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CONCEPTUAL CARBON-REDUCTION ORIENTED ASSESSMENT OF LOCAL FLUE GAS WASTE HEAT RECOVERY

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Abstract: *The paper is focused on local recovery of flue gas waste heat from industrial combustion equipment (such as process furnaces, water- or steam-boilers, etc.). A simple and systematic assessment is introduced evaluating overall amount of produced carbon dioxide related to a specific option of the available flue gas waste heat recovery (FGWHR). The assessment compares the total* CO_2 *balance each of locally available option of FGWHR including production of* CO_2 *associated with the FGWHR system realization and savings of* CO_2 *associated with the FWGHR system operation. Based on an assessment of the total* CO_2 *balance of all potentially competitive options of FGWHR applicable in a considered location it is possible to identify the most environmentally friendly option of FGWHR system.*

Keywords: Available waste heat of flue gases, flue gas waste heat recovery, minimalization of total CO_2 **production, conceptual carbon-reduction oriented assessment**

1. Introduction

With increasing energy consumption, rising energy prices and stricter environmental protection requirements, industrial process operators are increasingly motivated to search the most efficient ways of using energy and its new potential sources. One such option is the recovery of waste heat (WH) produced in industrial processes.

Most literature defines WH as a heat leaving the process without further use. However, the flaw in this definition is, that it does not specify its potential. It consists of several aspects. These include, not only, availability of the WH, the mode of its transfer and the type of heat carriers, but also the distance between the WH source and the place of use and its temperature levels (Forman et al., 2016). Due to these aspects, a large amount of WH has a very low potential and its reuse is most of times inefficient. The following images show potential of WH for recovery in different parts of the industry in a) European Union and b) Czech Republic (Panayiotou et al., 2017).

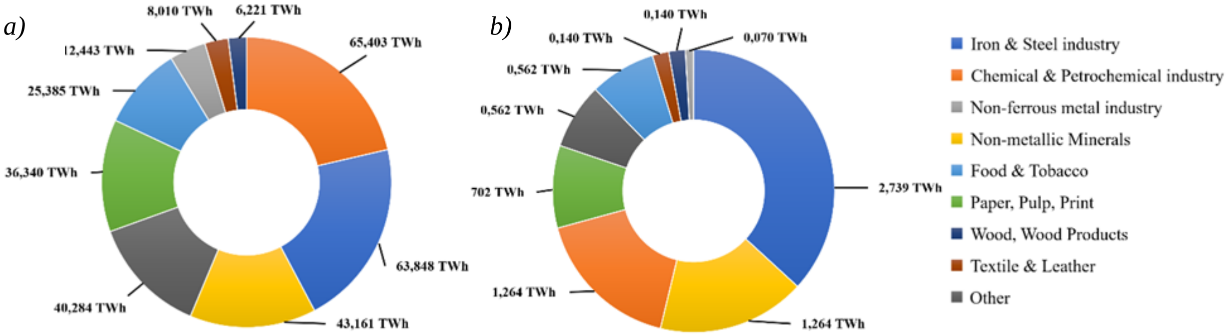

Fig. 1: WH available for recovery a) in European Union, b) in Czech Republic (Panayiotou et al., 2017)

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2. Assessment of local flue gas waste heat recovery based on carbon-reduction concept

This work focuses on the local recovery of flue gas waste heat (FGWH) from industrial combustion equipment (such as process furnaces, water- and steam- boilers, etc.). The FGWH can be utilized locally in various ways, for example for preheating process or combustion air, heating water or other heat carriers (e.g., thermos-oils), etc. However, the different way of flue gas waste heat recovery (FGWHR) will vary in terms of investment and operating costs and environmental impact. To make a comprehensive, systematic and rapid assessment of which of the available FGWHR options is the most environmentally friendly, the carbon-reduction oriented assessment has been developed and will now be presented.

2.1 Thermodynamic representation of industrial combustion equipment

For the thermodynamic representation of the combustion equipment, the temperature-heat flow (T-Q) diagram is used (see Fig. 2a). This diagram is generally and long-time used in conceptual considerations of combustion equipment design as well as in its retrofit (Jegla et al., 2000). The flue gas side is represented in this diagram as a hot stream cooled from the theoretical flame temperature (T_{TFT}) to ambient temperature (T_O), considering the flue gas exits the equipment at the stack temperature (T_{STACK}). The heat released in the equipment by the fuel combustion is denoted as Q_F, the unused FGWH leaving to the stack as Q_S, and the heat transferred to the heated stream in the equipment as Q_H. The heated process stream in the combustion equipment enters the equipment at temperature T_1 and exits at temperature T_2. As mentioned in the introduction, there is a potential for FGWHR. In the case of unused FGWH Q_S, its utilizable potential (or recovery quantity) Q_R is defined by the limiting flue gas temperature T_L – see Fig. 2b). This limit temperature is specified as the safe minimum flue gas temperature for reliable operation of FGWHR (to avoid, for example, the risk of flue gas condensation, increased equipment corrosion and fouling, etc.).

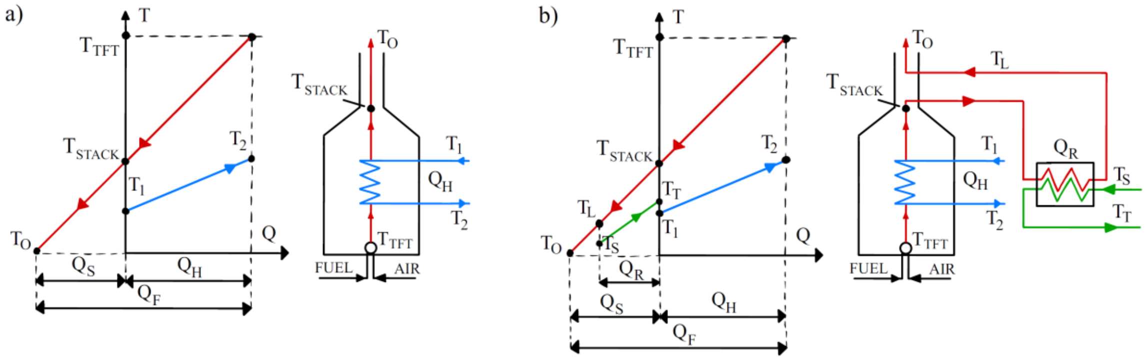

Fig. 2: Representation of combustion equipment: a) without FGWHR; b) with FGWHR

Figure 2b shows schematically the FGWHR of the available FGWH potential by a general fluid, heated from its supply temperature (T_S) to the target temperature (T_T). This fluid can realistically be any locally applicable process fluid to the site under consideration – i.e., for example, FGWHR allows preheat a technology air for the process, or combustion air for the burners of the combustion equipment, or it can heat the water (process or utility), or it can preheat any other locally utilizable heat carrier (e.g. thermo-oil), etc. Each of these options is then characterized in the T-Q diagram by a different specification - i.e., flow rate and inlet and outlet temperature. While the two heated fluid temperatures are represented directly, the heated fluid quantity is considered by the slope of the fluid line, which represents the heat capacity of the flow (CP [W/°C]). The CP is the product of the flow quantity ($m^{\bullet}$ [kg/s]) and the specific heat capacity (c_p [J/(kg·°C)]) of the fluid. In Figure 3, the detail of the T-Q diagram in the FGWHR area shows a typical situation for the three most common cases (heating of air, water, thermo-oil).

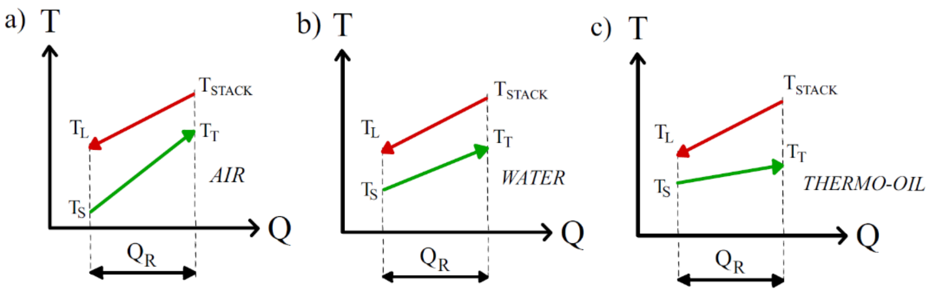

Fig. 3: Typical FGWHR options for preheating: a) air; b) water; c) thermo-oil.

2.2 Carbon-reduction assessment concept for the flue gas waste heat recovery system selection

The selection of the most environmentally friendly FGWHR system based on the developed carbon-reduction concept will be explained through an illustrative industrial case study. Flue gas (FG) from the combustor (see Fig. 2b) is available at T_{STACK} =330°C and can be used up to T_L =120°C. This corresponds to Q_R = 2 MW, which can be used for preheating of technology air (TA), combustion air (CA), hot water (HW) or thermo-oil (TO). The input operating data of these streams for the conceptual assessment of FGWHR options are presented in Table 1.

Tab. 1: Input operating data for the conceptual assessment of FGWHR options.

Stream	FG	TA	CA	HW	TO
Input (supply) temperature (°C)	330	20	20	15	20
Output (target) temperature (°C)	120	85	220	125	150
CP (MW/°C)	0.0096	0.0308	0.01	0.018	0.0154
Film heat transfer coefficient (W/m^2°C)	80	35	50	5000	1000

Developed carbon-reduction concept for the most environmentally friendly FGWHR system selection is based on assessment of the totally balanced amount of CO_2 emissions associated with the implementation (realization) and operation of each potential FGWHR system option.

The determination of the amount of CO_2 emissions associated with the implementation of the FGWHR system for the case study assumes that the FGWHR system will work for 10 years and will be implemented using a tube bank heat exchanger (HE), which can be used for all possible options of FGWHR system and wide range of flue gas temperatures and operating conditions (Kilkovský et al., 2014), i.e., it is suitable not only for operating data of our case study (non-fouling FHWGR with temperatures below 330°C), but also for fouling FGWHR and higher temperatures. First, the overall heat transfer coefficient of the HE is determined (based on data from Table 1) and then its heat transfer surface (HTS) is determined based on the well-known calculation of the logarithmic mean temperature difference (LMTD) assuming a counter-current arrangement of fluids inside the HE. The total length of the HE´s tubes is then calculated from HTS, assuming that the HE is made from the steel tubes ø 35x2 mm. The amount of CO_2 emissions related to the realization (implementation) of the FGWHR system is then calculated using (Chilana et al., 2016), considering the value of total steel pipe CO_2 emissions (including manufacturing, fabrication, transportation, installation and operation of tubes) 1481 lb CO_2 per 1ft of tube length (i.e., 2204 kg CO_2 per 1m of tube length).

The amount of CO_2 emissions associated with the annual operation of the FGWHR system (assuming 8000 hours/yr) is determined assuming the FGWHR system saves the amount of fuel (equivalent to the Q_R used to heat the fluid) that would have to be burned in the combustion plant where the fluid would have been heated if it had not been heated in the FGWHR system. The amount of CO_2 emissions associated with the operation of a FGWHR system is therefore related to the type of fuel burned in the local combustion equipment providing FGWHR.

In our case study, the fuel considered is natural gas (NG) with a heating value of 50 MJ/kg$_{fuel}$. From the ideal combustion of NG, the amount of CO_2 emissions produced for 1 kg of NG burned is determined and the NG composed of 100% methane is considered. Through the ratio of the molar masses of CH_4 and CO_2 entering the reaction a value of 2.75 kg CO_2 emissions per 1 kg of NG is obtained. The 85% thermal efficiency of combustion equipment is considered and the amount of fuel saved (kg/s) employing the Q_R as available FGWHR is calculated using equation: $m_{F1}=Q_R/(LHV\cdot\eta)$, where LHV is the fuel (i.e. NG) low heating value (MJ/kg) and η is the thermal efficiency of the combustion equipment (as decimal number). This amount of saved NG is converted to the amount of CO_2 emissions equivalent to the fuel saved.

Mentioned calculation considers the situation when a FGWHR of size Q_R is used for preheating the process stream (such as TA, HW, TO, etc.). However, if the FGWHR of size Q_R is used to preheat the CA for the combustion equipment, there is a further reduction of CO_2 emissions since the preheated CA contributes to reduce the actual fuel consumption in combustion process of the combustion equipment. The reduced fuel consumption of the combustion equipment by using preheated CA with heat Q_R can be calculated from the equation: $m_{F2}= m_{F1} - (Q_R/LHV)$. Thus, the total fuel savings when the FGWHR of Q_R is used to preheat the CA for the combustion equipment can be considered as the sum of the saved (unburned) fuel m_{F1}, that would otherwise need to be burned to heat the CA in the combustion equipment plus the savings of the unburned fuel in the combustion equipment, expressed by the relation (m_{F1} - m_{F2}), which the supply of preheated CA to the combustion equipment burners actually yields. Thus, for the purpose of the conceptual carbon-reduction assessment, the amount of fuel saved by using a FGWHR of size Q_R to preheat the CA for the combustion equipment in question is then given by the relation: $m_F = m_{F1} + (m_{F1} - m_{F2}) = 2 \cdot m_{F1} - m_{F2}$. This amount of saved NG is then converted to a CO_2 emission equivalent to the fuel saved.

In addition to savings in CO_2 emissions due to reduced fuel consumption, it is also necessary to consider savings in CO_2 emissions related to the reduction of fuel extraction and transport. The case study considers the NG as fuel and the situation in Germany, where (according to a study by company WINGAS GmbH) the total CO_2 emissions of NG are formed by 37% attributable to CO_2 emissions from NG combustion and the remaining 63% to CO_2 emissions from NG extraction and transport (E&T).

3. Conclusions

Paper presents developed conceptual carbon-reduction oriented assessment of FGWHR for local combustion equipment and illustrate the application of developed assessment via an industrial case study, where the conceptual assessment is applied to the several options of FGWHR system (namely preheating TA, CA, HW and/or TO) according to description from chapter 2. Obtained results of conceptual assessment are presented in Table 2.

Tab. 2: Results of conceptual assessment of industrial case study for individual options of FGWHR

Local FGWHR option:	FG-TA	FG-CA	FG-HW	FG-TO
LMDT (°C)	161.8	104.9	149.5	136.1
Heat transfer surface (m^2)	507.6	619.5	169.9	198.4
Total length of exchanger´s tubes (m)	4616.8	5634.4	1545.6	1804.2
CO_2 production from exchanger implementation (t/y)	1017.5	1241.8	340.6	397.6
CO_2 savings due to fuel combustion savings (t/y)	3727.1	6895.1	3727.1	3727.1
CO_2 savings due to fuel E&T savings (t/y)	6348.1	11740.2	6348.1	6348.1
Total CO_2 balance (t/y) (i.e. production minus savings)	-9055.6	-17393.5	-9732.5	-9675.5

Results of developed carbon-reduction oriented assessment presented for the solved industrial case study in Table 2 clearly show that the most environmentally friendly FGWHR is the CA option, which has the highest total saved CO_2 emissions amount reaching 17393.5 t/yr. The second-best alternatives of FGWHR are HW and TO options with 9732.5 t/y and 9675.5 t/y of totally saved CO_2 emissions. The least environmentally friendly FGWHR alternative is TA option, which reaches 9055.6 t/y of totally saved CO_2 emissions.

The presented approach can serve as an effective method for the initial and rapid carbon reduction-oriented assessment of local FGWHR possibilities and the selection of its most suitable option.

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References

European Commission (2022) *EU energy in figures: statistical pocket book*, ISBN 978-92-76-49120-0, doi:10.2833/334050

Panayiotou, G., Bianchi, G., Georgiou, G., Aresti, L., Argyrou, M., Agathokleous, R., Tsamos, K., Tassou, S., Florides, G., Kalogirou, S., Christodoulides, P. (2017) Preliminary assessment of waste heat potential in major European industries. *Energy Procedia*, 123, pp. 335–345.

Forman, C., Muritala, I., Pardemann, R., Meyer, B. (2016) Estimating the global waste heat potential. *Renewable and Sustainable Energy Reviews*, 57, pp. 1568–1579.

Jegla Z., Stehlík P., Kohoutek J. (2000) Plant energy saving through efficient retrofit of furnaces, *Applied Thermal Engineering*, 20, pp. 1545-1560.

Kilkovský B., Stehlík P., Jegla Z., Tovazhnyansky L., Arsenyeva O., Kapustenko P. (2014) Heat exchangers for energy recovery in waste and biomass to energy technologies - I. Energy recovery from flue gas, *Applied Thermal Engineering*, vol. 64, no. 1- 2, pp. 213-223.

Chilana, L., Bhatt, A., Najafi, M., Sattler, M., (2016) Comparison of carbon footprints of steel versus concrete pipelines for water transmission. *Journal of the Air & Waste Management Association*, 66, pp. 518-527.