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DETERMINATION OF ENERGY AND EXERGY OF WASTE HEAT IN THE INDUSTRY OF THE BASQUE COUNTRY

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Abstract—The fuel costs and the impacts of energy use on the local environment make it necessary to reduce the consumption of energy of industrial processes. The use of waste heat recovery technologies is an effective way of achieving energy saving and therefore a reduction in energy consumption.

In order to assess accurately the potential of waste heat recovery, it is necessary to know in detail the characteristics of the process streams. It is also necessary to examine in depth the different recovery technologies, to be able to integrate the set: waste heat-recovery technology-useful flow.

Using the Basque Country industrial database and thermodynamic properties databases, the energy and exergy of waste heat have been determined for 10 industrial sectors of the Basque Country. The sectors have been classified according to their type into gases, liquid effluents and solid product streams, and also according to the temperature levels associated with them.

In accordance with available data, energy content of waste heats amounts to 40% of total energy consumption in the industrial sectors of the Basque Country. Making a breakdown for types, we found that 33% of the energy of waste heat appears in the gas streams from combustion equipment, 27% is sensible heat of solid products, 16% is vapour, 11% liquid effluents and the rest appears as radiation, gases or by-products. More than half of this energy content appears at temperatures higher than 523 K.

Keywords—Heat recovery, waste heat, Basque region, technological assessment, industry.

INTRODUCTION

E.V.E. is the office responsible for planning, coordination and control of the energy activities in the Basque Country. Recently it has carried out several studies aimed at obtaining details of the technological and energy situation. Now, databases for industrial sectors are available, which are periodically updated, and are the base for the energy policy.

Any analysis about the use of energy requires a classification of the consumption depending on the final use for types of energy and ranges of temperature. It is also necessary to carry out an analysis of the efficiency of the use of energy. This type of analysis should not be limited to comparing the amounts of energy at the exit of the equipment with the amounts of energy supplied to them. Rather, the analysis has to take into account the quality of the energy, differentiating the energy flows not just for its content in energy, but also in its availability.

An appropiate measure for a theoretical minimum energy requirement for a given task can be defined with the second law of thermodynamics. The distinction between energy and exergy efficiency is theoretically very important because it allows us to determine the ultimate potential of efficiency improvements. The exergy efficiency, whose maximum is always one by definition, provides a rapid insight into the performance of a specific device executing a specified task. It shows the maximum theoretical potential for the improvement of any given energy system.

This type of exergy analysis has been carried out for the Basque industry, having defined the potentials of technological improvement of the industrial sectors, distinguishing between the recoverable losses and the exergy destruction. With this, data sectorial programs of modernisation have been defined and the maximum achievable goals have been agreed through an energy policy.

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INDUSTRIAL DATABASE OF THE BASQUE COUNTRY

As mentioned earlier, E.V.E. has been carrying out a series of surveys and studies to get in-depth information about the energy situation in this community in order to assess the efficiency improvements required.

The main reason for knowing how energy is used in the Basque industry is to achieve better planning and therefore achieve a more efficient and rational use of energy. To satisfy this goal, survey forms are periodically sent to the industries (every 2 years), who, in close collaboration with the manufacturer, take charge of filling some records previously prepared.

This information is collected from the productive industrial centers whose annual consumption of energy exceeds 41 800 GJ, or 5000 MWh, reaching in 1994, 91% of the total energy consumption in the industry. In the last update, those productive centres that have an important consumption of raw materials have been added. Keeping in mind these approaches, a total of 290 industrial establishments have been studied.

The information obtained from the records is processed and stored in the following data files:

1. Activity and localization.
2. Energy.
3. Raw materials.
4. Products.
5. Types of basic operations.
6. Equipment.
7. Main diagrams of products.

Activity and localization

Twenty-two sectors of activity have been considered, according to a three-digit classification established by the International Classification System. The location of each industry is pointed out, making a distinction between the three historical territories of the Basque Country. Also, eight possible operation systems are distinguished, according to the number of shifts, and whether or not people work on Saturdays, etc.

Energy

A file of energy has been created containing 13 types of conventional fuels and eight types of non-conventional fuels. With regard to electric power, four possible situations are considered: external electricity, thermal or hydraulic self-production and transference to the mains.

Raw materials

A classification of the raw materials has been set up through 19 main groups. In turn, each main group is divided into several secondary sets, each one of these containing different types of materials.

Products

In a similar way, a file of products has been built. For each industrial sector the main groups of products are defined, the specific denomination of each product being settled within every group.

Types of basic operations

Continuing with the same approach, 31 main types of operations have been distinguished, subdividing each main group in a series of basic operations under their specific denominations.

Equipment

Bearing in mind the great variety of equipment that is used in the different industrial processes, a classification has been made, each including different types of equipment.

Main diagrams of products

The information available at the moment in the database allows us to obtain, for each group, a diagram showing several pieces of data, such as: the basic intervening operations, the input raw materials, the addition and elimination of material, the main equipment being involved, as well as some of their characteristics.

DETERMINATION OF THE WASTE HEAT

Next we present the methodology that has been followed in order to obtain the waste heat, assembling the data according to the type and the thermal level in which it is produced, using the above-referred industrial database of the Basque Country as a starting point. In order to describe it, we have selected an industrial sector with an important consumption of energy, such as the cement sector.

The cement sector

In the Basque Country the greatest amount of cement produced is the Portland type, obtained by means of dry processes, whose outlines have been used as a reference for the analysis of this sector.

Nearly 80% of the whole energy consumption corresponds to fuel-oil while the remaining 20% is distributed approximately equally between solid fuels and electricity.

Diagram type of material

In general terms, the production of a ton of Portland cement requires 1355 kg of raw materials (limestones and clays) with a mean humidity of about 10% and whose typical compositions are showed in Table 9 of Appendix A.

These raw materials, previously blended in proportions of 69.5% and 30.5%, respectively, give rise to a mixed product that after grinding and drying decreases its humidity to 0.5%. After the clinking process, the 1220 kg of dry material initially supplied become 930 kg of clinker (product for obtaining the Portland cement), with a mean composition that is presented in Table 10 of Appendix A.

Finally, after the supply of additives and the grinding of the whole, 930 kg of clinker yield a ton of finished cement. These stages of production are represented in the diagram in Fig. 1, showing the characteristic flows of material for this subsector.

In the elaboration of the above-mentioned diagram, four considerations have been adopted:

1. The pre-heating, previous to the clinker, is carried out in four stages.
2. The final cooling is made in grilles.
3. Only 65% of the air is used for cooling the clinker and the remainder is incorporated in the combustion.
4. The 92% of the combustion gases is used for drying the crude.

Diagram-type of energy

Figure 2 defines the flows and the balance of energy that are representative of the cement production in the Basque Country. The energy contents of the fuels and electricity consumed by a ton of cement have been taken into account, as well as the waste heats liberated with the products, by-products and gases. To estimate the latter, the mean specific heats of Table 11 of Appendix A have been adopted.

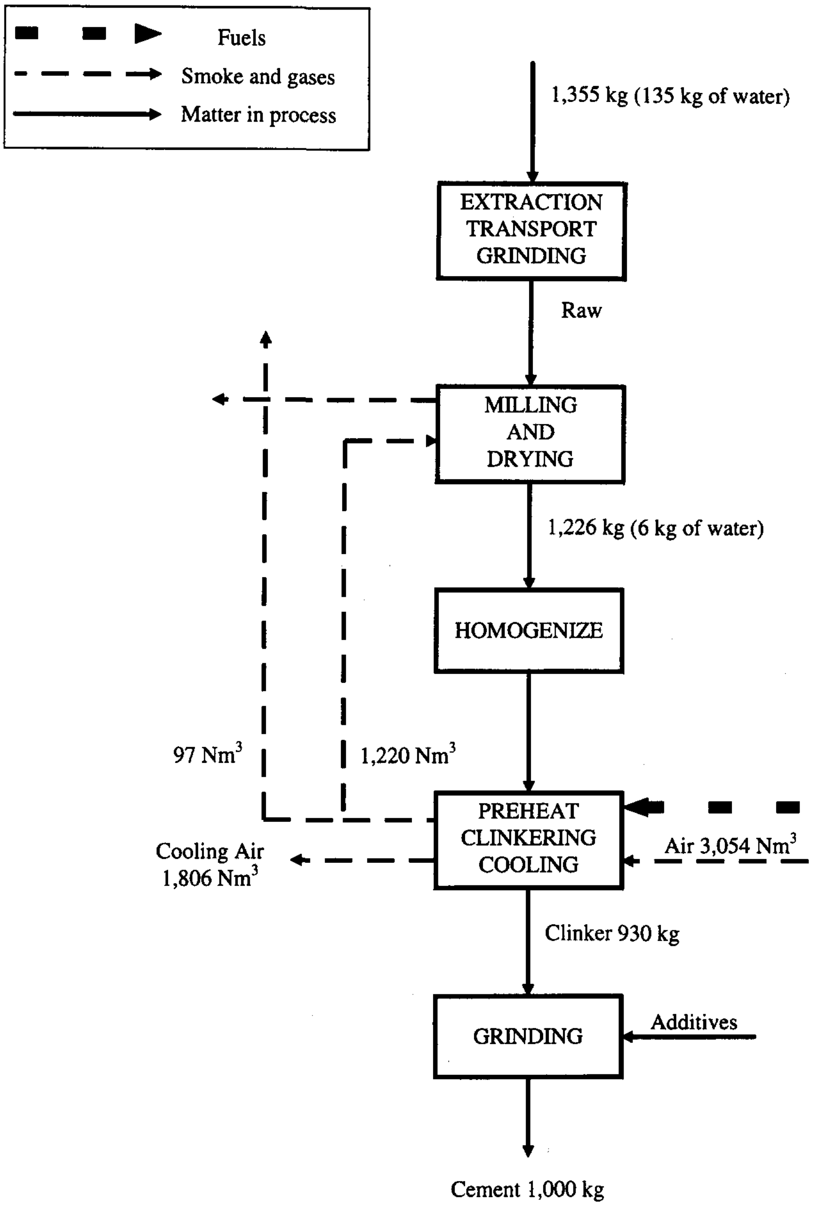

Fig. 1. Cement, flows and matter balance.

From the same diagram (Fig. 2) it can be deduced that the production of one ton of cement requires the contribution of:

Fuels:	3908.3 GJ
Electricity:	133 kWh

and the waste heats are:

Clinker:	0.221 GJ
Cooling air:	0.501 GJ
Smoke:	0.184 GJ
Water vapour at 363 K:	0.342 GJ.

Waste heat

Tables 1 and 2 show the energy and exergy contents of the waste heat in the cement subsector, broken down according to different types and ranges of temperature.

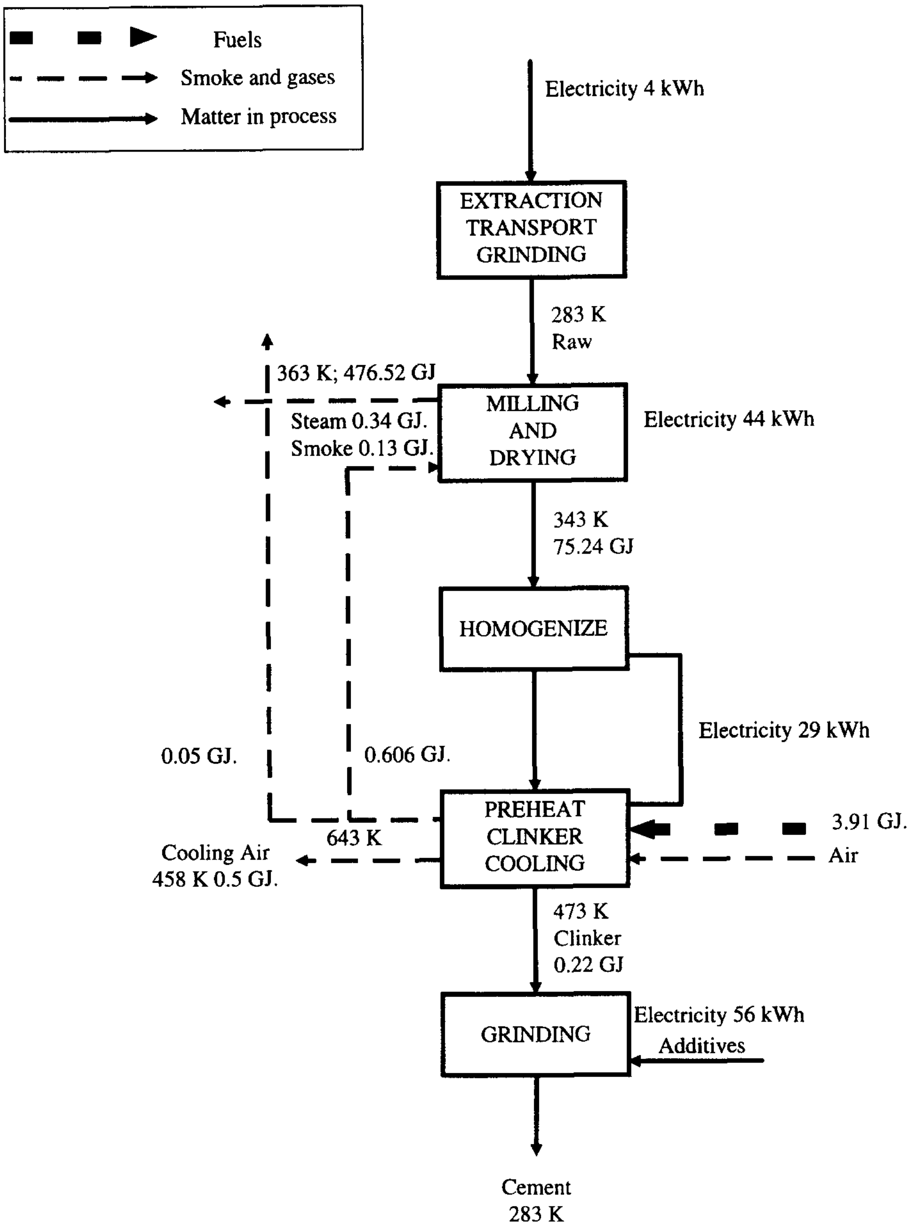

Fig. 2. Cement, flows and energy balance.

The sensible heat of the air (637 826 GJ) constitutes most of the waste heat not recovered; almost half of the exergy contents of the whole waste heat corresponds to it.

For a range of temperatures, over 393 K, the 75% of the exergy lost in waste heat is liberated and almost two-thirds of this percentage corresponds to the sensible heat of the cooling air (458 K).

Lastly, it is necessary to point out that the ratio between the energy of the waste heats over 393 K (977 785 GJ) and the one used for heating and basic operations below that temperature (213 514 GJ) is superior to 4. This means that, with a global efficiency that would reach 25%, this waste heat could meet the energy needs of this sector concerning low temperature applications [1].

The same methodology has been used for the definition of the waste heat of a total of nine industrial subsectors, in addition to the residential and commercial sectors. The results obtained are presented next.

Table 1. Waste heat detached by types

Types	Energy		Exergy	
	GJ	%	GJ	%
Sensible heat				
Smoke	231 614	15	68 970	13
Air	636 154	40	236 128	47
Products	280 436	18	109 683	22
Water steam	433 800	27	89 619	18
Total	1 582 004	100	504 400	100

Table 2. Waste heat detached by ranges of temperature

Temperature range	Energy		Exergy	
	GJ	%	GJ	%
$473 \leq T \leq 673$ K	61 195	4	33 774	7
$393 \leq T < 473$ K	916 590	58	345 811	68
$353 \leq T < 393$ K	604 219	38	124 815	25
Total	1 582 004	100	504 400	100

WASTE HEAT IN THE INDUSTRY OF THE BASQUE COUNTRY

Table 3 shows the waste heat of the different industrial sectors of the Basque Country according to ranges of temperature. The corresponding distribution in percentages, concerning the total consumption of energy, is also presented.

In accordance with these values, the energy contents of the waste heat for the whole Basque industry represents a total of 520 232.76 GJ, equivalent to the 40% of the annual consumption of energy of this collective. As can be appreciated, approximately half of that residual energy is liberated over 673 K.

Detachment for types

The detachment of the waste heat is presented in Table 4. As can be appreciated, smoke, vapour and gases (types of waste heat whose recovery is more feasible) total more than half of the whole energy of this heat.

Figure 3 presents the percentages of the waste heat depending on the thermal level and their type [2].

Detachment for sub-sectors

The waste heat in each industrial sector provides the energy contents that are shown in Table 5. As can be appreciated, the residential and commercial sectors are also included, although their waste heat hardly represents 5% of the whole.

The greatest flows of thermal waste energy correspond to the iron and paper sectors. Between them 83% of the total content of energy is reached. In the integral iron sector, the losses in sensible heats of products and by-products total 5 964 233 GJ (49% of the residual liberated heat), mostly over 1073 K.

Table 3. Waste heat in the Basque Country specified by temperature ranges

Thermal level	Energy (GJ)	%
> 1473 K	10 673 000	21
1073–1473 K	5 907 000	11
673–1073 K	9 620 000	19
473–673 K	4 182 000	8
393–473 K	2 443 000	5
353–393 K	5 711 000	23
< 353 K	10 151 000	8
Others	2 502 000	5
Total	51 187 274	100

Table 4. Waste heat in the Basque Country specified by types

Types	Energy (GJ)	%
Gas streams	16 935 000	32
Solid product streams	13 856 000	27
Steams	8 181 000	16
Liquid streams	5 795 000	13
Others		
Gases	1 670 000	3.3
Radiation	1 423 000	2.8
By-products	1 310 000	2
Air and others	2 019 000	3.9
Total	51 187 274	100

In addition to this, with the partial recovery of another 4 054 600 GJ liberated over 1073 K, the energy needs in applications below that temperature level (more than 1 254 000 GJ) could be satisfied.

In the non-integral iron sector, almost 80% of the supplied energy becomes lost as heat, mostly over 673 K. It is very outstanding the energy contents that correspond to the sensible heat not recovered from:

- Waste gases:

  2 591 600 GJ over 1473 K.
  8 276 400 GJ between 673 and 1073 K.

- Products:
- 4 180 000 GJ over 1473 K.
- 3 762 000 GJ between 1073 and 1473 K.

Almost half of the fuel consumed in hot straining and lamination could be saved if those processes took advantage of the sensible heat of the outcoming products from the production stages

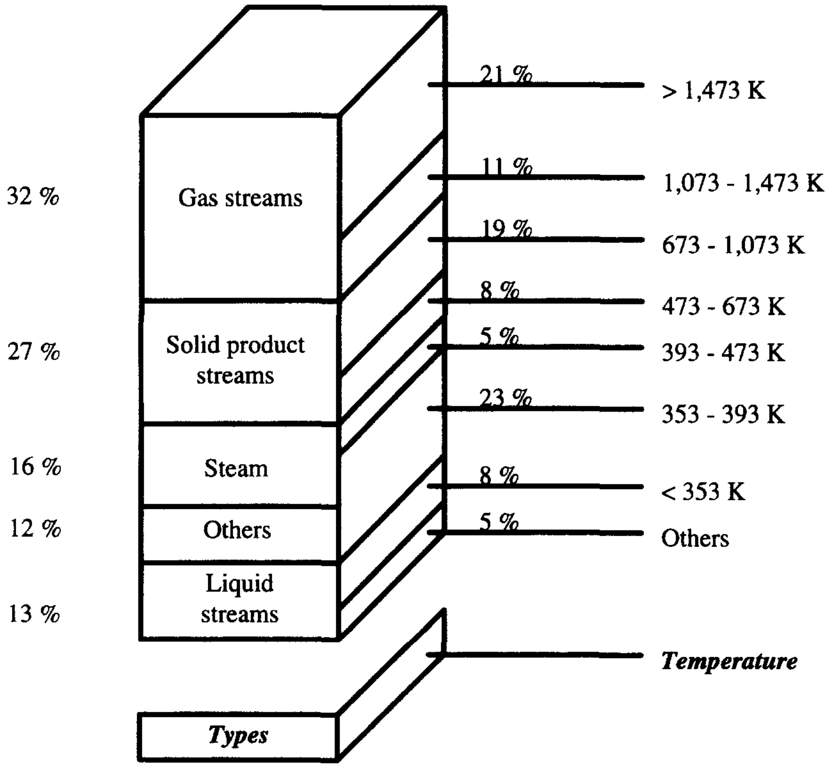

Fig. 3. Percentages of waste heat according to their thermal level and type.

Table 5. Waste heat in the industrial sectors

Sectors	Energy (GJ)	%
Integral siderurgy	11 953 713	23.6
Non-integral siderurgy	22 430 674	43.8
Paper	7 773 797	15.2
Metal transforms	833 074	1.6
Cement	1 582 004	3.1
Chemical industries	607 646	1.2
Food, drinks and tobacco	1 150 670	2.2
Glass	1 205 595	3.2
Rubber	636 781	1.3
Residence	1 789 667	3.5
Public and commerce	680 253	1.3
Total	51 187 274	100

preceding them. Besides, the sensible heat of the waste gases would be more than enough to supply the current needs of fuel in applications below 673 K and for self-producing 20% of the electricity demanded by this sector.

Against what happens in the siderurgy, the waste heats of the paper sub-sector are liberated at low temperatures (87% under 393 K). Due to this, in spite of their high energy contents (73% of the final consumption), they could just supply the 14% of the energy needs of this sector (indirect heating at low temperature and heating).

EXERGY OF THE WASTE HEAT

Besides the energy contents of the waste heats, it is likewise important to know the exergy level of them. This value depends on the composition of those flows as well as on their thermodynamic state (temperature and pressure).

There are many books and publications which develop the exergy theory and the method of its analysis. The expressions that have been used for the calculation of the exergy are presented and summarized in Appendix B. When the waste heat is a material flow, its exergy is the sum of the physical exergy (consequence of the thermal and mechanic unbalance with regard to the state of reference) and the chemical exergy (consequence of their different composition, also in relation to that state of reference). If the waste heat is a flow of heat, its exergy is calculated starting from the corresponding Carnot's factor [3].

The conventional energy analysis of the industrial processes are based on the First Law of Thermodynamics. However, this type of analysis constitutes a simple energy accounting, by means of which the inputs and outputs of energy to and from the mentioned system are quantified. In this way, the energy that is supplied to a basic operation together with fuels, electricity and flows of material, should be present in the products and by-products. Under this perspective, the outputs of energy not used are considered as losses.

However, the analysis under the Second Law of Thermodynamics takes into account, besides the amount of energy, its quality. That is why a process is considered as ideal when it is carried out without any destruction of exergy. The exergy method allows direct valuation of the actual losses of any process, that is to say, it evaluates the decrease of the available work of the energy sources being used as a consequence, in fact to the realization of the process [4].

Table 6 shows the exergy of the waste heat according to ranges of temperature. Aiming to allow comparisons the energy values which were presented in Table 4 are now also included.

In Table 7 the detachment for types is shown. In the same way, for comparative purposes, the values of energy that were picked up in Table 4 are included.

The differences that have been observed between energy and exergy contents of the waste heats are outstanding. We could point out the following remarks:

- The sensible heats of products, whose energy content represents 27% of the total, constitute 40% of the exergy lost by the waste heat. On the contrary, between both the gaseous and liquid outflows, whose energy content is the same (27%), the flow of exergy hardly reaches 6%.

Table 6. Energy and exergy of waste heat in the Basque Country

Thermal level	Energy		Exergy	
	GJ	%	GJ	%
> 1473 K	10 673 000	21	8 451 082	31.7
1073–1473 K	5 907 000	11	4 658 735	17.5
673–1073 K	9 620 000	19	6 567 323	24.6
473–673 K	4 182 000	8	1 979 773	7.4
393–473 K	2 443 000	5	815 685	3.1
353–393 K	5 711 000	23	1 238 032	4.6
< 353 K	10 151 000	8	1 126 635	4.2
Others	2 502 000	5	1 838 782	6.9
Total	51 187 274	100	26 678 346	100

Table 7. Energy and exergy of waste heat in the Basque Country

Types	Energy		Exergy	
	GJ	%	GJ	%
Waste gaseous steam	16 934 601	33.1	10 656 199	39.9
Sensible heat of products	13 855 989	27.1	10 588 107	39.7
Fumes and steams	8 180 929	16.0	1 185 113	4.4
Liquid outflows	5 795 277	11.3	511 590	1.9
Gases	1 669 993	3.3	1 301 234	4.9
Radiation	1 422 495	2.8	813 762	3.1
By-products	1 309 385	2.5	1 096 581	4.1
Air and others	2 018 605	3.9	525 760	2.0
Total	51 187 274	100	26 678 346	100

Table 8. Exergy losses in the industrial sectors of the Basque Country

Sectors	Irreversibilities	Residual heats	Total losses	
	GJ	GJ	GJ	%
Integral iron sector	7 877 043	6 824 017	14 701 060	17.4
Non-integral iron sector	10 086 047	14 838 038	22 834 086	29.5
Paper	7 926 367	1 653 357	9 370 724	11.3
Metal transforms	5 448 337	459 215	5 907 552	7.0
Cement	1 260 395	504 400	1 763 960	2.1
Chemical industries	2 859 329	225 845	3 085 174	3.7
Food, drinks and tobacco	2 379 298	282 777	2 662 075	3.2
Glass	2 487 100	931 596	3 418 696	4.0
Rubber	2 379 925	187 974	2 564 555	3.0
Domestic	11 486 013	529 689	12 015 702	14.2
Public and commerce	3 569 176	244 781	3 813 957	4.6
Total	57 759 030	26 681 688	79 572 986	100

- The waste energy over 1073 K represents approximately 50% of the exergy of the waste heat, as long as for the waste heat below 473 K (36%) their exergy goes up to 12% of the total.

Lastly, in Table 8, the exergy of the waste heat is detached by sub-sectors. This table also presents the destruction of exergy as a consequence of the irreversibilities, as well as the sum of both exergy losses.

CONCLUSIONS

Owing to the increasing costs of energy, but mainly because of the necessity for using our natural resources in an efficient way, an energy conservation policy in industrial processes is very important.

Among the 'losses' that are produced in an industrial plant, the most important one is, without any doubt, the loss due to waste heat, either in the form of gases, liquids or even hot solids.

Each industrial sector has been carefully analysed, taking account of the basic operations that integrate a productive process and defining in detail the diagrams of flow of matter and energy. Starting with this information there has been defined the waste heat of each industrial sub-sector, characterizing them according to the thermal level in which they are placed as well as to their type, being distinguished among gases, liquids and sensible heats in solids.

In the industry of the Basque Country, the waste heat produced and not recovered represents 40.5% of the total consumption of energy and is mostly liberated in the form of waste gaseous products (33%) and sensible heats of products (37%). That waste heat represents 20.6% of the total exergy supplied to the processes in the form of fuels and electricity.

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APPENDIX A: THERMODYNAMIC AND COMPOSITION DATA FOR THE CEMENT MANUFACTURING

Tables A1, A2 and A3

Table A1. Typical compositions of the raw materials of cement

Constituents	% over dry matter	
	Clay	Limestone
$CaCO_3$	13.6	93.8
$MgCO_3$	1.6	1.5
Fe_3O_2	24.8	2.9
SiO_2	26.1	1.8
Kaolinite	27.3	—
Others	6.6	—

Table A2. Average composition of clinker

Constituents	% mass
3 CaO. SiO_2	60.0
2 CaO. SiO_2	18.1
3 CaO. Al_2O_3	11.7
Fe_2O_3	5.5
MgO	1.2
Others	3.5

Table A3. Average specific heats in the cement sector

Products/by-products	*Cp*
Solid	kcal/kg K
Raw at 343 K	0.24
Clinker at 473 K	0.30
Gaseous	kcal/Nm^3 K
Air at 458 K	0.31
Water vapor at 363 K	0.35
Smoke	0.33

APPENDIX B: CALCULATION OF THE EXERGY OF THE WASTE HEAT

The concept of exergy allows us to give up all the specific definitions of efficiencies, and to substitute them by a general one, independent of the processes and dependent only on the physical–chemical state of the substances that take part in the same processes.

According to some authors [5–7], the following expression for exergy has been adopted:

$$e = (h - h_0) - T_0(s - s_0 + \sum_i x_i[\mu_i(T_0,P_0,x_1 \ldots x_{n-1}) - \mu_{i0}] \tag{1}$$

where h = specific enthalpy; s = specific entropy; x_i = fraction of matter in mass or molar base of the component i; T_0 = temperature of the stable state of reference; h_0 = enthalpy in the conditions of the stable state of reference; s_0 = entropy in the conditions of the stable state of reference; μ_{i0} = chemical potential of the component i in the conditions of the stable state of reference; μ_i = chemical potential of the component i in the conditions of the state stable of reference.

The term $(h - h_0) - T_0(s - s_0)$ represents the group of thermal and mechanical imbalances with the stable state of reference (that is to say, inbalances of physical type).

The term $\sum_i x_i[\mu_i(T_0,P_0,x_1 \ldots x_{n-1}) - \mu_{i0}]$ represents the imbalance of the components of the substance regarding the composition of the stable state of reference (that is to say, imbalances of chemical type).

For the calculation of the exergy of the waste heat the problem has been split into two parts, calculating the physical and the chemical components separately.

As for the assesment of the physical component, the waste heat has been detached into three large blocks:

Condensed phases

They are treated like incompressible substances. As for the enthalpy and the entropy we use the following expressions:

$$h = h_0 + \int_{T_0}^{T} Cp\,\mathrm{d}T + v(P - P_0) + \Delta h_f \tag{2}$$

$$s = s_0 + \int_{T_0}^{T} \frac{Cp}{T}\,\mathrm{d}T + \Delta S_f \tag{3}$$

where C_p = specific heat; Δh_f = enthalpy of transition of phase (if it exists) and Δs_f = entropy of transition of phase (if it exists).

Vapours

The data offered by [8, 9] have been used.

Ideal gases

For the enthalpy and the entropy the following expressions have been used:

$$h = h_0 + \int_{T_0}^{T} C_p\,\mathrm{d}T \tag{4}$$

$$s = s_0 + \int_{T_0}^{T} (C_p/T)\,\mathrm{d}T - R\ln P/P_0. \tag{5}$$

Their calculation requires knowledge of the coefficient of specific heat $c_p(T)$; several expressions [10] are available in the references.

Concerning the determination of the chemical component of the exergy, it is necessary to know the value of the Gibbs function for each intervening substance at the conditions of temperature and pressure of the stable state of reference. For this we have used the data included in [11, 12].