ANALYSIS OF ENERGY EFFICIENCY OF EXTERNAL RECUPERATION OF HEAT FROM FLUE GASSES FROM INDUSTRIAL PROCESSES

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The paper presents a case study regarding the energy efficiency of recuperation of heat from flue gasses from a thermal treatment furnace. The authors have presented the main solutions for external recuperation of secondary energy resources. There have also been presented energy, environmental and economic aspects of recuperation of secondary energy resources. The case study presents the recuperation of heat from flue gasses for warm water preparation and for heating. The obtained results lead to fuel savings and the payback period is lower than 2 years, showing a high economic efficiency of the project.

Keywords: secondary energy resources, external recuperation, flue gasses

1. Introduction

Flue gasses represent one of the main categories from the secondary energy resources (SER). For main technological processes from different industrial sectors, such as metallurgy, machine manufacturing, building materials, chemical industry, temperatures vary in a very large domain. Thus, the flue gasses resulting from these processes have temperatures between 300 – 2800 °C, represent an important potential of secondary energy resources [4, 5].

Pyrotechnical processes represent technological processes that imply combustion of fuel or thermal treatment of fuel. These processes are met very often within different industrial sectors: metallurgy, machine manufacturing, chemical industry, petrochemical industry, building materials industry [6, 7].

The efficiencies of these processes are, generally speaking, quite low, thus leading to large heat losses, which represent a considerable source of secondary energy resources, especially as flue gasses. In the majority of cases the flue gasses come from the pyrotechnical processes that imply the fuel combustion. Due to high temperature imposed by these processes, the heat contained within the flue gasses can be between 35 and 60 % from the total quantity of consumed energy.

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2. Characteristics of external recuperation of heat from flue gasses. Possible solutions for recuperation

External recuperation of heat from flue gasses can be performed when the flue gasses resulted from an industrial process (especially a fuel combustion process) are used outside the process they come from for covering heat or/and power demand. These recuperation solutions can be performed either as independent solutions or as complementary solutions to internal recuperation in order to increase the overall recuperation ratio.

Table 1 presents the main solutions for external heat recuperation from flue gasses resulted from a fuel combustion process.

Comparing the internal and external heat recuperation from flue gasses the latter shows the following characteristic aspects:

- External recuperation of energy from secondary energy resources leads to some limits due to unsynchronised production of SER and its consumption having either a quantitative aspect (in case of heat generation) or qualitative aspect (in case of power generation).
- The energy effects obtained through fuel savings are reflected at the SER consumer, usually through fossil fuel.
- The economic effects due to fuel savings and investments and expenses with heat recuperation equipment influence the economic balance of the SER consumer.
- The ecologic effects due to fuel savings come through reduction of environmental impact within the analysed contour, which contains the SER generator and SER user.

Table 1

Main solutions for external heat recuperation from flue gasses

Type of recuperation	Purpose of recuperation	Characteristics of recuperation solutions
Thermal	a. Heat supply to technological processes; b. Heating, ventilation, air conditioning of buifings; c. Warm water preparation.	a. Has a great annual recuperation ratio due to permanent demand; b. Due to sezonal demand the annual utilisation time is about 2500-3000 h/year, much lower than the availability of flue gasses (6000-7000 h/year, depending on the combustion process), which leads to a low annual recuperation ratio; c.limitările de regim care apar sunt de natură cantitativă, necesarul de căldură pentru prepararea apei calde fiind mult mai mic decât căldura conținută de gaze, diferența neputând fi recuperată.
Electric	Power generation	– Heat recovery from the flue gasses with high thermal potential is performed within heat recovery steam generators ; steam then is used in turbines for power generation; – Depending on the characteristics of flue gasses, they can be directly used in gas turbines for power generation;

Type of recuperation	Purpose of recuperation	Characteristics of recuperation solutions
		– The annual recuperation ratio depends mainly on the load limits that can be imposed be the power system.
Cogeneration / trigeneration	Combined production of heat and power / power, heat and cold	– Generated steam can be used within a cogeneration/trigeneration plant for combined production of power and heat or power, heat and cold; – For gas turbines using flue gasses the exhaust gasses can be used for heat or cold production.

3. Theoretical aspects regarding energy, economic and environmental analysis of external recuperation of heat from flue gasses

3.1. The effects of recuperation of secondary energy resources

The effects of external recuperation of secondary energy resources can have energy, economic and environmental aspects.

Energy aspects

The energy aspects can be quantified through fuel savings obtained through recuperation at the level of energy consumer. Thus, due to this fact energy consumption is lower and therefore the use of fossil fuels is reduced.

The main energy criteria used to analyse the energy efficiency of a solution are the following:

- Fuel equivalent of saved energy (fuel savings in absolute or relative value) – is defined as difference between the fuel consumption before and after recuperation.
- The recuperation ratio – is defined as ratio between the effectively recovered heat, taking into account all thermodynamic and technical-economic restrictions, and the heat contained within the SER.

Environmental effects

The recuperation of the secondary energy resources has a great, direct and indirect, effect on the environment.

The recuperation of heat from flue gasses from the combustion processes leads to significant reduction of heat emission into atmosphere, thus reducing the green house gas effect, which is a very important factor for maintaining the ecologic equilibrium.

Fuel extraction, especially when talking about coal or lignite extraction, has a great negative impact upon the environment. Thus, any fuel savings that can be obtained through recuperation solutions can lead to diminishing the need in fossil fuels, leading to reduction of environmental impact.

Therefore, from the environmental point of view the effect of implementation of recuperation of heat from flue gasses can be quantified through reduction of values for the impact criteria compared with the reference solution. From the economic point of view the environmental effects can be quantified through the eco-taxes.

Economic effects

The economic aspects take into consideration the fuel savings that can be obtained at the consumer's site.

3.2. The utilisation of heat recovery equipment for external recuperation of heat from flue gasses

Generally, the heat recovery equipment represents the most used solution for external recuperation of heat from flue gasses from the combustion processes. Recuperation of heat for warm or hot water preparation, or for steam generation can be a second stage of external recuperation, which can follow an internal recuperation, or can be a single stage recuperation process.

The heat recuperation equipment have to simultaneously fulfil several requirements (generally, depending on the process):

- High energy efficiency.
- High reliability.
- Simple in exploitation, few personnel, low control and supervision needs.
- High adaptability for incorporating into the technological process.

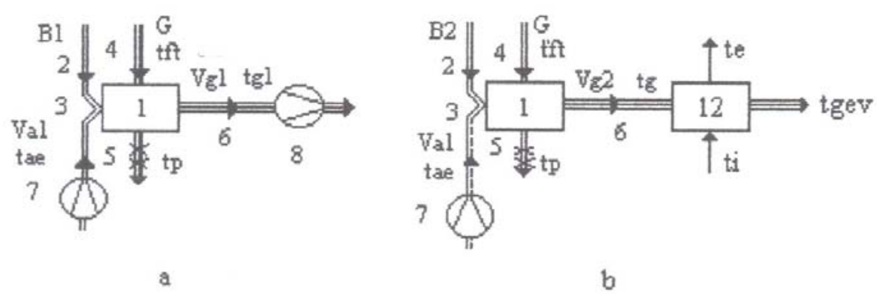

Fig. 1. Simplified scheme of external recuperation of heat from flue gasses: a – without heat recovery equipment; b – with heat recovery equipment. 1 – fuel combustion process (heat treatment furnace); a. Initial situation – without recuperation: B_1 – fuel consumption, 3 combustion air, 4 cold technological materials, 5 processed technological materials, 6 – flue gasses at the exit of furnace, 7, 8 – air fans, 12 – heat recovery equipment; t_i, t_e – temperatures of cold and hot water.

For the case of recuperation of heat from flue gasses for thermal needs the energy efficiency is dependent on the general scheme of electricity and heat supply of the analysed contour through its effects of recuperation.

In the analysed case it has been considered that electricity is supplied from the national power grid and heat is generated in a thermal plant on site.

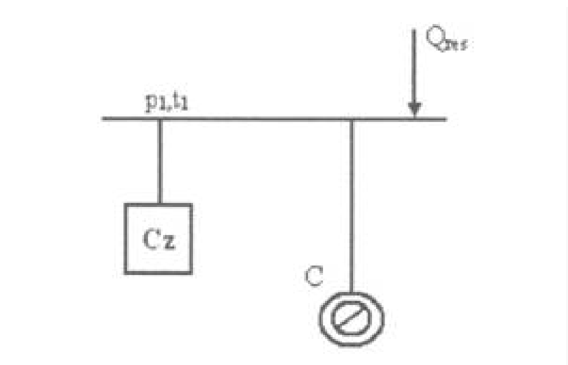

Fig. 2. Separate electricity supply from national power grid and heat supply from thermal plant. Cz – boiler, C – heat consumer, Qres – heat recovered from SER.

Fuel savings are dependent on the efficiencies of the boiler and on the fuel type saved through recuperation.

The energy efficiency is higher when the total recuperation ratio is higher (high energy efficiency for recuperation of heat from flue gasses for heat supply of some consumers: industrial processes and warm water with high annual duration periods compared to other consumers with seasonal character of consumption: heating). Thus, the consumer that uses the recuperation solution is very important for the overall efficiency.

The weight of the supplementary fuel consumption within the net fuel savings is as low as the recuperation is performed closer to the place of SER generation (the supplementary energy consumption for recuperation is lower) and the specific fuel consumption for supplementary energy production is lower.

$$\Delta B_{en}^{t} = \Delta B_{en}^{t*} - \Delta B_{\sup l}^{t}\text{, [kg c.c./s]} \quad (1)$$

Where: ΔB_{en}^{t*} - represents the brut fuel savings, kg c.c./s.

$\Delta B_{\sup l}^{t}$ - represents the fuel equivalent of supplementary energy consumption for additional equipment needed for recuperation, kg c.c./s.

The brut fuel savings can be calculated:

$$\Delta B_{en}^{t*} = \frac{\Delta Q_{en}^{t}}{H_i} = \frac{Q_{res} \cdot \delta_r^t}{\eta_{CT} \cdot H_i}, \text{ [kg c.c./s]} \tag{2}$$

Where: ΔQ_{en}^{t} - represents the brut heat savings due to recuperation, kW.

The specific fuel savings are:

$$\Delta b_{en}^{t} = \frac{\Delta B_{en}^{t*}}{Q_{res}}, \text{ [kg c.c./s]} \tag{3}$$

The fuel equivalent of supplementary fuel consumption is:

$$\Delta B_{\sup l}^{t} = \frac{\Delta P_{\sup l} \cdot b_{SEN}}{3600}, \text{ [kg c.c./s]} \tag{4}$$

Where: $\Delta P_{\sup l}$ - represents the supplementary power needed for the recovery equipment and for blowing the flue gasses from the recovery spot to the heat recovery equipment (and backwards if needed).

b_{SEN} - specific fuel consumption for power generation at the national power grid level, kg c.c./kWh.

The heat recuperation ratio is dependent on the thermal agent generated within the recovery equipment (hot water or steam), on its parameters and on the recovered heat utilisation (for: warm water preparation, heating, industrial consumption):

$$\delta_r^t = \frac{Q_{gar}}{Q_{ga}}, \tag{5}$$

Where: Q_{ga} - represents the heat flow within the flue gasses, kW.

Q_{gar} - represents the heat flow that can be effectively recovered from flue gasses, kW.

The economic effect of increasing energy efficiency within the analysed contour can be quantified through the reduction of expenses with fuel.

The economic efficiency of SER recuperation is established compared to solution “without recuperation”. When analyzing multiple solutions for recuperation, the optimal solution is set through comparative economic analysis of each proposed solution with the reference solution (without recuperation).

The recovery solution that leads to the maximum economic effect – based on an economic criterion – is considered to be the optimal one.

The most used economic criterion for the energy efficiency projects is "Payback Period". It can be calculated using the following formula:

$$TR = \Delta I / \Delta C, \text{ years} \tag{6}$$

Where: ΔI – represents the plus of invenstment for solution with heat recuperation, monetary units/year.

ΔC – represents the reduction of expenses, monetary units/year.

For the case when the eco-taxes are taken into account the payback period is calculated as follows:

$$TR^{*} = \Delta I / \Delta C + \Delta ec, \tag{7}$$

Where: ΔEc – represents the reduction of expenses due to eco-taxes, monetary units/year.

4. Case study – external recuperation of heat from flue gasses from a thermal treatment furnace for hot water generation in a recovery boiler

4.1. Presentation of the analysed solution

The analysed industrial contour represents a furnace for thermal treatment for different pieces designed for machinery construction industrial sector.

The energy audit revealed the following: low energy efficiency of the furnace, which uses natural gas as fuel. There have been identified considerable energy losses.

There has been considered that the furnace operates 7200 h/year.

The inventory of the secondary energy resources has revealed the following aspects:

- A great potential of the flue gasses from the furnace.
- The temperature of the flue gasses at the exit of the furnace is 1000 °C, thus the major energy losses occur due to this fact.

The case study analyses the implementation of a recovery boiler for hot water generation at a temperature of 150 °C. The investment has been estimated at about 96700 Euros.

The heat recovered from the flue gasses within the recovery boiler is used for covering a part of the heat demand for warm water preparation and for heating needed on site.

The data used within the energy efficiency analysis of implementation of the recovery boiler for heat recuperation from flue gasses are presented in table 2.

Table 2

Initial data for energy efficiency analysis

No.	Item	Notation	Unit	Value
1	Lower heating value (CH_4)	H_i	kJ/m^3_N	36000
2	Fuel consumption before recuperation	B_1	m^3_N/h	1256.4
3	Cold water temperature	t_i	°C	10
4	Hot water temperature	t_e	°C	150
5	Flue gasses temperature at entrance into recovery boiler	t_g	°C	1000
6	Flue gasses temperature at exit from recovery boiler	t_{gev}	°C	380

The present case study analyses the energy and economic efficiencies of implementation of a recovery boiler into the technological process. For this complex analysis there have been considered the following:

- Thermo-physical characteristics of secondary energy resources.
- The parameters of flue gasses correlated with technological process.
- Composition of secondary energy resources.
- Economic data.

The energy and economic evaluation of recuperation of heat from flue gasses resulted from a furnace within a recovery boiler is performed used energy and economic criteria.

4.2. Calculus of energy efficiency of implementation of recovery boiler

A. Calculus of the main parameters for the flue gasses.

Table 3 presents the main parameters for flue gasses.

Table 3

Main parameters for flue gasses

No.	Item	Notation	Unit	Formula	Value
1	Theoretic volume of flue gasses	V_{g0}	m^3_N/ m^3_N	-	13.5
2	Theoretic volume of combustion air	v_{a0}	m^3_N/ m^3_N	-	12.5
3	Real volume of flue gasses before recuperation	V_{g1}	m^3_N/ m^3_N	$V_{g1} = V_{g0}+(\lambda_1-1) V_{a0}$	13.5
4	Real volume of combustion air before recuperation	V_{al}	m^3_N/ m^3_N	$V_{a1}=\lambda_1*V_{a0}$	12.5
5	Enthalpy of flue gasses after furnace	i_g	kJ/m^3_N	$i_g=c_{pg}*t_g$	2000.2
6	Enthalpy of air (without recovery)	i_{ae}	kJ/m^3_N	$i_{ae}=c_{pae}*t_{ae}$	25.952
7	Fuel enthalpy	i_b	kJ/m^3_N	$i_b=c_{pb}*t_b$	44.24
8	Heat contained within flue gasses at exit from furnace	Q_{g1}	kW	$Q_{g1}=B_1* V_{g1}*i_g$	9423.94

No.	Item	Notation	Unit	Formula	Value
9	Heat introduced with combustion air	Q_{al}	kW	$Q_{a1}=B_1*\lambda*v_{a0}i_{ae}$	113.215
10	Heat introduced with fuel (without recovery)	Q_{c1}	kW	$Q_{c1}=B_1*(H_i+i_b)$	12579.5

B. Calculus of energy criteria

B1. Heat recovery ratio from flue gasses

$$\delta_r^t = \frac{Q_{rec}}{Q_{res}} = \frac{(i_g - i_{gev})*\eta_{cz}}{i_g} = \frac{(2000.2-671.878)}{2000.2}*0.85 = 0.564, \quad (8)$$

B2. Fuel savings due to recuperation

$$Q_{res} = B_1 v_{g1} i_g = 0.349*13.5*2002.2 = 9423.9423 \text{ [kW]}, \quad (9)$$

$$\Delta B_{enCT}^{t*} = \frac{Q_{res}*\delta_r^t}{\eta_{CT\,in}*H_i} x = \frac{9423.9423*0.564}{0.85*36000} = 0.1737\,[m_N^3/s], \quad (10)$$

$$Q_{rec} = B_1 v_{g1*}(i_g - i_{gev})*\eta_{cz} = 0.349*13.5*(2000.2-671.878)*0.85 = 5319.631 \text{[kW]}, \quad (11)$$

$$\Delta t = 150-10 = 140 [°C], \quad (12)$$

- Hot water flow

$$D_{apa} = \frac{Q_{rec}}{c_p \Delta t} = \frac{5319.6307}{4.186*140} = 9.07[kg/s], \quad (13)$$

- Temperature difference

$$\Delta t_{med} = \frac{\Delta t_{\max} - \Delta t_{\min}}{\ln \frac{\Delta t_{\max}}{\Delta t_{\min}}} = \frac{(1000-150)-(380-10)}{\ln \frac{(1000-150)}{(380-10)}} = 577.11[°C], \quad (14)$$

- Heat transfer area

$$S_{CR} = \frac{Q_{rec}}{k \Delta t_{med}} = \frac{5319.6307}{110*577.11} = 83.79[m^2], \quad (15)$$

- Power surplus of pumps and fans

$$\Delta P_{pompa} = \frac{1.1 D_{apă} * \Delta p_{pp}}{\rho_{apă} * \eta_{pp} * 10^3} = \frac{1.1 * 9.07 * 1500 * 10^3}{1000 * 0.85 * 10^3} = 17.6[kW], \quad (16)$$

$$\Delta P_{supl} = \Delta P_{PP} + \Delta P_{VG} = 17.6 + 1.339 = 19[kW], \quad (17)$$

$$\Delta B^t_{supl} = \frac{\Delta P * b_{SEN}}{3600} = \frac{19 * 0.35}{3600} = 1.85 * 10^{-3}[m^3_N / s], \quad (18)$$

$$\Delta B^t_{enCT} = \Delta B^{t*}_{enCT} - \Delta B^t_{supl} = 0.1737 - 1.85 * 10^{-3} = 0.1718[m^3_N/s] \quad (19)$$

$$\Delta B_{annual} = \Delta B^{t*}_{enCT} * \tau_u = 0.1718 * 3650 * 3,6 = 2.2574 * 10^4 [m^3_N/year], \quad (20)$$

Table 4 shows the main energy criteria for the solution of external recuperation.

Table 4

Main energy criteria

No.	Item	Notation	Unit	Value
1	Brut fuel savings	ΔB^{t*}_{enCT}	m^3_N/ s	0.1737
2	Net fuel savings	ΔB^t_{enCT}	m^3_N/ s	0.1718
3	Annual net fuel savings	ΔB_{annual}	m^3_N/ an	$22574 * 10^4$
4	Recuperation ratio	δ^t_r	-	0.564

C. Economic efficiency calculus

The total investment for the recuperation solution consists in investments in recovery boiler, fan for flue gasses (surplus of installed capacity) and pump for feeding water of boiler.

$$I_{ef} = I_{CR} + I_{VG} + I_{PP} \text{ [euro]}, \quad (21)$$

$$I_{ef} = I_{cr} + I_{vg} + I_{PP} = 96200 + 273.8 + 288.6 = 96762.4 \text{ [euro]}, \quad (22)$$

- Annual expenses reduction

$C_{\Delta B}$ = ΔB*p_c=2.2574*10^4*2.7778*10^-6*36000*25=56435.45[euro/year], (23)

- Annual exploitation expenses

$C_{ex} = 0.04 * I_{ef} = 3870.5$ [euro/year], (24)

- Difference of annual expenses

$\Delta C_{cz} = C_{\Delta B} - C_{ex} = 52564.95$[euro/year], (25)

- Payback period

$$T_r = \frac{I_{ef}}{\Delta C_{cz}} = \frac{96762.4}{52564.95} = 1.7\,[years], \quad (26)$$

$$T_r < T_{rn} = 2 \text{ [years]}, \quad (27)$$

6. Conclusions

Valorisation of secondary energy resources, and especially the heat from flue gasses, represents one of the most effective methods for increasing energy efficiency of consumed energy within industrial processes. Even though the utilisation of secondary energy resources outside the process they came from leads to different limitations of operating regimes due to different periods of operation, the energy effects due to fuel savings are reflected at the consumer's site. This recuperation method can lead to important energy benefits for the company or industrial platform were analysis is performed.

Generally, the final decision regarding the implementation of a solution of recuperation of secondary energy resources is always taken based on the economic criteria. When the economic criteria internalise also the environmental effects (through eco-taxes, with condition of adequate legislative framework) the decision is more concluding.

In the analysed case study the fuel savings and recuperation ratio (see table 4) show the high level of energy efficiency of the proposed solution for external recuperation of heat from flue gasses.

The value for the payback period is under 2 years (the reference value for the payback period for the energy efficiency projects), which shows the high economic efficiency of the proposed solution.

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