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Increasing the energy efficiency of a hot-dip galvanizing plant and reducing its environmental impact

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Abstract

Most industrial plants prioritize efficient, uninterrupted production, with production costs coming in second even though they are no less important. Any commitment to boosting energy efficiency while cutting pollution and energy waste is treated as an after-thought. This article presents an in-depth analysis of energy efficiency and its related emissions reduction opportunities in the context of a hot-dip galvanizing plant. This paper describes the modernization of the galvanization process in terms of the current situation with the process and possible energy efficiency improvement actions (such as operating parameters and changes at system level), which affect the overall exhaust emissions without changing current production or the technology used. Results show that the energy requirement dropped by 23%, from 399.3 MJ/tonne at baseline to 307 MJ/tonne in the improvement scenario, while emission intensity NO dropped by 96%.

Keywords: Energy efficiency; galvanizing; environmental impact; modernization

1. Introduction

Changing energy markets, growth in energy demand and increasingly strident energy politics are putting various pressures on industry, especially in the U.S. manufacturing sector [1]. As a result, much effort has gone into enhancing energy efficiency in industrial plants and reducing their adverse impact on the environment. Efficiency improvements such as the adoption of multiple energy efficiency measures are part and parcel of the drive to boost industrial process performance born of a desire to cut the related economic costs and mitigate the significant environmental impacts. The link between production and the environment was examined in [2], where profitability and environmental problems are increasingly viewed as key elements in meeting the goals of European Union energy policy [3]. Empirical evidence to support this positive relationship demonstrates the rapidly increasing importance of environmental issues [4].

The idea of environmentally sound production (energy transition to a low-carbon energy economy) was reflected in activities and a study concerning the provision of energy services with the lowest environmental impact and cost [3]. According to IEA [5], increased investment by SMEs in energy efficiency could also boost markets of energy service companies and markets for financial products; nearly 83% of the global energy service industry is a combination of small and regional players.

Efforts to improve energy efficiency performance are emphasized in the Energy Efficiency Directive [6] and other energy efficiency programs [7, 8, 9]. In these programs, energy audits have been used as a way to facilitate implementation of energy efficiency measures, and thus decrease energy consumption of industry as a whole. The key drawback of these programs is the fact that individual energy saving initiatives cannot sustain a high awareness level over time [10]. On the other hand, energy efficiency improvements in industrial facilities have proven difficult due to having to juggle operational procedures, environmental constraints and business goals in real time. This difficulty is further compounded by the fact that any action must be taken with a full understanding of its future implications for manufacturing operations. Therefore, a broad-based assessment must be made before introducing optimization methods and actions for operations managers in existing facilities. In addition to demonstrating the limits imposed by programmers, benefits could be highlighted [11, 12, 13].

Industrial facilities or manufacturing sectors account for approximately 28% of U.S. manufacturing primary energy consumption (fossil energy) [14] and 94% of U.S. manufacturing combustion causing greenhouse gas (GHG) emissions.

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Energy losses in manufacturing processes remain inevitable even if all potential savings are harvested from energy efficiency improvements (the results of energy audits). Analysis of energy intense processes in industrial plants has traditionally centered on energy and cost savings [15, 12]. To increase energy efficiency and in related moves reduce environmental damage by pollution control, energy efficiency improvement actions are needed. This could be supported by accelerating the development and widespread market take-up of low carbon technologies or fuel substitution [16, 17]. Some technologies hold potential for dramatic gains in resource efficiency, while others—such as carbon capture and storage (CCS)—may bring more costs than benefits [18]. Economic potential for energy efficiency improvements in U.S. industry in 2020 in terms of selected technologies and industrial subsectors is presented in the study [19].

Therefore, the potential for energy efficiency improvements remains largely untapped and is referred to as “the energy efficiency gap” [20] in small- and mid-sized industrial plants (SMEs). Many opportunities still exist for energy conservation and cost optimization in industries with complex infrastructure, with energy audits playing a key role in making the case for change. Several energy audits with respect to selecting cost-effective solutions regarding energy efficiency measures have been conducted in many production processes [21] and versatile industrial practices [22].

The analyzed literature supports the idea that there is a direct link between carrying out energy audits and achieving tangible energy savings, but is less clear about the extent to which energy audits can trigger real changes in companies’ behavior and moves to transition to an environmentally conscious industrial plant. The energy audit approach addresses the need to simultaneously identify energy efficiency measures, build capacity and raise awareness [23]. Moreover, the literature on energy efficiency methods applied to industrial processes is still under development [24, 25, 26]. To strengthen the link between energy audits and industrial practices, the focus of this study is on investigating the outcomes of energy efficiency improvements based on a hot-dip galvanizing plant. The results can also emphasize the role of the “fourth fuel”—energy efficiency—and the role of relatively novel technologies such as flameless combustion [27].

This paper shows measures to improve energy efficiency and sets out criteria for selecting ways of optimizing energy use. It supplies background knowledge to the industry concerned and analyses the proposed plant in terms of energy efficiency measures. The potential to increase energy efficiency lies in upgrading the system through applying combined heat and power technology without changing the current production. It relies on e.g. changing the main parameters and layout of the system and adding new devices.

2. Description of the current system

Hot-dip galvanizing produces a protective zinc-based coating on steel and iron items by immersing them in a bath of molten zinc. The typical bath chemistry used in hot-dip galvanizing is 98% pure zinc. A typical hot-dip galvanizing cycle and temperature profile is shown in Fig. 1. In order to form an alloy layer, the molten zinc and the steel surface need to be roughly the same temperature, usually about 450...490°C (850...915°F)—with the zinc in the molten state [28, 29]. As the steel exits the molten zinc bath, air "knives" blow off the excess coating from the steel sheet to ensure the coating meets the specified thickness requirement (to obtain the desired coating weight). Before the steel proceeds to the zinc bath, it is pre-heated in a direct fired, non-oxidizing furnace, which volatilizes the organic surface contaminants and can reduce small amounts of iron oxide (FeO) to iron (Fe). The steel strip then goes into a radiant tube annealing furnace under rolls, to optimize the iron content of the coating. Depending on its size, a radiant tube furnace may have as many as eight heating zones and a soak zone. Annealing temperatures vary from 720°C (1330°F) to 845°C (1550°F). Usually, a rapid jet cooler follows the heating zone which is able to cool the strip steel at rates of up to 316°C (600°F) [30]. Fig. 1 shows typical heating and cooling profiles for the analyzed case. This process combines in one line the cleaning, annealing, galvanizing (galvannealing), temper rolling and surface treatment. The process for the production of hot-dip galvanized strip directly follows the cold-rolling. Prior to galvanizing, the steel was initially degreased, pickled and fluxed in the appropriate solutions. The steel is heated to alloy temperature in a de-oxidizing atmosphere before it comes in contact with the zinc.

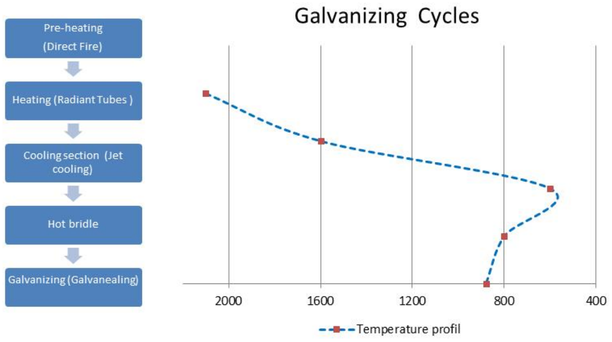

Figure 1: Hot-dip galvanizing cycle

3. Analysis of the current system

3.1. Existing steam production system

In current conditions the installation produces 34 tonnes of galvanized steel per hour in a continuous process and the metal line speed is about 27 m/min. A diagram of all the main thermodynamic processes is shown in Fig. 2. Additionally, there are two electric heaters of 50 kW each in the zinc bath, where the temperature is kept constant at 470°C (880°F), as presented in Fig. 3. Currently, the electric heaters are used to melt and heat the zinc rods for the galvanizing operation.

It is much more expensive and inefficient to use electricity for heating operations than natural gas. The electricity received by the facility is converted from natural gas at 30%; therefore the facility is paying the energy company for the conversion and its inefficiency when it can simply use natural gas to heat the zinc rods.

The installation comprises a boiler, heat exchanger, bath and a furnace fueled by natural gas. The heat of the hot flue gases is used to pre-heat the air used in the combustion process. The air output temperature after the heat exchanger is about 330°C and the flue gases (at $T_{EXHAUST\#0}$ =1186°C) are first diluted by fresh cold air and later cooled from $T_{EXHAUST\#1}$ = 925°C to about $T_{EXHAUST\#2}$ = 371°C.

The raw steel is directed to the furnace where it is strongly heated then processed in an N_2/H_2 atmosphere. After these operations the heated material is soaked in the zinc bath. A constant temperature of about 470°C should be maintained in the bath.

In this system there are two sources of heat: natural gas in the furnace and two electric heaters. The boiler produces hot water at parameters $T_{WATER\_OUT} = 82°C$ and $p_{WATER\_OUT} = 6.2$ bar using heat from the flue gases, but hot water demand is too small to use the full stream of flue gas heat, so part of the heat is released outside.

As relatively hot flue gases leave the installation, there is still potential for increasing energy recovery. The second aspect is the electric heaters which work with nearly no interruptions, which might be replaced by steam heat exchangers.

In the calculations of this (basic) system the following assumptions will be considered:

- operation hours in a year, 6000 hrs,
- constant electric power consumption where 100 kW is used for two electric heaters in the bath and the rest is other electric power consumers,
- constant natural gas consumption, V_{NG} = 362.5 m^3/h ($m_{NG} = 0.0475$ kg/s at heat value 36.13 MJ/m^3), so the boiler heat power is 13097 MJ/h (3638 kW).

In light of the above mentioned considerations there are three "and/or" ways to increase the energy efficiency of the installation and reduce its environmental impact:

1. increasing water/steam parameters to use a cogeneration system,
2. use steam to heat the zinc in the bath,
3. in the furnace - use flameless instead of typical flame combustion [27].

3.2. Energy balance for the current system

Table 1: The mixture compounds parameters at $T_{FLUE\_GAS} = 925°C$ and $1186°C$ ($\lambda = 1.1$)

Compound	Mole mass	Number of moles	Mass at $\lambda = 1.1$	Mass fraction g
	kg/kmol		kg	%
CO_2	44	1	44	0.138
N_2	28	8.27	231.56	0.728
O_2	32	0.2	6.4	0.020
H_2O	18	2	36	0.113
Sum =			317.96	

In the first step of the energy balance analysis, incoming air should be calculated for the combustion chamber and heat exchanger flue gas. Classical combustion in industrial furnaces should be run with the excess air ratio λ taken from the range 1.05 to 1.4 dependent on the type of fuel (air, oil, lignite, coal). In this case, where fuel is a methane air mix, excess air ratio λ should be about 1.1. This value will be taken for further calculations (the momentary values of this factor were not accurately measured). In the current installation, λ can be indirectly measured and calculated using a simple formula (1):

$$\lambda = \frac{21}{21 - O_2} \tag{1}$$

where O_2 denotes the content of oxygen in flue gas. Unfortunately in this case measurements were not carried out, so the final value of λ should be assumed from the range of gaseous fuels on the basis of furnace specification and the literature [31, 32]. For methane combustion in pure oxygen, a simple chemical stoichiometric reaction is shown in equation (2):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{2}$$

In this case where combustion in air is carried out with $\lambda = 1.1$, the chemical reaction can resemble equations (3) and (4):

$$CH_4 + \lambda \cdot (2O_2 + 7.52N_2 \rightarrow CO_2 + 2H_2O + 2 \cdot (\lambda - 1)O_2 + 7.52\lambda N_2 \tag{3}$$

$$CH_4 + \ 2.2O_2 + 8.27N_2 \rightarrow CO_2 + 2H_2O + 0.2O_2 + 8.27N_2 \tag{4}$$

The combustion chamber is a special type of heat exchanger where two (or more) mass fluxes mix and where a few entering and exiting heat fluxes can be specified. Entering fluxes are gas heat flux Q_{NG} (main one in the energy balance) and air heat flux Q_{AIR}. As an output, one main heat flux can be determined—heat of flue gases Q_{FLUE_GAS}.

Specific values of the components are shown in Table 1, but enthalpies and mass flows at characteristic points of this system are depicted in Table 2. A mathematical model of the existing system is shown in Table 3.

The enthalpy of gas after the combustion chamber and after dilution was calculated using the formula (5) and values from Table 2.

$$h_{FLUE\_GAS} = \int (h_i \times g_i) \tag{5}$$

Additional air is a part of the air which is taken into the system from the environment through leakages with galvanized steel. Adding cold fresh air to flue gases lowers the temperature of the flue gases, so dilution can also protect the heat exchanger (recuperator) against burnout. The value of the

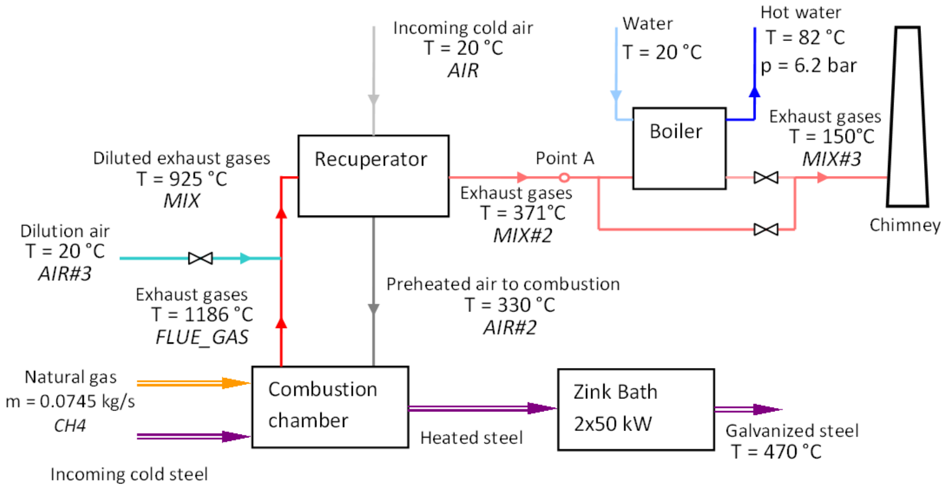

Figure 2: Diagram of thermodynamic transformations in the hot-dip galvanizing line

Table 2: System main parameters

air at $T = 25°C$	$h_{AIR}(20°C) = 25.61$ kJ/kg	$m_{AIR} = 1.406$ kg/s
preheated air at $T = 330°C$	$h_{AIR\#2}(25°C) = 603.15$ kJ/kg	$m_{AIR\#2} = 1.406$ kg/s
additional air at $T = 25°C$	$h_{AIR\#3}(25°C) = 25.61$ kJ/kg	$m_{AIR\#3} = 1.4805$ kg/s
flue gas at $T = 925°C$	$h_{FLUE\,GAS}(925°C) = 1144$ kJ/kg	$m_{FLUE\,GAS} = 1.4805$ kg/s
mixture flue gas and additional air at $T = 584.9°C$	$h_{MIX\#1}(850°C) = 584.9$ kJ/kg	$m_{MIX\#1} = 2.961$ kg/s
mixture after heat exchanger at $T = 371°C$	$h_{MIX\#2}(371°C) = 427.3$ kJ/kg	$m_{MIX\#2} = 2.961$ kg/s
mixture after secondary boiler at $T = 150°C$	$h_{MIX\#3}(150°C) = 169.2$ kJ/kg	$m_{MIX} = 2.961$ kg/s

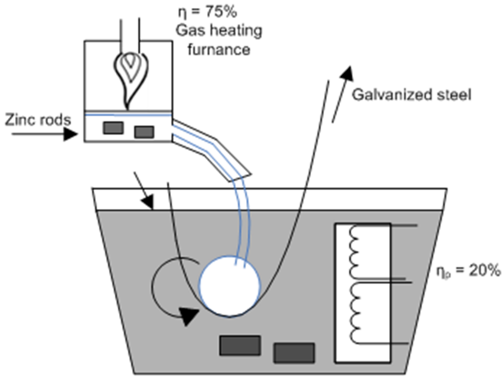

Figure 3: Use of electrical energy in the hot-dip galvanizing process bath

air flow was not measured directly, but it can be calculated indirectly using temperature and the content of the mixture. The efficiency of the furnace depends on what is regarded as product and what is loss. In a basic layout product is the heat given to the steel, but without more detailed information it is impossible to calculate this part of the heat or divide losses and heat transferred to the steel.

As regards the heat exchanger (recuperator), it is possible to define its energy balanced efficiency as equation (6):

$$\eta_{REC} = \frac{m_{MIX\#1}}{m_{AIR}} \times \frac{(h_{MIX\#1} - h_{MIX\#2})}{(h_{AIR\#2} - h_{AIR\#2})} = 0.956 \qquad (6)$$

where

$$h_{MIX} = \frac{h_{FLU\_GAS} \times m_{FLU_{GAS}} + h_{AIR\#3} \times m_{AIR\#3}}{m_{MIX}}$$

The described system energy recovery is realized in the boiler (second heat exchanger), where additional hot water is produced. This water is used for technological purposes. Flue gases are cooled here from 371°C to 150°C and water is heated from $T_{WATER} = 20°C$ to $T_{WATER\#2} = 82°C$. Using the energy balance and assuming heat losses described by its efficiency $\eta_{BOILER} = 0.957$ the mass of hot water can be calculated as equation (7):

$$m_{WATER} = \eta_{BOILER} \times m_{MIX\#3} \frac{(h_{MIX\#2} - h_{MIX\#3})}{(h_{WATER\#2} - h_{WATER})} = 2.8\ \frac{\text{kg}}{\text{s}} \qquad (7)$$

The calculated hot water mass is sufficient for technological demands, but if hot water demands increased, the source would be insufficient and a new energy source should be introduced.

3.3. Entropy increase and irreversible losses for the current basic system

Each energy transfer causes an increase of entropy. In heat exchangers heat is transferred from hot to cold fluid as natural phenomena. The higher the temperature difference - the higher the heat, the smaller the heat exchanger area and exchanger cost. On the other hand, if the temperature difference is higher, the entropy increase is higher, meaning the heat exchanger design must optimize between manufacturing costs and energy/entropy losses.

In terms of aAnalysis, the results obtained are correct if the boundary temperatures are qualitatively good and the curves Temperature-Heat and Temperature-Entropy are straight lines (assumption: specific heats are constant). A good qualitative verification would be to prepare calculations

Table 3: Mathematical model of the existing system

Description	Used equations	Data	Results	Units
Mass of all compounds on each side of reaction	$M = M_{CH4} + M_{O2} + M_{N2}$	M=1 kmol×(12 kg/kmol+4×1 kg/kmol)+2.2 kmol×32 kg/kmol +8.27 kmol×28 kg/kmol	317.96	kg
Mass of all compounds on products side of reaction[1]	$M = M_{CO2} + M_{H2O} + M_{O2} + M_{N2}$	See Table 2	317.96	kg
Total flux of the flue gas to combustion[2]	$m_{FLUE\_GAS} = (M_{LUE\_GAS}/M_{CH4}) \times m_{CH4}$	$\lambda = 1.1, M_{FLUE\_GAS} = 317.96\ kg, m_{CH4} = 0.0745$ kg/s $M_{CH4} = 16$ kg/s $m_{CH4} = 0.0745$ kg/s	1.4805	kg/s
Total flux of the air to combustion	$m_{FLUE\_GAS} = (M_{LUE\_GAS}/M_{CH4}) \times m_{CH4}$	$m_{FLUE\_GAS} = 1.4805$ kg/s, $m_{CH4} = 0.0745$ kg/s	1.406	kg/s
Fan power	$P_{FAN} = m_{AIR} \times \varDelta p_{FAN}/(\rho_{AIR} \cdot \eta_{FAN})$	$\varDelta p_{FAN} = 5000$ Pa, $\eta_{FAN} = 0.75$ (maximum efficiency), ρ_{AIR}=1.2 kg/m^3(air density)	7.8	kW
Power of the furnace	$Q_{CH4} = m_{CH4} \times W_{CH4}$	$m_{CH4} = 0.0745$ kg/s	3600	kW
Power of inflow air	$Q_{AIR}(25°C) = m_{AIR\#3} \times h_{AIR\#3}(25°\text{C})$	$h_{AIR\#3}(25°C) = 603.15$ kJ/kg, $m_{AIR} = 1.406$ kg/s	35	kW
Power of the preheated air	$Q_{AIR\#2}(330°C) = m_{AIR\#2} \times_{AIR\#2} (330°C)$	See Table 3	848	kW
Power of the flue gas	$Q_{FLUE\_GAS} = m_{FLUE\_GAS} \times_{FLUE\_GAS} (925°\text{C})$	$h_{FLUE\_GAS}(925°C) = 1144$ kJ/kg	1693.7	kW
Power of additional air	$Q_{AIR\#3}(330°) = m_{AIR\#3} \cdot h_{AIR\#3}(25°C)$	$m_{AIR\#3'} = 1.4805$ kg, $h_{AIR\#3}(25°C) = 25.61$ kJ/kg	37.91	kW
Power stream				
Power losses and power absorbed by the heated metal	$Q_{METAL\&LOSS} = Q_{CH4} + Q_{AIR} - Q_{FLUE\_GAS} + Q_{AIR\#3}$		2283.8	kW

1. The same mass value due to mass conservation law
2. Based on the chemical reactions involved in methane combustion in air (with$\lambda = 1.1$) for every 16 kg of CH_4, 301.96 kg of air should be used and 317.96 kg of flue gases will be generated

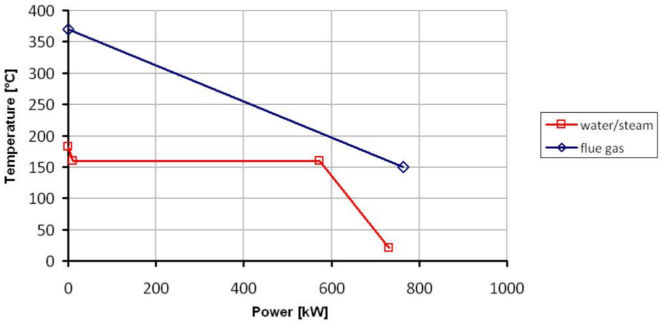

Figure 4: Heat flux balance in the flue gas-water heat exchanger

Table 4: Mole fraction and mole specific heats in flue gas for $T_{AVERAGE} = 260\,^{\circ}\mathrm{C}$

Type	Mole number	Mole fraction z_i	Mole specific heat C_{pi}
		%	kJ/(kmol × K)
CO_2	1	0.087184	36.96
N_2	8.27	0.721011	29.09
O_2	0.2	0.017437	29.43
H_2O	2	0.174368	76

using the assumptions that the product is not hot water, but steam at temperature $T = 182^{\circ}$C, where three phases exist—heating of water, evaporation and heating of steam. The heat flux balance for flue gas-water heat exchanger is presented in Fig. 4.

Particular heat fluxes in the flue gas and entropy balance for the boiler are calculated using data from Table 4, as presented in Table 5.

Fig. 5 presents the balance of two streams in the heat exchanger, where total entropy after heat exchange between flue gas and water increases.

The curves Temperature-Heat and Temperature-Entropy do not cross, the distance between the lines where the temperature difference is the smallest is positive and larger than the values in similar constructions (by a few degrees) so these results are physically appropriate and are not contradictory.

In the current system 3.7 tonnes per hour is produced, which means that with a heat source of 3638 kW and electrical energy of 100 kW, 399.3 MJ/ton is consumed in the manufacturing of galvanized steel.

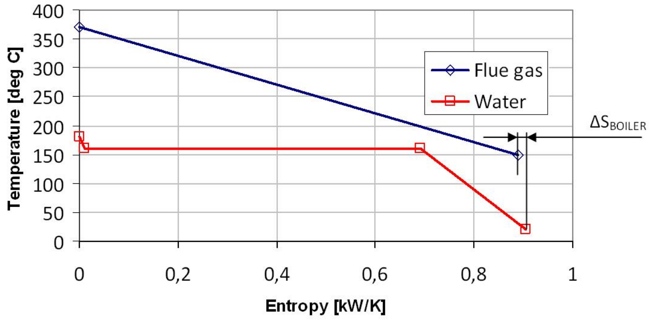

Figure 5: Entropy balance in the flue gas – water heat exchanger

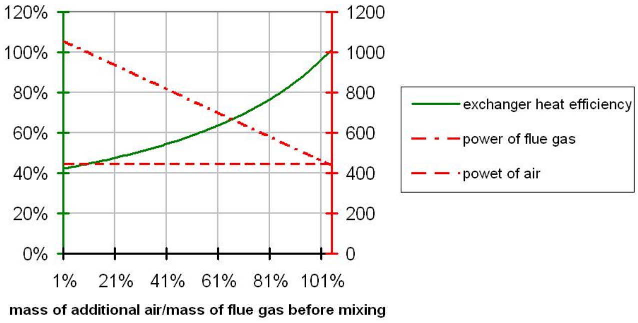

Figure 6: Impact of additional air percentage on exchanger efficiency, flue gas and water power

The efficiency of the system in the described configuration depends on the efficiency of the furnace and its fan, the efficiency of the two heat exchangers, steam transportation losses, the efficiency of the water pump and its drive and on all supporting equipment. Most components can be calculated or estimated. The second problem is to organize this process so as to minimize entropy increase. The main devices where a large entropy increase take place are the furnace and the two heat exchangers. Since an increase in the heated fluid inlet temperature in the heat exchanger decreases its total entropy increase, the total entropy increase is lower if the water temperature is higher than 20°C and the parameters of hot gas remain the same.

3.4. Effect of additional air

Additional air in these calculations was assumed in a specific range. It is known that all temperatures and gas consumption are accurate, because they are measured and heat exchangers losses are small as a consequence; so this value should be big enough to satisfy all energy balance equations. This value is constant and only depends on the furnace construction (technological leakages), but operators cannot regulate it technically. This value has a significant impact on the heat transfer, irreversible losses and the amount of water (steam) produced in this system.

Fig. 6 depicts the impact of additional air percentage on exchanger efficiency, flue gas and water power. This percentage is measured as the amount of additional air compared to "pure" flue gas. While it is not possible to dynamically regulate the amount of additional air here, this graph is useful in adjusting the amount of additional air by technical modification of the furnace and system. It is clear that real heat efficiencies of typical heat exchangers (in good condition and with typical heat insulation) are very high and close to 100%, and so this efficiency is assumed at about 96%. The amount of additional air is nearly equal to the flow of "pure" flue gas ($m_{AIR\#3} \approx m_{FLUE\_GAS}$).

Table 5: Particular heat fluxes in the flue gas and entropy balance for the boiler

Description	Equations used	Data	Results	Units
Heat fluxes in the flue gas				
Heat flux Q_{STEAM}	$Q_{STEAM} = Q_{STEAM\_1} + Q_{STEAM\_2} + Q_{STEAM\_3}$	$Q_{STEAM\_1} = m_{STEAM} \times [h'_{WATER}(p = 6.2$ bar)–$h_{WATER}(T = 20°$C, $p = 6.2$ bar)] $Q_{STEAM\_2} = m_{STEAM} \times [h"_{WATER}(p = 6.2$ bar)–$h'_{WATER}(p = 6.2$ bar)] $Q_{STEAM\_3} = m_{STEAM} \times [h_{WATER}(p = 6.2$ bar)–$h_{WATER}(T = 180°$C, $p = 6.2$ bar)]	730.93	kW
Heat of diluted flue gas	$Q_{MIX\#3} = m_{MIX\#3} \times h_{MIX\#2}(T = 371°C)$	See Table 2	1265.2	kW
Heat of boiler	$Q_{BOILER} = m_{MIX\#3} \times [h_{MIX\#2}(T = 371\ °C)$ $-h_{MIX\#3}(T = 150\ °C)]$	See Table 2	764.23	kW
Boiler efficiency	$\eta_{BOILER} = Q_{STEAM} / Q_{BOILER}$		0.956	
Entropy balance for the boiler				
Mixture of ideal gas $\Delta S_{FLUE\_GAS\#2}$ [1]	$\Delta S_{FLUE\_GAS\#2} =$ $= m_{FLUE\_GAS\#2}/\mu_{FLUE\_GAS\#2} \times$ $\times C_{pMIX} \times \ln(T_{FLUE\_GAS\#3}/T_{FLUE\_GAS\#2})$	$C_{pMIX} = \Sigma z_i \times C_{pi} = 39.76$ kJ/(kmolK), mole fraction z and specific heats of each compounds C_p are shown in Table 5, and $\mu_{FLUE\_GAS\#2}$ denotes flue gas mole mass $\mu_{FLUE\_GAS\#2} = 27.72$ kg/kmol.	-27.35	kJ/(kmolK)
Entropy increase of steam	$\Delta S_{STEAM} = m_{STEAM} \times [c_{p1} \cdot ln(373/293) + r/T_0 + c_{p2} \ln(453/373)]$	$\Delta S_{STEAM} = 0.1305 \times [4.2 \times \ln(433.1/293) + 2257/433.1 + 1.84 \times \ln(453/433.1)]$, $\mu_{STEAM} = 18$ kg/kmol (water mole mass)	0.905	kW/K
Resultant value of entropy[2]	$\Delta S_{BOILER} = \Delta S_{FLUE\_GAS2} + \Delta S_{WATER}$	$\Delta S_{FLUE\_GAS2} = -0.8893$, $\Delta S_{WATER} = 0.905$ kW/K	106.3	kJ/(kmolK)
Specific entropy increase	$\Delta S_{BOILER} = \Delta S_{HEAT\_EX2}/\Delta S_{WATER}$		0.017	

[1] The entropy increase of hot flue gases is negative (temperature drops from $T_1 = 371°$C to $T_2 = 150°$C). It can be calculated with the assumption that the gas is a mixture of ideal gases $\Delta S_{FLUE\_GAS\#2}$

[2] The resultant value of entropy increase is finally positive

4. Energy efficiency improvement actions

It is possible to increase energy efficiency and reduce the losses and environmental harm of the considered installation by generating additional energy and using heat from the flue gases. Several actions can be taken to this end—some are less and some are more costly—but only two will be discussed here: (a) cogeneration, replacing electrical heaters and (b) flameless combustion. Among other technical solutions that could be analyzed, are: (1) use of steam for direct heating of the bath, optimization (adding or replacing) of the heat exchangers, (2) improving of the combustion process—optimization of the excess air ratio), (3) improving of the drives of the pump and furnace fan, (4) improving of the furnace and heat exchangers insulation.

- Use of the cogeneration system, replacing electrical heaters

Cogeneration known as Combined and Heat and Power Plants (CHP) is the generation and use of electrical (mechanical) and thermal energy using only one heat source. Combining electricity and thermal energy generation into a single process can save up to 35% of the energy required to perform these tasks separately. While the traditional method of separately producing usable heat and power has a typical combined efficiency of 45%, CHP systems can operate at efficiency levels as high as 80% [33]. In a typical power plant[1] heat is waste and is lost to the environment. There are many technical configurations for CHP systems, which is why only the most important parameters and benefits will be discussed here. A proposed system is shown in Fig. 7.

While “Point A” is shown in Fig. 2, the same starting point for the CHP installation is outlined in Fig. 7. This system consists of one boiler with an additional source of heat (natural gas #2); one turbine generating mechanical energy, a generator, two heat exchangers (one to use heat from new heat source flue gases and the second to use heat from the “basic” installation), three pumps, a condenser and a degasser. The same amount of hot water is produced and used by the technology. The efficiency of a typical small CHP installation is not particularly high, so it can be assumed that for each 1 kW electrical power about 2.85 kW of heat power is generated. If the generated electric power, P_{EL}, were 200 kW, this would mean 100 kW for the electric heaters in the bath and 100 kW to drive all three pumps and other devices and to sell it to the system. In such installations all pumps consume about $(3.5 \div 4)$% of generated electrical power. So if $P_{EL} = 200$ kW, then heat $Q_{HEAT} = 570$ kW. Given the heat from the “old” source (point “A”) is equal to $Q_{BOILER} = 764$ kW, therefore the lack of power is equal to formula (8):

$$Q_{CH4\#2} = P_{EL} + Q_{HEAT} - Q_{BOILER} = 200 + 570 - 764 = 6\text{ kW} \qquad (8)$$

If the natural gas heat value is equal to Wu$_{CH4}$ = 36.13 MJ/m^3, then in that solution the additional gas consumption is equal to:

$$V_{CH4\#2} = \frac{Q_{CH4\#2}}{W_{uCH4}} = \frac{6\text{ kW}}{36130\,\frac{\text{kJ}}{m^3}} = 0.6\ \frac{\text{m}^3}{\text{h}} \qquad (9)$$

Compared to the value of V$_{CH4}$ = 362.5 m^3/h, $V_{CH4\#2}$ is only 0.16%, so the costs of the additional source of heat is negligible.
The energy consumed in this improved cogeneration system is: 3638 kW, main source, and 6 kW, additional source. Energy on-site production is: 192 kW net of electrical energy and 570 kW of heat. As a result, the energy consumption coefficient is:

$$\frac{(3638 + 6192 - 570)}{\left(33.7 \times \frac{1000}{3600}\right)} = 307.9\ \frac{\text{MJ}}{\text{t}} \qquad (10)$$

- Use of flameless combustion

Flameless combustion is a special type of combustion. In contrast to classical combustion, the flame is not visible in the combustion chamber and the temperature field is much more uniform. In classical flame combustion excess air ratio λ is higher than 1—in this case it is about $\lambda = 1.1$—but in flameless combustion all reactions are at $\lambda < 1$, e.g. $\lambda = 0.92$. To achieve flameless combustion, the temperature in the combustion chamber must be greater than $850 \div 900$°C [27], as this kind of combustion is not very flexible and it takes a long time to start up this installation. It is also risky, because if $\lambda < 1$, then the fuel-oxidizer mixture is rich and there is a serious danger of explosion before the combustion chamber reaches a high enough temperature and/or the start-up procedure is too fast.

During classical combustion, like for example in typical boilers, the flame is very visible. Inside the flame the temperature is high, but it drops dramatically as you move away from the center of the flame, resulting in a veryuneven spread of temperature. High temperature is conducive to NOx generation. A comparison of several types and methods of combustion where the fuel is natural gas is presented in Fig. 8. In classical combustion NO concentration is more than 100 ppm in flue gases. In flameless mode this value can be more than 10 times less, which is very appealing. Flameless combustion also lowers CO$_2$ emissions noticeably. The second aspect is noise. In flameless combustion noise can be significantly lower. The reduction can even be by as much as 10 dB, achieving about 90 dB. This is a desirable outcome which can help avoid penalties for breach of environmental standards.
Successfully harnessing flameless combustion is more than an issue of achieving the correct temperature—the combustion chamber must be modified to enable strong circulation of fresh hot flue gases.

5. Conclusions

Energy efficiency is regarded as the fourth fuel, as in many cases a tangible energy effect can be achieved with-

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[1] Typical large cogeneration systems are commonly operated as Combined and Heat and Power Plants (CHP), with generated electrical power of several megawatts, but small, packaged cogeneration systems can also be built.

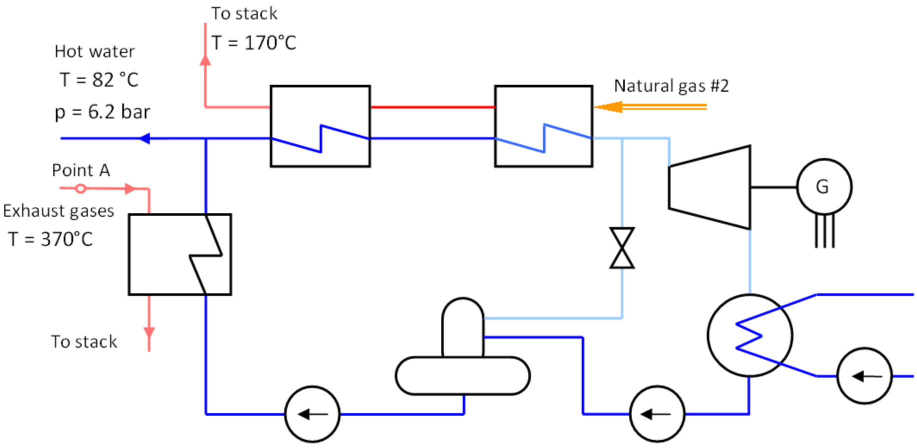

Figure 7: Cogeneration system for hot-dip installation

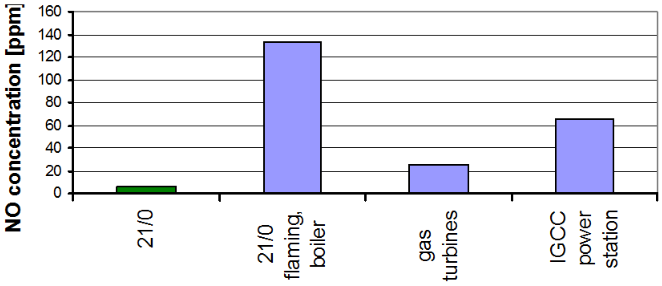

Figure 8: NO emission in a flameless combustion chamber (case 21/0) and other typical flame combustion devices and systems

out adding additional amounts of fuel. Implementing post-audit recommendations can go beyond delivering energy savings and yield a more efficient manufacturing process. Modernization of the galvanization process through energy-efficient improvement actions decreased energy by 23%, from 399.3 MJ/tonne to 307 MJ/tonne GJ/tonne between the baseline and improvement scenario, while emission intensity NO dropped 96%.

The research conducted on the galvanizing process system confirmed that cogeneration is a highly effective way to improve the flow of energy, thereby making important savings. Moreover, novel technologies, like for example flameless combustion, can be used to boost energy efficiency still further, but much research is needed prior to achieving efficient industrial application..

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