, which is the side with a smaller heat transfer coefficient [15]. Selection of the specific enhancement technology is dependent on the type and geometry of existing WG heater and media process parameters, as temperatures, fouling sensitivity, or corrosivity.
- **Increasing the heat transfer area** by implementation of fins etc. This modification is, however, usually relatively costly, thus it should be considered as the last option to enhance the heat transfer in the existing WG heater.

All recommendations described above, however, increase a pressure drop within the heater. The benefit of such modifications must be, therefore, carefully considered. Furthermore, the WG heater enhancement cannot result in exceeding the WG outlet temperature above the maximum allowed temperature T_{max}^{WG}.
According to the HRSD illustrated in Figure 4, the WG outlet temperature from the WG heater is below T_{max}^{WG}, therefore the heater´s enhancement can be performed. The modification illustrated in Figure 5 brings considerable fuel savings, but the available heat ($\dot{Q}_a$) is not yet fully utilized, therefore the reached fuel savings still did not meet the target. In that case, a new HE must be introduced as discussed in the paper further.

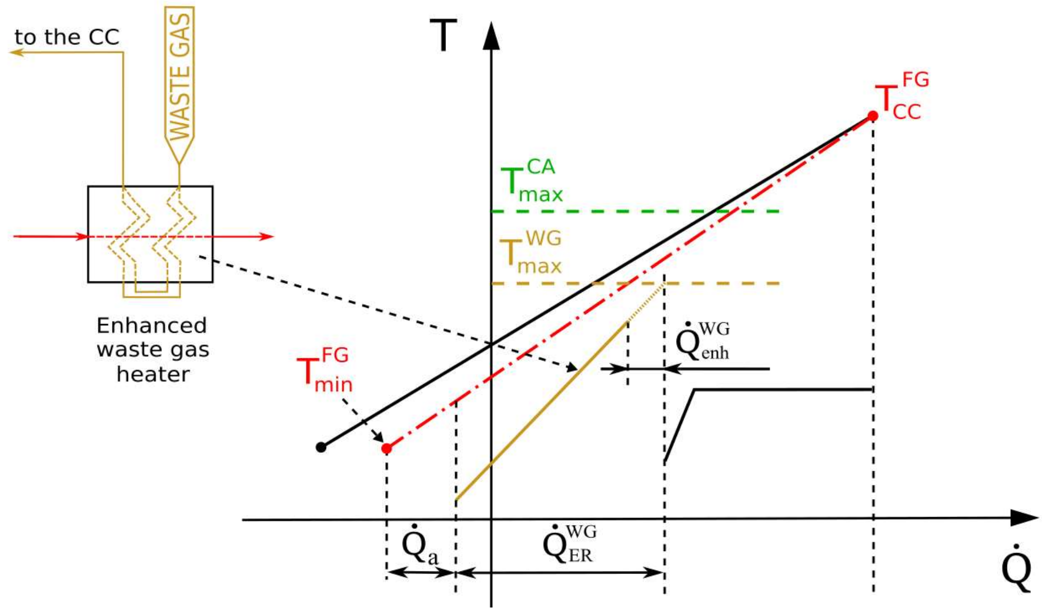

Figure 5 – The existing WG heater enhancement

New preheater insertion

If there are not available any existing heaters for the heat transfer enhancement and the fuel saving target is still not met, then a new preheater must be introduced. As the WG stream of the studied WGtE unit reaches its maximum allowed temperature after performed modification, then the CA is the remaining stream suitable for preheating. The CA preheater´s suitable placement is important for the unit´s performance. According to the technological arrangement (see Figure 1), the new HE can be placed directly behind the CC, between the steam generator and WG heater, and then behind the WG heater. The new preheater placed upstream to the existing HEs would, however, negatively affect their heat load, which is generally not desirable. Thus, the suitable position of the CA preheater is behind the WG heater, which is drawn to the HRSD as shown in Figure 6.

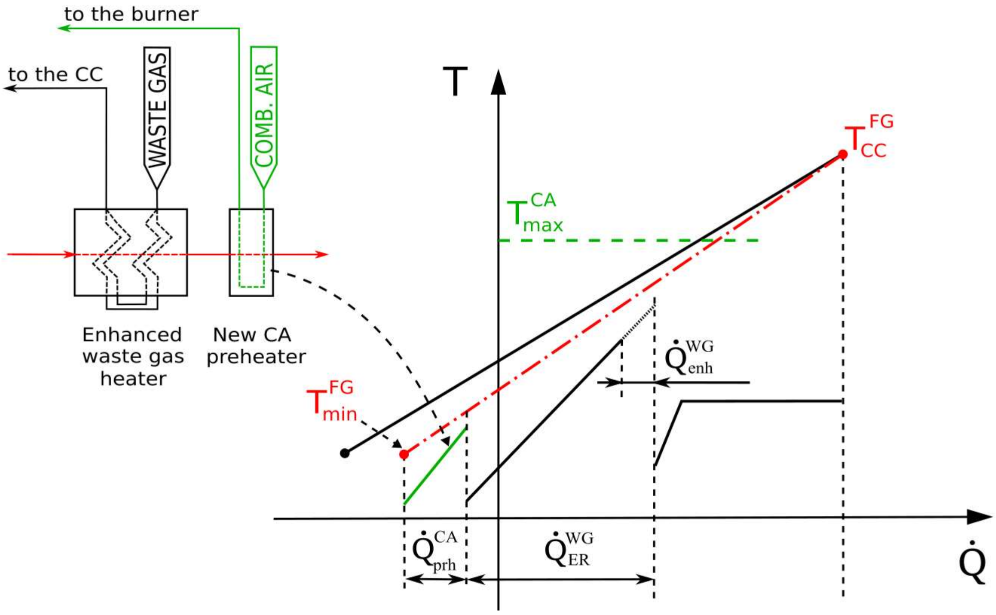

Figure 6 – The new preheater introduction

All performed modifications improved the FG heat utilization, which results in fuel demand reduction. All available FG heat to reach the ER target ($\dot{Q}_a$) is used, therefore the desired target ($\Delta\dot{f}_s^{target}$) is met. The final technological layout of the studied unit after performed ER is shown in Figure 7.

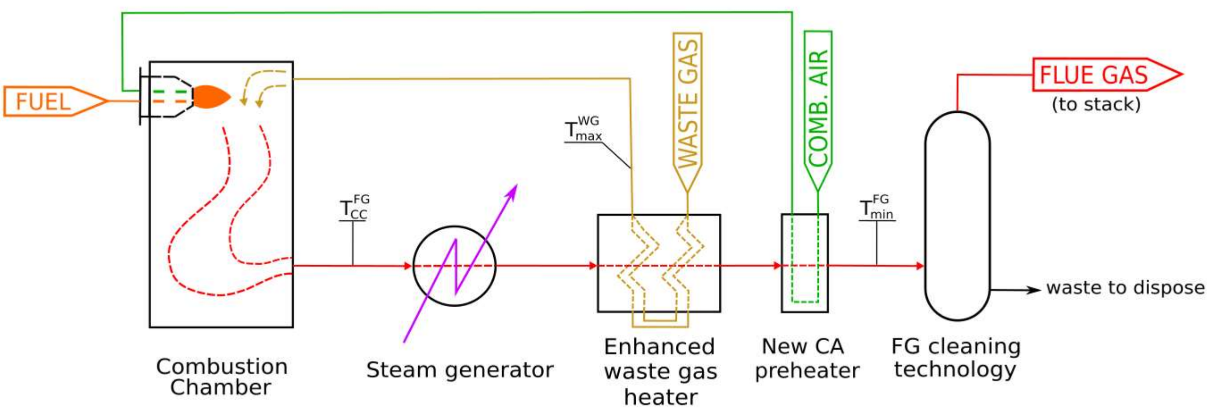

Figure 7 – The WGtE unit after the ER

If the new HE must be placed upstream to any existing HE, the heat load of the existing HE is considerably reduced due to the FG inlet temperature reduction. In that case, the CDM provides a simple and non-iterative tool for an estimation of the modified heat load of the existing heat exchanger called the Heat Exchanger´s Temperature Drop Line (TDL^{HE}). In the HRSD, the TDL^{HE} is drawn from the point given by the outlet temperature of the cold stream from the studied HE. The second parameter defining TDL^{HE} is its slope (s_{TDL}), calculated by eq. (19). The whole concept of TDL^{HE} is derived from eq. (1), (2), and (3). The example of the described HE´s heat load reassessment is illustrated in Figure 8.

$$s_{TDL} = \left(1 - \frac{\dot{m}^{c} \cdot \bar{c}_p^{c} - \dot{m}^{FG} \cdot \bar{c}_p^{FG}}{e^{\psi} \cdot \dot{m}^{c} \cdot \bar{c}_p^{c} - \dot{m}^{FG} \cdot \bar{c}_p^{FG}}\right) \cdot \frac{1}{\dot{m}^{c} \cdot \bar{c}_p^{c}} \qquad (19)$$

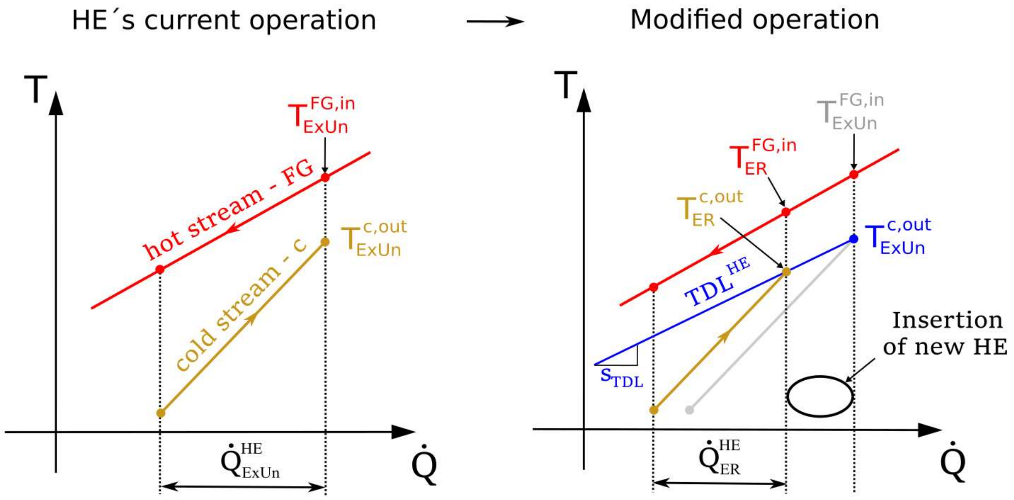

Figure 8 – Existing exchanger´s heat load reassessment by TDL_{HE}

In summary, the described CDM provides a set of mathematical relationships and graphic tools to calculate the reachable fuel saving as the ER target and further to design the specific technological modifications enhancing the current unit´s operation in order to meet the calculated target.

The applicability of the developed procedure to the various types of WGtE units is further verified by its application to two case studies. The first case study is focused on the ER of a large industrial WGtE unit, while the second deals with a compact MIE technology.

The results of both case studies are then compared to the advanced non-linear simulations of the subject units performed in software CHEMCAD 7 from Chemstations Inc. [13] to verify the accuracy of the CDM.

CASE STUDY 1

High capacity industrial WGtE unit, illustrated in Figure 9, processes three waste gases containing VOC, mainly Benzene and Toluene. The thermal treatment of the WGs takes place in the furnace, where the primary fuel (natural gas) is combusted to ensure the pollutant thermal decomposition. The produced FG´s heat is utilized for combined heat and power (CHP) production, and then for thermal oil (TO) heating to cover a part of process heat duty of the industrial complex, where the studied unit is placed. The rest of the heat is used to preheat the largest WG stream, the main waste gas (MWG), in the MWG heater in order to decrease the unit´s primary fuel consumption in the furnace. Remaining secondary WGs (SWG 1 and SWG 2) enter the furnace unpreheated. The generated FG contains solid particles, thus the baghouse filter is placed at the end of the studied process.

The Energy Retrofit is required to reach the maximum achievable fuel saving, while the energy production had to be maintained and the FG temperature in front of the baghouse filter cannot drop below 165 °C to avoid the FG condensation. The existing MWG heater can be enhanced.

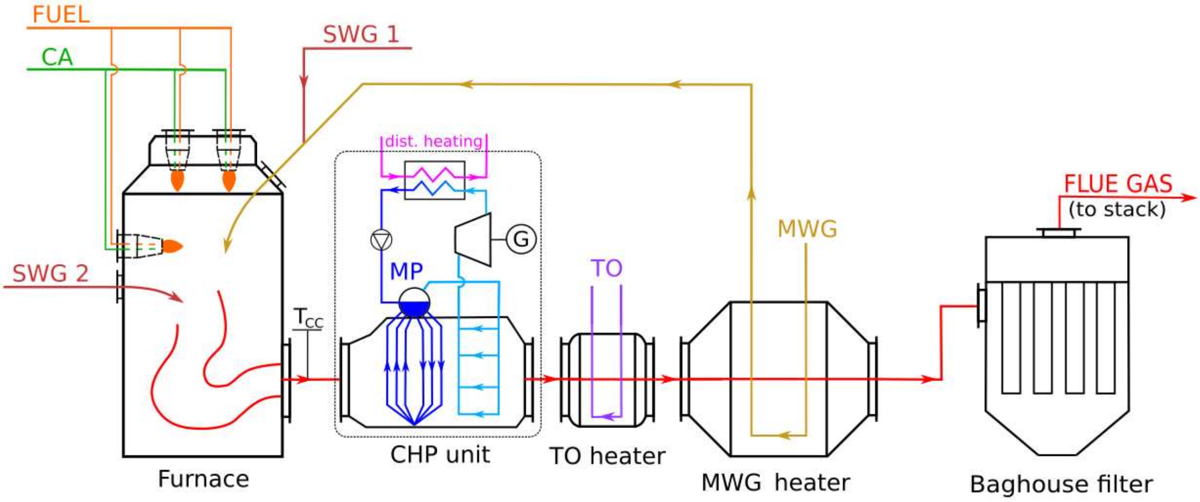

Figure 9 – Studied high capacity WGtE unit

RESULTS AND DISCUSSION – CASE STUDY 1

To perform the ER of the studied WGtE unit, the CDM was applied according to the algorithm illustrated in Figure 3.

The initial data about the selected process streams are gathered in Table 1. The fuel/oxidizer characteristics are in Table 2. Further, the unit´s HRS consists of four HEs, an evaporator and a superheater (within the CHP unit), the TO heater, and the MWG heater. The main characteristics of selected HEs are given in

Table 3.

Table 1 – Basic characteristics of selected process streams

Stream	FG	MWG	SWG 1	SWG 2	MP*	TO
Flowrate [kg/h]	51 439	32 930	3 951	1 946	9 000	9 500
Spec. heat cap. ($\bar{c}_p$) [kJ/(kg×K)]	1.160	1.030	1.210	1.028	–***	2.770
Limit temperature [°C]	165	330	330	–**	–****	–****

* MP is medium-pressure water fed to the CHP unit, where the superheated MP steam is then generated.

** SWG 2 contains VOC at high concentration, so preheating is not possible to avoid the risk of explosion.

*** There is not a single c_p value of MP stream due to its multiphase character. Steam tables are used to generate the stream lines to the HRSD.

**** There are not specified any upper or lower limit temperatures for TO and MP.

Table 2 – Fuel/oxidizer characteristics

Stream	Flowrate [kg/h]	LHV [MJ/kg]	FHV_{CC} [MJ/kg]	$\bar{c}_p$ [kJ/(kg×K)]	T_{limit} [°C]	T_{init} [°C]	T_{TFT} [°C]	K [kg/kg]
Natural gas	639.2	49.06	29.22*	–	–	20**	1 892***	18.73****
Combustion air	11 973	–	–	1.019	280			

* Fuel Heating Value related to T_{CC}^{FG} (FHV_{CC}) was calculated according to eq. (4), where n_{cor}=1.07.

** As the fuel and CA temperatures are both 20 °C, the initial fuel/oxidizer temperature (T_{init}) is also the same. Otherwise T_{init} is calculated according to gas mixture energy balance.

*** Theoretical Flame Temperature (T_{TFT}) is calculated as Adiabatic Flame Temperature.

**** The CA/fuel mass ratio is determined with assumption of 10% CA excess.

Table 3 - Selected process characteristics of existing heat exchangers

Heat exchanger	Hot side		Cold side		Heat load [kW]*	FUA^{HE} [kW/°C]*
	Fluid - location	T^{in-out} [°C]*	Fluid - location	T^{in-out} [°C]*		
CHP unit - evaporator	FG - shell side	850 - 512	MP - tube side	134 - 224	5 600.0	11.387**
CHP unit - superheater	FG - shell side	512 - 446	MP - tube side	224 - 400	1 100.4	6.851
TO heater	FG - shell side	446 - 379	TO - tube side	50 - 200	1 096.5	3.838
MWG heater	FG - shell side	379 - 220	MWG - tube side	20 - 300	2 636.8	20.141

* The values are extracted from existing unit or calculated according to eq. (1), (2), and (3).

** As the phase change occurs in the CHP unit´s evaporator, the FUA^{HE} is determined only approximately due to the uncertainty caused by the simplified determination of $LMTD^{HE}$ by eq. (2).

According to the eq. (6), the limit thermal efficiency (η_{limit}) of heat recovery in the current unit is 91.82% which indicates very efficient heat utilization. On the other hand, the current heat loss ($\dot{Q}_{loss}^{FG}$) according to eq. (5) is almost 929 kW, thus there is a great potential to utilize the waste heat to reach considerable fuel savings.
Following the CDM algorithm in Figure 3, the ER targeting was performed according to eq. (7) – (11). Flowrates of the variable-flow streams were then recalculated according to eq. (12) – (14). The results of the described calculation are summarized in Table 4. The achievable primary fuel saving target was limited by the amount of waste heat contained in the FG, i.e., $\Delta\dot{f}_s^{target} = \Delta\dot{f}_s^{\dot{Q}_{loss}}$. Thus, all available heat in the FG must be recovered to preheat the streams entering the furnace to reach the target.

Table 4 – The ER target determination and variable-flow streams reassessment

$\Delta\dot{f}_s^{\dot{Q}_{loss}}$ [kg/h]	$\Delta\dot{f}_s^{T_{max}}$ [kg/h]	$\Delta\dot{\boldsymbol{f}}_{\boldsymbol{s}}^{\boldsymbol{target}}$ [kg/h]	$\dot{f}_{ER}$ [kg/h]	$\dot{m}_{ER}^{CA}$ [kg/h]	$\dot{m}_{ER}^{FG}$ [kg/h]
74.47	158.92	**74.47**	564.75	10 578.79	49 969.14

Based on the obtained data, the HRSD of the studied unit was then generated to design specific technological modifications to reach the ER target. The application of the HRSD is illustrated in Figure 10 and specific steps are described in paragraphs below.
The FG flowrate was reduced by the ER only slightly, as seen by comparing the data in Table 1 and Table 4, therefore the heat loads of the CHP unit and TO heater in the studied unit can be estimated as unchanged. The FG line rotation occurred as a result of the FG flowrate reduction, generating the SFGL. Further, the amount of available heat contained in the FG ($\dot{Q}_a$), calculated according to eq. (18), is equal to 604 kW. This heat must be fully recovered to preheat the streams entering the furnace in order to reach the ER target.
As the energy production must remain the same, the technological modifications could take place only downstream to the TO heater in order to keep constant the heat loads of the CHP unit and the TO heater. According to the CDM procedure, the SWG 1 was then brought to the MWG heater in order to increase the heat transfer coefficient at the cold side of the HE. This modification provides a cheap solution to increase the FUA^{HE} value approximately by 15%. Following eq. (15) – (17), the modified heat load of the MWG heater was then calculated considering the modified operation of the MWG heater, i.e., the FG inlet temperature is determined from the SFGL and the WG inlet temperature is calculated according to the heat balance of a gas mixture containing MWG and SWG 1. The remaining

SWG 2 could not be brought to the MWG heater as its preheating is not allowed (see Table 1). The heat enhancement technology was not applied to avoid the excessive pressure drop in the heat exchanger.

The heat load of the MWG heater was increased by 128.4 kW, which is less than the required value ($\dot{Q}_a$=604 kW), so the new heat exchanger was introduced behind the MWG heater in order to preheat the last available stream entering the furnace, the CA. The process characteristics of the CA are given in Table 2 and Table 4 and the heat load of the CA preheater is set as the FG waste heat must be fully recovered, i.e., $\dot{Q}_{ER}^{CA}$=604–128.4=475.6 kW. The CA stream line is drawn in Figure 10.

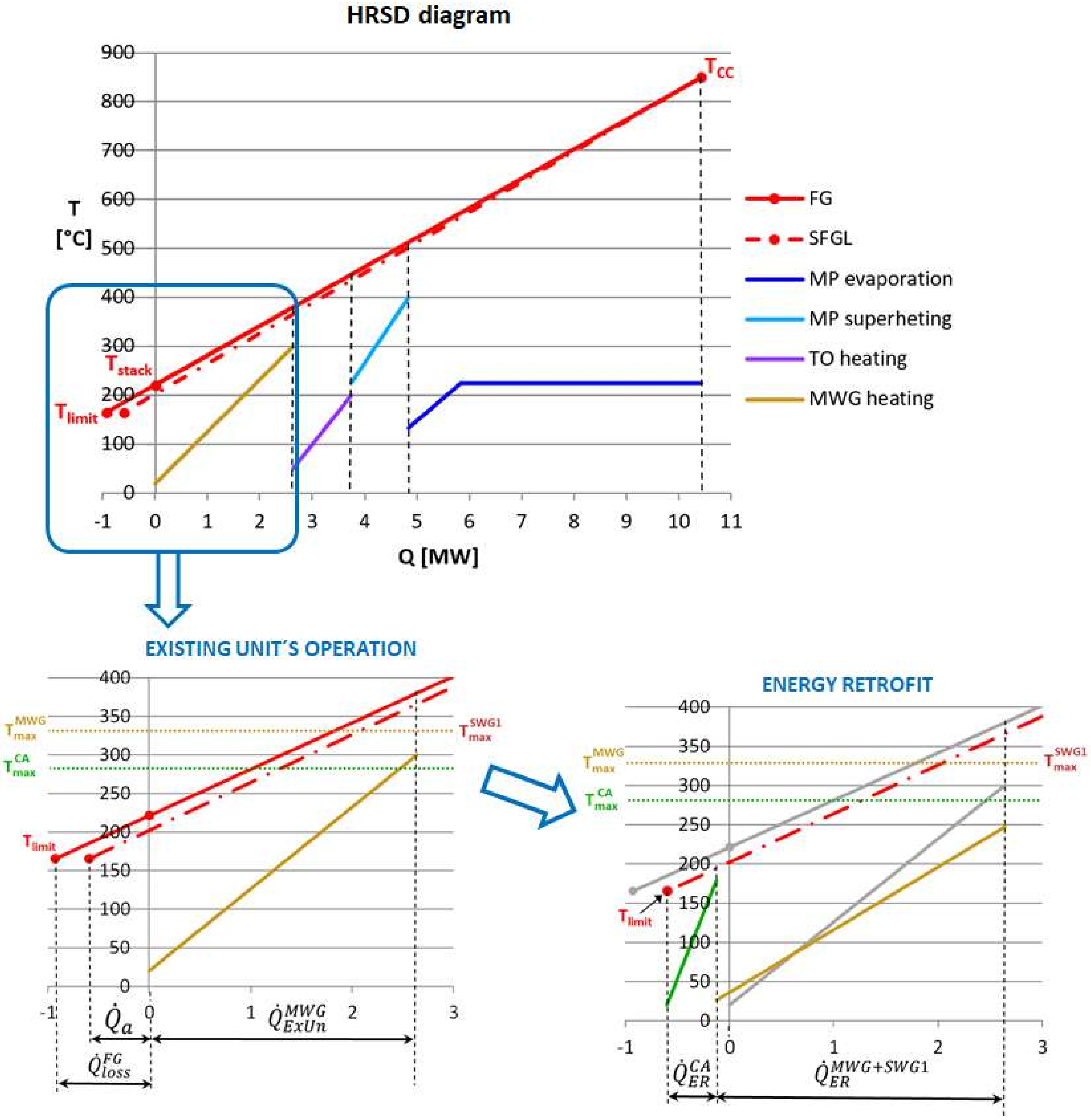

Figure 10 – Application of the HRSD to the ER of the studied WGtE unit.

In summary, the ER of the studied WGtE unit was performed by the application of the CDM. The conceptual design of the technological modifications was proposed in order to reach the maximum primary fuel savings. The MWG, SWG 1, and CA outlet temperatures from the HRS did not exceed the limit temperatures, thus the operation of the modified WGtE unit is safe. The modified unit is illustrated in Figure 11.

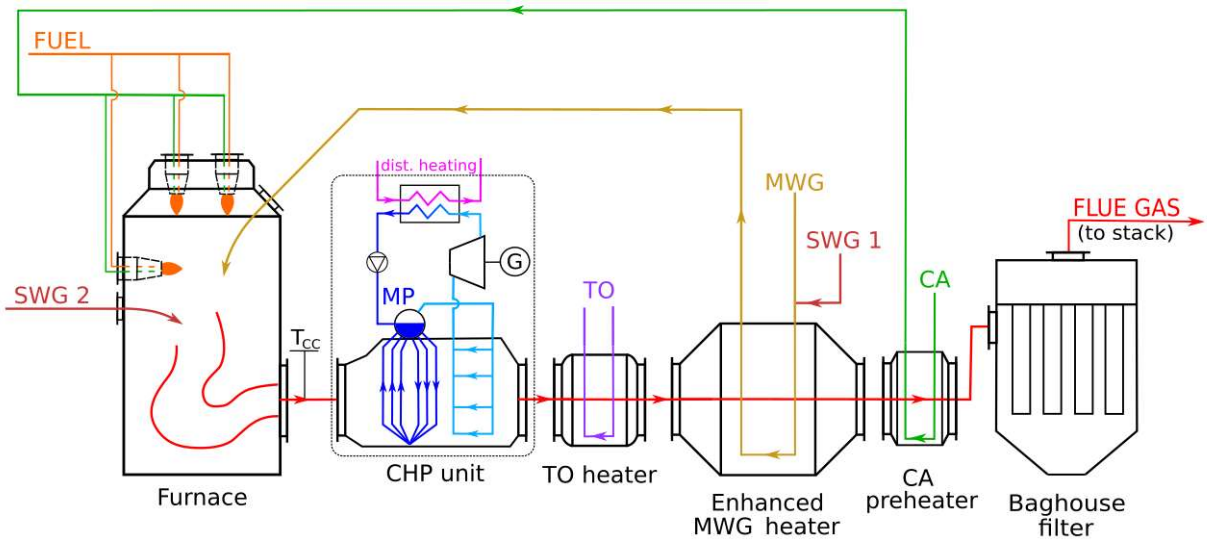

Figure 11 – The modified WGtE unit

Verification of the CDM´s accuracy by comparing to the non-linear simulation

As demonstrated above, the CDM can be effectively used to the ER of a large WGtE unit. It follows a simple procedure based on the linear model of the studied unit. Some other simplifications were also estimated, as neglecting the influence of the ER on the heat loads of the CHP unit and the TO heater. To verify the CDM´s accuracy, the obtained results of the performed ER were further compared to a non-linear simulation performed in software CHEMCAD. The results are summarized in Table 5.

Table 5 – Comparison of the results of the CDM with the non-linear simulation

	$\Delta\dot{f}_s$ [kg/h]	$T^{FG}_{ER-stack}$ [°C]	$\dot{Q}^{CHP}_{ER}$ [kW]	$\dot{Q}^{TO}_{ER}$ [kW]	$\dot{Q}^{MWG+SWG1}_{ER}$ [kW]	$\dot{Q}^{CA}_{ER}$ [kW]	η_{limit} [%]
CDM	74.47	165	6 700.4	1 096.5	2 765.2	476.0	100
Non-lin. simul.	76.42	165	6 603.9	1 058.7	2 801.7	456.0	100
Deviation [%]	**-2.5**	**0**	**1.46**	**3.5**	**-1.3**	**4.4**	**0**

The obtained results confirmed the CDM´s accuracy and reliability. The reached fuel saving corresponds to the result of the non-linear simulation with a negligible difference of 2.5%.
Due to the FG flowrate reduction, the heat loads of the CHP unit and the TO heater decreased very slightly, so it could be neglected. The heat loads of the MWG heater and newly added CA preheater also match with the non-linear simulation results very well. The CDM, therefore, has proved as a very promising tool for the ER of large industrial WGtE units.
In order to verify the applicability of the CDM to the wide range of WG processing technology, the developed method is further applied to the second case study, which is the ER of the compact WGtE unit representing the modern integrated technology (MIE) for the WG thermal processing.

CASE STUDY 2

WG containing VOC (mainly Hexane), which is produced in a wastewater treatment plant, is thermally processed in a single compact thermal oxidation unit. VOC are decomposed in the CC, while the FG is produced. The FG heat is then utilized to heat the WG entering the unit in the WG heater, which is constructed as a set of concentric metal sheet cylinders surrounding the CC in order to minimize the unit´s heat loss and to improve the compactness. Natural gas (as a primary fuel) is combusted in the CC in order to keep the FG temperature approximately 680 °C. The existing unit is illustrated in Figure 12.

The ER is required to reach the maximum primary fuel saving. The WG heater cannot be enhanced, and potential technological modifications must respect strict space limitations concerning other equipment placed nearby the unit. For this reason, only small HE can be introduced at the FG outlet from the unit.

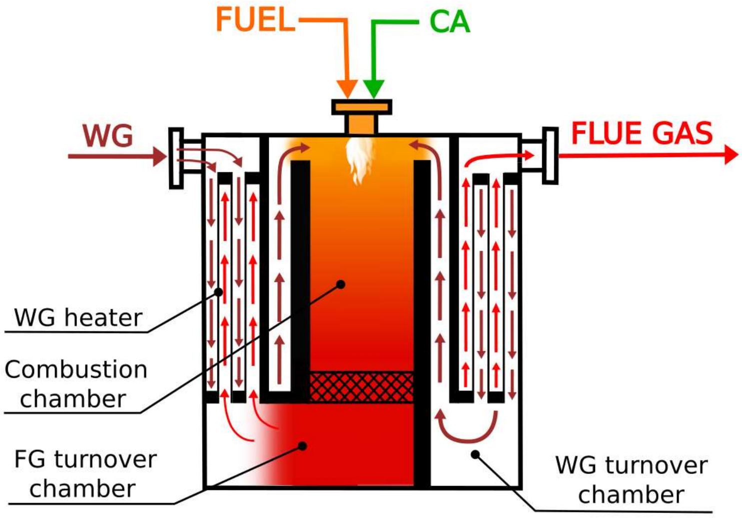

Figure 12 – Existing MIE unit

RESULTS AND DISCUSSION – CASE STUDY 2

The CDM was applied to the studied unit in order to determine the achievable fuel saving and then to design the technological modifications to reach the fuel saving target.

The studied unit is very different from the first case study. However, the CDM could be applied according to the same procedure as presented in Figure 3. The basic parameters of the process streams are gathered in Table 6. The Theoretical Flame Temperature is 1892 °C and *LHV* of the primary fuel is 49.94 MJ/kg. The initial temperature of the oxidizer/fuel mixture (T_{init}) and the oxidizer/fuel mass ratio (K) are the same as in the first case study (see Table 2). According to eq. (4), the FHV_{CC} is then 34.61 MJ/kg.

Selected process parameters of the existing WG heater are summarized in

Table 7.

Table 6 – Basic characteristics of the process streams

Stream	FG	WG	Fuel	CA
Flowrate [kg/h]	3 527	3 092	22.2	416
Spec. heat cap. ($\bar{c}_p$) [kJ/(kg×K)]	1.123	1.040	-	1.021
Limit temperature [°C]	165	460	-	230

Table 7 - Selected process characteristics of WG heater

Hot side		Cold side		Heat load [kW]	FUA^{HE} [kW/°C]
Fluid	**$T^{in\text{-}out}$ [°C]**	**Fluid**	**$T^{in\text{-}out}$ [°C]**		
FG	680 - 347	WG	20 - 430	366.3	1.28

The targeting was then performed according to the eq. (7) – (11). The variable-flow streams´ flowrates were recalculated according to eq. (12) – (14). The results are summarized in Table 8. The achievable primary fuel saving target was limited by the maximum allowed temperatures of the WG and the CA, i.e., $\Delta\dot{f}_s^{target} = \Delta\dot{f}_s^{T_{max}}$. Both streams (WG and CA) must be, therefore, maximally preheated. The heat transfer in the studied unit must be increased according to eq. (18) by 62.2 kW.

Table 8 – The ER target determination and variable-flow streams reassessment

$\Delta\dot{f}_s^{\dot{Q}_{loss}}$ [kg/h]	$\Delta\dot{f}_s^{T_{max}}$ [kg/h]	$\Delta\dot{\boldsymbol{f}}_{\boldsymbol{s}}^{\boldsymbol{target}}$ [kg/h]	$\dot{f}_{ER}$ [kg/h]	$\dot{m}_{ER}^{CA}$ [kg/h]	$\dot{m}_{ER}^{FG}$ [kg/h]
15.66	6.47	**6.47**	15.73	10 578.79	49 969.14

Following the CDM, the HRSD was then generated to perform the specific technological modifications as illustrated in Figure 14. The target fuel saving was determined by maximum temperatures of the WG and the CA, which requires an enhancement of the current HRS.

As the existing WG heater couldn´t be enhanced, then a new HE had to be employed to preheat the WG stream to the limit temperature. The space limitations for the ER offered only one possible location for the new WG heater, which is a FG turnover chamber (see Figure 12). The new WG heater was, therefore, placed upstream to the existing WG heater, which negatively influenced its heat load as discussed in Methods section. To determine the heat load of the new MWG heater considering the heat load reduction of the existing WG heater, while the maximum allowed temperature of the WG had to be reached, the Temperature Drop Line (TDL^{HE}) was applied according to eq. (19). The use of TDL^{HE} is illustrated in Figure 14.

Finally, the CA preheater was placed to the HRSD behind the existing WG heater, which represents the FG outlet from the studied unit. The CA preheater is a small HE, thus the space restrictions were not exceeded. The modified unit is illustrated in Figure 13.

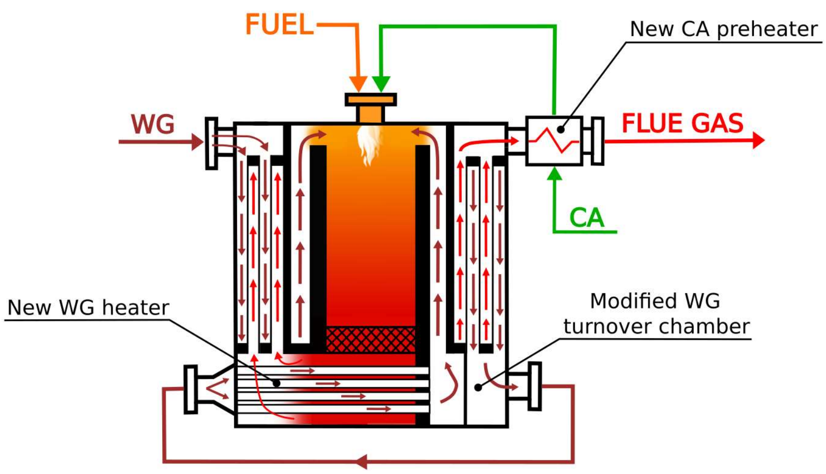

Figure 13 – The modified compact thermal oxidation unit

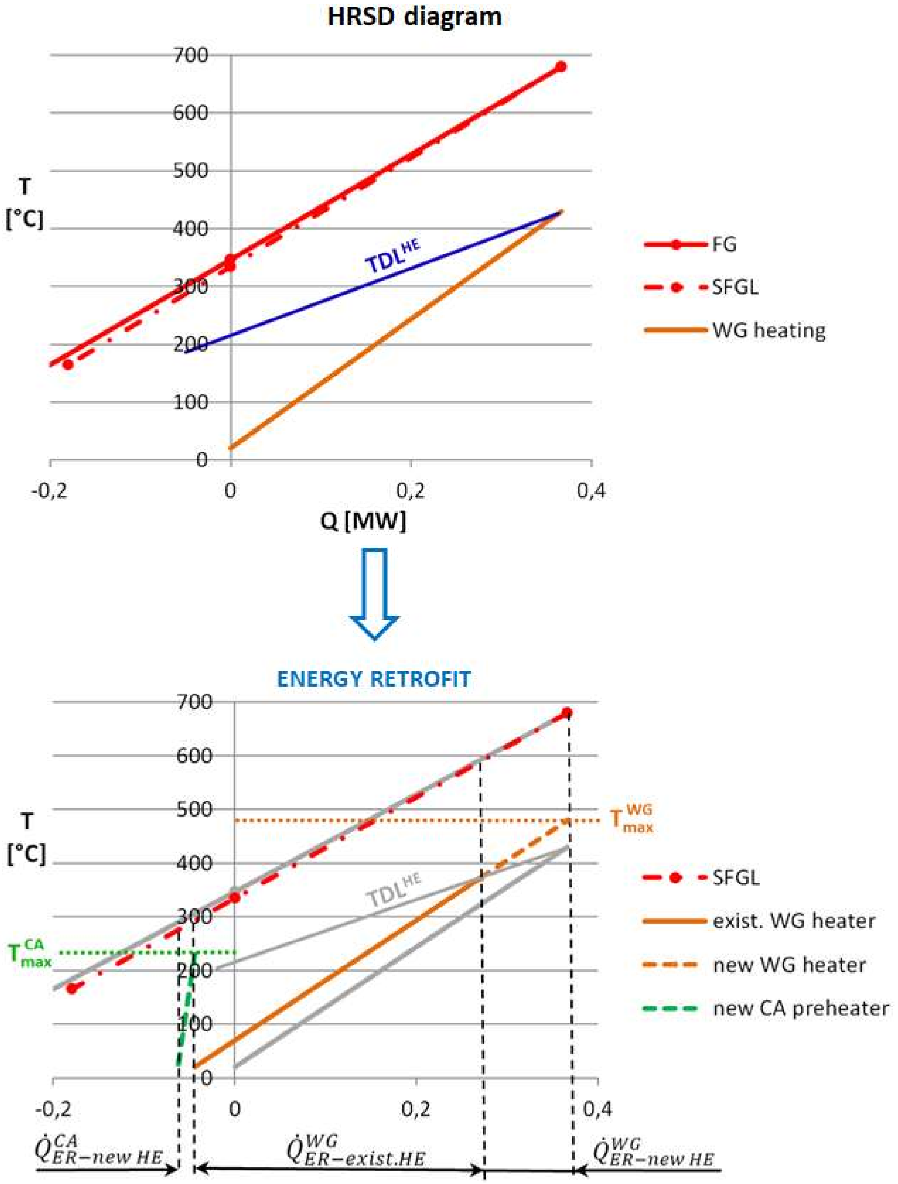

Figure 14 – HRSD of the studied unit and the design of technological modifications

According to the HRSD, both process streams (WG and CA) reached their maximum allowed temperatures (T_{max}^{WG} and T_{max}^{CA}), thus the maximum fuel saving was achieved. The FG heat utilization was increased by 62.2 kW as required to reach the fuel saving target. The obtained results were then compared to the results of the non-linear simulation performed in software CHEMCAD in order to verify the accuracy of the obtained results.

Verification of the CDM´s accuracy by comparing to the non-linear simulation

The target fuel saving was calculated by the CDM fairly accurately with a deviation of 5.1% compared to the non-linear simulation.

The heat load of the existing WG heater, which was recalculated by the TDL^{HE} (as the CDM tool), also matches the result of the non-linear simulation very well. However, this inaccuracy caused a difference 8.9% in the heat load of the newly introduced WG heater. As the CDM is based on the linear model of the WGtE unit (i.e., the heat capacity of the process streams is assumed as constant) then these deviations are inevitable. Due to the same reason, there is also a relatively big deviation in the FG heat loss calculation, which is 15.6%.

On the other hand, the total heat load for the WG preheating $\dot{Q}_{ER-total}^{WG}$ was calculated very accurately as well as the heat load of the CA preheater.

Table 9 – Comparison the results of the CDM with the non-linear simulation

	$\Delta\dot{f}_s$ [kg/h]	$\dot{Q}_{ER-new\ HE}^{WG}$ [kW]	$\dot{Q}_{ER-exist.HE}^{WG}$ [kW]	$\dot{Q}_{ER-total}^{WG}$ [kW]	$\dot{Q}_{ER-new\ HE}^{CA}$ [kW]	$\dot{Q}_{loss}^{FG}$ [%]
CDM	6.47	96.0	315.0	411.0	17.5	117.5
Non-lin. simul.	6.83	105.4	307.7	413.2	17.2	101.6
Deviation [%]	**-5.1**	**-8.9**	**2.4**	**-0.5**	**1.7**	**15.6**

CONCLUSION

In this paper, a systematic and easily applicable procedure for the Energy Retrofit of WGtE units, called the CDM (Conceptual Design Method), has been presented. Within the CDM, there is described a straightforward targeting procedure for an estimation of achievable fuel savings. Further, the support graphic tool called the HRSD (Heat Recovery Shifting Diagram) is proposed to visualize the heat transfer in the studied unit and to perform the specific technological modifications enhancing the Heat Recovery System (HRS) of the studied WGtE unit. The HRSD is additionally provided by a tool called the Heat Exchanger´s Temperature Drop Line (TDL^{HE}), which enables re-estimation of the operating parameters of the existing heat exchangers.

Furthermore, the CDM was applied to two case studies representing different industrial WGtE units. In the first case, the ER of a standard high capacity WGtE unit was performed and specific technological modifications were proposed in order to fully utilize the unit´s waste heat. Further, the CDM was used for the ER of a compact thermal oxidation unit representing a modern approach for the processing of waste gases. The results´ accuracy was finally verified by comparing to the results of the advanced non-linear simulation.

In summary, the CDM method has proven to be a reliable and sufficiently accurate tool that can be applied to the various types of the units based on the pollutants´ thermal oxidation in order to reduce the ecological impact by reducing energy demand of the WGtE unit.

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NOMENCLATURE

Symbols.

A - heat transfer area, m^2
$\bar{c}_p$ - average specific heat capacity, kJ/(kg×K)
F - correction factor of a driving force in a heat exchanger
FHV_{CC} - Fuel Heating Value utilizable to heat the combustion chamber, kJ/kg
$\dot{f}$ - flowrate of the primary fuel, kg/h
$\Delta\dot{f}$ - fuel flowrate change, kg/h
K - oxidizer/fuel ratio
LHV - Lower Heating Value, kJ/kg
$LMTD$ - Logarithmic Mean Temperature Difference, °C
$\dot{m}$ - mass flowrate, kg/h
n_{cor} - correction factor
$\dot{Q}$ - heat load, kW or MW
s_{TDL} - slope of Temperature Drop Line, °C/kW
T - temperature, °C
U - overall heat transfer coefficient, kW/(m^2×K)

Greek symbols.

η - efficiency
θ - auxiliary member for fuel saving calculation related to max. temperatures
ψ - auxiliary member for calculation of the modified heat load of heat exchanger

Subscripts.

a - available (in relation to the heat content)
CC - combustion chamber
ER - Energy Retrofit
$ExUn$ - existing unit
$init$ - initial (in relation to the temperature of fuel and oxidizer mixture)
$loss$ - loss related to the heat released to the environment
max - maximum
min - minimum
prh - preheat
s - saving (related to primary fuel)
TFT - Theoretical Flame Temperature

Superscripts.

c - cold stream
CA - combustion air
CHP - Combined Heat and Power
FG - flue gas
h - hot stream
HE - heat exchanger
MWG - main waste gas
SWG - secondary waste gas
TO - thermal oil
WG - waste gas

Abbreviations.

CA	- combustion air
CO	- Carbon Monoxide
CC	- combustion chamber
CDM	- Conceptual Design Method
CHP	- Combined Heat and Power
ER	- Energy Retrofit
HE	- heat exchanger
HRS	- Heat Recovery System
HRSD	- Heat Recovery Shifting Diagram
LEL	- Lower Explosive Limit
MIE	- Modern Integrated Equipment
MP	- medium-pressure water/steam
MWG	- main waste gas
NO_x	- Nitrogen Oxides
SFGL	- Shifting Flue Gas Line
SWG	- secondary waste gas
TDL	- Temperature Drop Line
TO	- thermal oil
VOC	- Volatile Organic Compounds
WG	- waste gas
WGtE	- waste gas-to-energy

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