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Industrial furnaces and associated processing equipment — Method of measuring energy balance and calculating energy efficiency —

Part 11: **Evaluation of various kinds of efficiency**

Fours industriels et équipements associés — Méthode de mesure du bilan énergétique et de calcul de l'efficacité —

Partie 11: Évaluation de différents types d'efficacité

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 244, *Industrial furnaces and associated processing equipment*.

A list of all parts in the ISO 13579 series can be found on the ISO website.

Introduction

The Kyoto Protocol of the UN Framework Convention on Climate Change defines a system for emission reduction called the Clean Development Mechanism (CDM). In order for the industrial furnace manufacturers industry to address global warming based on the Kyoto Protocol, it is necessary to have fair guidelines to make use of CDM.

ISO 13579-1 to ISO 13579-4 focus on evaluating the overall efficiency of industrial furnaces and associated processing equipment (TPE) system, including electrical energy consumption as fuel equivalent energy, to help the industry facilitate implementation of CDM.

However, these documents do not define and specify efficiencies of each specific component of TPE (e.g. heat recovery equipment, heating chambers, etc.), which are directly related to and available for energy-saving measures. With this in mind, this document has been developed to specify and provide the following information:

— definitions of the various kinds of efficiency of TPE using designation systems and by defining energy balance boundaries within the TPE based on its elements;

  NOTE The definition for TPE efficiency varies according to region.

— evaluation formulae of energy reduction factors, which are available for actual energy conservation based on the energy balance measurements.

In addition to these evaluations in terms of enthalpy, this document also deals with energy efficiency based on exergy, i.e. efficiency based on availability of fuel energy, for the following reasons.

— The whole amount of “energy” in the “closed” terrestrial system is preserved due to the conservation law of energy while “exergy” inherently decreases. The term “energy” related to energy crisis or energy issue is “exergy”. Therefore, it may be said that controlling the degrees of a decrease in exergy (or dissipation of available energy) is the essence of the energy crisis. As such, exergy is one of the indexes to evaluate the energy efficiency of TPE.

— It enables a fair comparison among heating furnaces with different heating conditions or heated materials as a result of a common thermodynamic viewpoint.

— Improvement in exergy efficiency leads to essential efficiency-enhancing measures in energy usage.

Industrial furnaces and associated processing equipment — Method of measuring energy balance and calculating energy efficiency —

Part 11: Evaluation of various kinds of efficiency

1 Scope

This document specifies classifications and designations in the methodology of energy efficiency evaluation of industrial furnaces and associated processing equipment (TPE), including energy efficiency in terms of exergy as well as enthalpy.

This document does not apply to the following types of TPE:

— blast furnaces, basic oxygen furnaces, coke ovens;

— furnaces that generate gases to be used as fuel (including by-product gases);

— special atmosphere gas generators;

— industrial furnaces that are designed for chemical plants or petroleum plants;

— installations where heating or combustion is performed in an open space;

— installations that combust solid fuel;

— waste incinerators.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 13574:2015, *Industrial furnaces and associated processing equipment — Vocabulary*

ISO 13579-1:2013, *Industrial furnaces and associated processing equipment — Method of measuring energy balance and calculating efficiency — Part 1: General methodology*

ISO 13579-2:2013, *Industrial furnaces and associated processing equipment — Method of measuring energy balance and calculating efficiency — Part 2: Reheating furnaces for steel*

ISO 13579-3:2013, *Industrial furnaces and associated processing equipment — Method of measuring energy balance and calculating efficiency — Part 3: Batch-type aluminium melting furnaces*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13574, ISO 13579-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at www.iso.org/obp

— IEC Electropedia: available at www.electropedia.org

3.1 General terms

3.1.1
boundary
enclosed section that is defined for an energy balance evaluation of object(s)

Note 1 to entry: The energy efficiency evaluations are possible once a boundary is set.

3.1.2
product
item processed in a TPE, including auxiliary material

EXAMPLE Auxiliary material loaded in scrap melting process in addition to the main material (i.e. scraps).

Note 1 to entry: Product does not include by-products formed in the thermo-processing, e.g. formation of oxidized substance such as iron-scale and aluminium oxide.

Note 2 to entry: Product does not include the accessories, e.g. jigs or fixtures that are heated simultaneously with product.

[SOURCE: ISO 13574:2015, 2.134, modified]

3.1.3
energy balance analysis
grouping of energy values into either input energy or output energy, by measuring and calculating provided energy, including by exothermic reaction and outflowing energy, which also includes by endothermic reaction to/from the boundary

Note 1 to entry: The total energy input and the total energy output inherently balance.

3.1.4
energy efficiency
efficiency defined as *specific energy output* (3.1.5) divided by *specific energy input* (3.1.6)

Note 1 to entry: Energy efficiencies are expressed in percentages. Specific energy output and specific energy input are defined in this document.

3.1.5
specific energy output
specific energy defined in this document as effective energy output from the boundary for calculation of an index of efficiency of TPE

EXAMPLE Enthalpy accumulated in product through a TPE process.

3.1.6
specific energy input
amount of supplied energy defined in this document as energy brought to the boundary for calculation of an index of efficiency

3.1.7
available heat
calorific value which is required in a heating chamber of a furnace under specified operating or equipment conditions

Note 1 to entry: Available heat is a form of specific energy output defined in 6.2.5.

Note 2 to entry: “Available energy” in exergy terms has a different concept.

Note 3 to entry: See A.2.5.

3.1.8
available heat ratio
index of efficiency defined as *available heat* (3.1.7) divided by the calorific value of fuel

Note 1 to entry: This term is one of the significant indexes of a combustion furnace.

3.1.9
fuel equivalent energy of electricity
amount of primary energy which is equivalent to the calorific value of fuel input consumed in electrical generation

3.1.10
fuel equivalent energy conversion
conversion of electrical energy consumption to *fuel equivalent energy of electricity* (3.1.9)

Note 1 to entry: The factor for calculation, which is generally available, is not considered loss between the power receiving station to the TPE's power receiving terminal.

Note 2 to entry: The unit kJ/kWh is generally used.

Note 3 to entry: The value for fuel equivalent energy conversion varies depending on governments or regions.

Note 4 to entry: It should be indicated when the conversion is conducted.

3.1.11
energy performance indicator
amount of energy that is consumed per specific production unit of utilities or per specific output of auxiliary equipment

3.1.12
exergy
maximum work which can be extracted under the ambient temperature of a place, which is generally defined as

$$EX = \Delta H - T_0 \Delta S$$

where

EX is the exergy (maximum work);

ΔH is the change in enthalpy;

T_0 is the ambient temperature, in Kelvin;

ΔS is the change in entropy.

Note 1 to entry: There are chemical exergy, pressure exergy, mixing exergy and thermal exergy in a combustion system. But pressure exergy and mixing exergy are negligibly small.

3.1.13
exergy loss
difference between exergy that flows in to and flows out from the targeted *boundary* (3.1.1)

3.1.14
furnace structure
sum of furnace walls, cooling water equipment, furnace opening, etc.

3.2 Balance table

NOTE See Table A.3 and Table A.7 as examples.

3.2.1
energy balance table
table on which breakdowns of energy input and energy output are listed

3.2.2
efficiency evaluation table
reorganized table from an *energy balance table* (3.2.1) to categorize energy groups such as *specific energy input* (3.1.6) or *specific energy output* (3.1.5) to calculate an efficiency index while maintaining the energy balance

4 Symbols

4.1 Symbols for energy/exergy

Symbol	Definition
E_{aux}	energy consumed in auxiliary equipment per tonne of product
$E_{available}$	available heat per tonne of product
$E_{available\ I}$	available heat of the baseline, in MJ/t
$E_{available\ II}$	available heat after energy saving measure, in MJ/t
E_{ex}	sensible heat of exhaust gas per tonne of product
$E_{ex,ir}$	sensible heat of exhaust gas from fuel at the inlet of heat recovery equipment per tonne of product
$E_{ex,oc}$	sensible heat of exhaust gas from fuel at the outlet of combustion chamber per tonne of product
$E_{ex,or}$	sensible heat of exhaust gas from fuel at the outlet of heat recovery equipment per tonne of product
$E_{exrm,ir}$	sensible heat of exhaust gas from raw materials at the inlet of heat recovery equipment per tonne of product
$E_{exrm,oc}$	sensible heat of exhaust gas from raw materials at the outlet of combustion chamber per tonne of product
$E_{exrm,or}$	sensible heat of exhaust gas from raw materials at the outlet of heat recovery equipment per tonne of product
$E_{fe,el}$	fuel equivalent energy of electricity per tonne of product
E_{h}	energy input to the heating chamber per tonne of product
$E_{h,el}$	heat energy by electroheating per tonne of product
$E_{h,fuel}$	calorific value of fuel per tonne of product
$E_{h,fuel\ I}$	energy consumption (calorific value of fuel) of the baseline, in MJ/t
$E_{h,fuel\ II}$	estimated energy consumption after energy saving measure, in MJ/t
$E_{h,re}$	recovery heat per tonne of product
$E_{h,reex}$	recovery heat from sensible heat of exhaust gas per tonne of product
$E_{h,repr}$	recovery heat from sensible heat of product per tonne of product
E_{l}	thermal energy loss per tonne of product
$E_{l,atm}$	energy loss by atmosphere gas per tonne of product
$E_{l,eg}$	electrical generation loss per tonne of product
$E_{l,eh}$	electrical energy loss in electroheating per tonne of product
$E_{l,exrm}$	energy loss by exhaust gas from raw material
$E_{l,fs}$	energy loss from furnace structure per tonne of product
$E_{l,j}$	energy required for heating jigs and other substance per tonne of product
$E_{l,hs}$	energy required for heat storage of furnace structure per tonne of product
$E_{l,other}$	other energy loss per tonne of product
$E_{l,uc}$	energy loss by uncombusted content per tonne of product
E_{p1}	enthalpy of product at the time of loading into the boundary per tonne

Symbol	Definition
E_{p2}	enthalpy of product at the time of extraction from the boundary per tonne
E_{pr}	energy required for process per tonne of product
$E_{pr,en}$	enthalpy change in product per tonne
$E_{pr,ev}$	energy required for drying and evaporation per tonne of product
$E_{pr,re}$	energy required for endothermic reaction for heated material (product)
E_{rcy}	recycled energy per tonne of product
$E_{s,air}$	sensible heat of combustion air or other oxidant which is not preheated per tonne of product
$E_{s,atomize}$	sensible heat of atomization agent per tonne of product
$E_{s,fuel}$	sensible heat of fuel per tonne of product
$E_{s,fluid}$	sensible heat of fluid at the inlet per tonne of product
$E_{s,infilt}$	sensible heat of infiltration air per tonne of product
$E_{sp\text{-}in}$	specific energy input per tonne of product
$E_{sp\text{-}out}$	specific energy output per tonne of product
$E_{react,exo}$	heat of exothermic reaction per tonne of product
$E_{u,gen}$	energy consumed in generation of utilities per tonne of product
EX_{aux}	exergy consumed in auxiliary equipment per tonne of product
$EX_{available}$	available exergy per tonne of product
$EX_{ex,ir}$	exergy of exhaust gas at the inlet of heat recovery equipment per tonne of product
$EX_{ex,oc}$	exergy of exhaust gas at the outlet of combustion chamber per tonne of product
$EX_{ex,or}$	exergy of exhaust gas at the outlet of heat recovery equipment per tonne of product
$EX_{h,el}$	exergy input from electrical source per tonne of product
$EX_{h,fuel}$	exergy of fuel per tonne of product
$EX_{h,re}$	recovery exergy per tonne of product
$EX_{l,atm}$	exergy in given enthalpy to atmosphere gas per tonne of product
$EX_{l,eh}$	exergy loss in electroheating per tonne of product
$EX_{l,fs}$	exergy in heat loss from furnace structure per tonne of product
$EX_{l,hs}$	exergy in energy required for heat storage of furnace structure per tonne of product
$EX_{l,j}$	exergy in required for heating jigs and other substance per tonne of product
$EX_{l,other}$	exergy in other energy loss per tonne of product
$EX_{pr,en}$	exergy in given enthalpy to product per tonne
$EX_{pr,ev}$	exergy in energy required for drying and evaporation per tonne of product
$EX_{pr,re}$	exergy required for endothermic reaction for heated material
$EX_{react,exo}$	exergy of exothermic reaction per tonne of product
$EX_{sp\text{-}in}$	specific exergy input per tonne of product
$EX_{sp\text{-}out}$	specific exergy output per tonne of product
$EX_{s,fluid}$	exergy of sensible heat of fluid at the inlet
EX_{rcy}	exergy of recycled energy per tonne of product
$EX_{u,gen}$	exergy consumed in generation of utilities per tonne of product
EX_{v}	recovery of exergy as steam

4.2 Other symbols

Symbol	Definition
A_0	theoretical volume of combustion air per unit fuel consumption, in m^3(n)
c	weight fraction of carbon contained in liquid fuel
C_a	mean specfic heat of air, in kJ/(kg·K)

Symbol	Definition
C_g	mean specific heat of exhaust gas, in kJ/(kg·K)
$c_{pm,ex}$	mean specific heat of exhaust gas, in kJ/(kg·K)
$c_{pm,fl}$	mean specific heat of fluid (fuel or combustion air), in kJ/(kg·K)
$c_{pm,c}$	mean specific heat of combustion gas, in kJ/(kg·K)
$c_{pm,w}$	mean specific heat of liquid water, in kJ/(kg·K)
$c_{pm,ph}$	mean specific heat of preheated item (e.g. product, fluid), in kJ/(kg·K)
$c_{pm,v}$	mean specific heat of water vapour, in kJ/(kg·K)
$e_c{}^0$	chemical exergy per unit quantity of fuel, in kJ/m^3(n)
G_0	theoretical volume of exhaust gas per unit fuel consumption, in m^3(n)
h	weight fraction of hydrogen contained in liquid fuel
H_{ex}	sensible heat of exhaust gas at the outlet of combustion chamber per unit fuel consumption, in MJ/m^3(n) or MJ/kg
H_h	gross calorific value of fuel per unit quantity of fuel, in kJ/kg or kJ/m^3(n)
H_l	net calorific value of fuel per unit quantity of fuel, in J/kg or kJ/m^3(n)
H_r	sensible heat of preheated combustion air per unit fuel consumption, in MJ/ m^3(n) or MJ/kg
H_v	recovered enthalpy by generation of steam per tonne of product, in kJ/t
ΔH	change in enthalpy per tonne of product, in kJ/t
L	latent heat of vaporization of water, in kJ/kg
m	air ratio
m_{I}	air ratio of baseline
m_{II}	air ratio after energy saving measure
m_{ex}	mass of exhaust gas per tonne of product, in kg/t
m_{fl}	mass of fluid (fuel or combustion air) per tonne of product, in kg/t
$m_{fl,c}$	summation of mass of fluid provided per tonne of product and mass of theoretical combustion air corresponding to the amount of fuel, in kg/t
m_{ph}	mass of preheated item (e.g. product, fluid) per tonne of product, in kg/t
m_{v1}	mass of steam as atomization agent required per tonne of product, in kg/t
m_{v2}	mass of steam recycled from exhausted energy required per tonne of product, in kg/t
O	weight fraction of oxygen contained in liquid fuel
R	gas constant
s	weight fraction of sulfur contained in liquid fuel
ΔS	change in entropy per tonne of product, in kJ/K/t
t_a	temperature of preheated combustion air, in K
t_{gout}	temperature of exhaust gas at the outlet of combustion chamber, in K
T_{ad}	adiabatic flame temperature, in K
T_0	ambient temperature, in K
T_{ex}	temperature of exhaust gas at defined location in K
T_{fc}	temperature inside furnace, in K
T_{fl}	temperature of fluid (fuel or combustion air), in K
T_{ph}	temperature of preheated item (e.g. product, fluid), in K
T_{v1}	temperature of water vapour as atomization agent, in K
T_{v2}	temperature of water vapour recycled from exhausted energy, in K
V_f	fuel consumption per tonne of product, in m^3(n)/t or kg/t
x_i	volume fraction of fuel component i
α_{es}	energy saving ratio (%)

Symbol	Definition
η	specific energy efficiency of enthalpy
η_1	overall efficiency in accordance with ISO 13579-1
η_2	heat efficiency on the whole calorific value basis
η_3	heat efficiency on the supplied calorific value basis
η_5	combusted fuel ratio
η_7	ratio of waste heat recovery in combustion furnace
η^*	available heat ratio
η^*_I	available heat ratio of the baseline
η^*_{II}	estimated available heat ratio after energy saving measure
η^*_0	converted available heat ratio where waste heat recovery is not considered
η_e	electrical generation efficiency
η_{exh}	ratio of waste heat of combustion exhaust gas to calorific value of fuel
η_{ex}	specific exergy efficiency
η_{ex}^*	ratio of exergy in available heat to the input exergy
η_{ex1}	overall exergy efficiency in accordance with ISO 13579-1 using Gibbs free energy of fuel
η_{ex2}	heat exergy efficiency on the whole calorific value basis using Gibbs free energy of fuel
η_{exh}	ratio of waste heat of combustion exhaust gas to calorific value of fuel
η_R	effective ratio of waste heat recovery in combustion furnace
$\eta_{R\,I}$	effective ratio of waste heat recovery in combustion furnace of the baseline
$\eta_{R\,II}$	effective waste heat recovery ratio in combustion furnace after energy saving measure
$\eta_{rcy,steam}$	ratio of enthalpy which is recovered in the generated steam to the whole enthalpy provided to the steam generator

5 Boundary and energy (enthalpy)

5.1 Configuration of the area of evaluation

The general configuration of the area of evaluation under the scope of this document consists of the following:

— heating chamber (key 1);

— burner (key 2);

— heat recovery equipment (preheating equipment using exhaust gas) (key 3);

— electrical generation (key 4);

— electrical auxiliary equipment (e.g. fan motor, compressor) (key 5);

— generation of utilities (e.g. endothermic gas generator) (key 6);

— electrical heating (key 7).

NOTE For keys, see Figure 1.

5.2 Classification of boundary

The codes for each classification of boundaries drawn for the evaluation of energy efficiency of TPE specified in Table 1 apply.

Table 1 — Classification of boundary

Symbol	Classification of boundary	Description
EB1	Overall process of TPE	As specified in ISO 13579-1. Electric generator[a] can be excluded when fuel equivalent energy conversion is not considered. See 6.2.2 for typical efficiency applicable to this boundary.
EB2a	Heating chamber with heat recovery equipment	Recovery heat shall be considered as internal circulating heat. Auxiliary equipment[b] and utility generator[c] shall be excluded. See 6.2.4, 6.2.5 and 6.2.7 for typical efficiency applicable to this boundary.
EB2b	Heating chamber and cooling zone with heat recovery equipment	
EB3a	Heating chamber	Heat recovery equipment shall be outside the boundary. Auxiliary equipment[b] and utility generator[c] shall be excluded. See 6.2.3, 6.2.5 and 6.2.7 for typical efficiency applicable to this boundary.
EB3b	Heating chamber and cooling zone	
EB4	Heat recovery equipment	Boundary shall be set adjacent to the heat recovery equipment[d]. See 6.2.6 for typical efficiency applicable to this boundary.
EB4a	Combustion air preheating equipment	
EB4f	Fuel preheating equipment	
EB4p	Product preheating equipment	
EB5	Auxiliary equipment	Auxiliary equipment[b] shall explicitly be specified[e].
EB6	Utility generator	Utility generator[c] shall explicitly be specified[f].

NOTE Keys mentioned are found in Figure 1.

a See key 4.

b See key 5.

c See key 6.

d See key 3.

e For example, blower.

f For example, O_2 generator.

5.3 Classification of energy (enthalpy)

The classification of energy types and symbols specified in Table 2 apply.

The basic unit of energy specified in Table 2 is 1 kJ per tonne (i.e. 1 000 kg) of product, unless otherwise specified.

For calculation of each classification of energy, see 5.4.

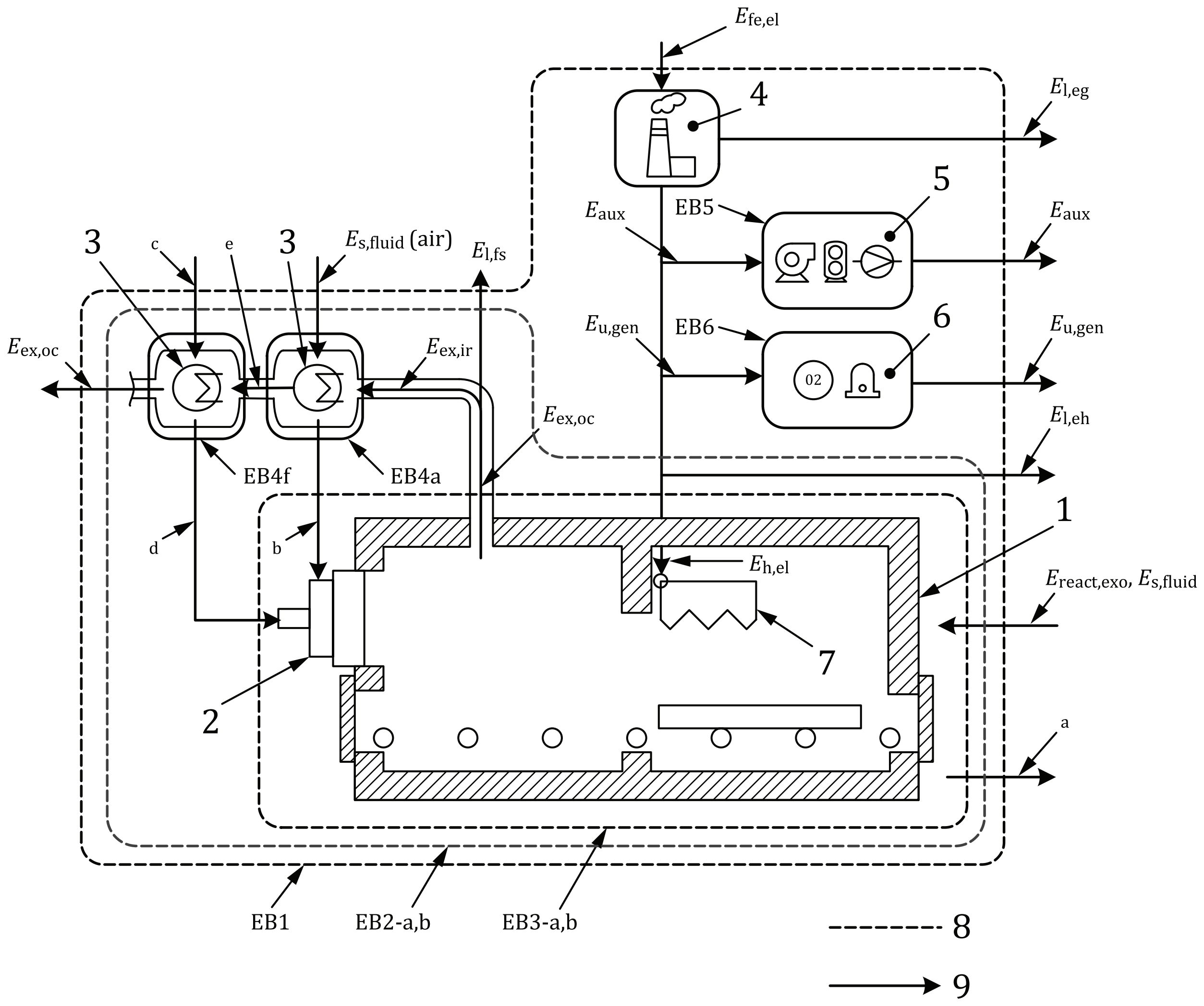
Table 2 — Classification of energy

Classification		Symbol	Description
Energy input to the heating chamber	Energy input from electrical source	E_{h}	5.4.1
		$E_{h,el}$	5.4.1.2
	Calorific value of fuel	$E_{h,fuel}$	5.4.1.3
	Heat of exothermic reaction	$E_{react,exo}$	5.4.1.4
	Sensible heat of fluid at the inlet	$E_{s,fluid}$	5.4.1.5

NOTE See Figure 1.

Table 2 *(continued)*

Classification		Symbol	Description
Energy required for process	Energy required for drying and evaporation	E_{pr}	5.4.2
		$E_{pr,ev}$	5.4.2.2
	Energy required for endothermic reaction for heated material (product)	$E_{pr,re}$	5.4.2.3
	Enthalpy change in product	$E_{pr,en}$	5.4.2.4
Sensible heat of exhaust gas at the outlet of combustion chamber	Sensible heat of exhaust gas from fuel	$E_{ex,oc}$	5.4.3.1
	Sensible heat of exhaust gas from raw materials	$E_{exrm,oc}$	5.4.3.2
Sensible heat of exhaust gas at the outlet of heat recovery equipment	Sensible heat of exhaust gas from fuel	$E_{ex,or}$	5.4.4.1
	Sensible heat of exhaust gas from raw materials	$E_{exrm,or}$	5.4.4.2
Sensible heat of exhaust gas at the inlet of heat recovery equipment	Sensible heat of exhaust gas from fuel	$E_{ex,ir}$	5.4.5.1
	Sensible heat of exhaust gas from raw materials	$E_{exrm,ir}$	5.4.5.2
Recovery heat	Recovery heat	$E_{h,re}$	5.4.6
	Recovery heat from sensible heat of exhaust gas	$E_{h,reex}$	5.4.6.2
	Recovery heat from sensible heat of product	$E_{h,repr}$	5.4.6.3
Thermal energy loss	Energy loss by uncombusted content	E_{l}	5.4.7
		$E_{l,uc}$	5.4.7.2
	Energy required for heating jigs and other substance	$E_{l,j}$	5.4.7.3
	Energy loss from furnace structure	$E_{l,fs}$	5.4.7.4
	Energy required for heat storage of furnace structure	$E_{l,hs}$	5.4.7.5
	Energy loss by atmosphere gas	$E_{l,atm}$	5.4.7.6
	Energy loss by exhaust gas from raw material	$E_{l,exrm}$	5.4.7.7
	Other energy loss	$E_{l,other}$	5.4.7.8
Electrical energy loss in electroheating	Electrical energy loss in electroheating	$E_{l,eh}$	5.4.8
Additional energy consumption	Energy consumed in auxiliary equipment	E_{aux}	5.4.9
	Energy consumed in generation of utilities	$E_{u,gen}$	5.4.10
Electrical generation loss	Electrical generation loss	$E_{l,eg}$	5.4.11
Fuel equivalent energy of electricity	Fuel equivalent energy of electricity	$E_{fe,el}$	5.4.12
Energy to be used outside TPE	Recycled energy	E_{rcy}	5.4.13
NOTE See Figure 1.			



Key

1 heating chamber/combustion chamber
2 burner
3 heat recovery equipment
4 electrical generation
5 electrical auxiliary equipment
6 generation of utilities
7 electrical heating
8 boundary of efficiency evaluation
9 energy flow

[a] Energy required for process (E_{pr}) and thermal energy losses (E_l).
[b] $E_{s,fluid}$ (air) + $E_{h,re}$.
[c] $E_{h,fuel}$ + $E_{s,fluid}$ (fuel).
[d] $E_{h,fuel}$ + $E_{s,fluid}$ (fuel) + $E_{h,re}$.
[e] $E_{ex,or}$ or $E_{ex,ir}$.

Figure 1 — Example configuration of TPE and boundaries of efficiency evaluation

5.4 Calculation of energy (enthalpy)

5.4.1 Energy input to the heating chamber (E_h)

5.4.1.1 General

Calculate energy input to the heating chamber per tonne of product using Formula (1):

$$E_h = \sum E_{h\,i} \tag{1}$$

where $E_{h\,i}$ is the individual applicable energy input to the heating chamber per tonne of product.

Calculate each applicable energy, as appropriate, in accordance with the following:

— energy input from electrical source ($E_{h,el}$), as defined in 5.4.1.2;

— calorific value of fuel ($E_{h,fuel}$), as defined in 5.4.1.3;

— heat of exothermic reaction ($E_{react,exo}$), as defined in 5.4.1.4;

— sensible heat of fluid at the inlet ($E_{s,fluid}$), as defined in 5.4.1.5.

5.4.1.2 Energy input from electrical source ($E_{h,el}$)

This classification is for energy supplied for electroheating as energy source. This includes resistance heating, induction heating, arc heating, dielectric heating and microwave heating. Fuel equivalent energy conversion is necessary depending on the condition of energy evaluation (e.g. in the case of EB1).

5.4.1.3 Calorific value of fuel ($E_{h,fuel}$)

This classification is for energy that is generated by combustion reaction of gaseous and/or liquid fuel. Sensible heat of fuel or air is not included.

Calculate calorific value of fuel according to ISO 13579-1:2013, 9.2.1, if applicable.

5.4.1.4 Heat of exothermic reaction ($E_{react,exo}$)

This classification is for energy that is generated by exothermic reactions such as oxidation reaction of product and calorific value by reactions such as exothermic reaction of auxiliary material or oxidation reaction of the electrode. Heat of exothermic reaction may be excluded from calculation of energy required for product depending on the condition of energy evaluation.

Calculate heat generated by the formation of scale of steel product according to ISO 13579-2:2013, 9.2.5, if applicable.

Calculate heat generated by the formation of aluminium oxide according to ISO 13579-3:2013, 9.2.7, if applicable.

5.4.1.5 Sensible heat of fluid at the inlet ($E_{s,\,fluid}$)

This classification is for summation of sensible heat of fluid and/or air at the inlet of heating chamber excluding recovery heat. This classification of energy includes sensible heat of infiltration air and atomization agent. When water/moisture is provided, its sensible heat and latent heat of vaporizing (as negative value) shall be taken into account. This item may be omitted when the value is small enough to neglect comparing to the entire energy input.

Calculate sensible heat input from fluid per tonne of product using Formula (2):

$$E_{s,\ fluid} = \sum E_{s,\ fluid\ i} \tag{2}$$

where $E_{s,\ fluid\ i}$ is the individual applicable sensible heat of fluid per tonne of product, e.g. sensible heat of fuel, sensible heat of combustion air, sensible heat of atomization agent, sensible heat of infiltration air, etc.

Calculate sensible heat of each fluid in accordance with the following references, where applicable:

— ISO 13579-1:2013, 9.2.4.1 for fuel ($E_{s,fuel}$);

— ISO 13579-1:2013, 9.2.5 for combustion air ($E_{s,air}$);

— ISO 13579-1:2013, 9.2.6 for atomization agent ($E_{s,atomize}$);

— ISO 13579-1:2013, 9.2.8 for infiltration air ($E_{s,infilt}$).

5.4.2 Energy required for process (E_{pr})

5.4.2.1 General

This classification is for the net energy required for the intended process itself. Energy required for the process is the summation of any combination of the following three classifications of energy:

— energy required for drying and evaporation ($E_{pr,ev}$), as defined in 5.4.2.2;

— energy required for endothermic reaction for heated material ($E_{pr,re}$), as defined in 5.4.2.3;

— enthalpy change in product ($E_{pr,en}$), as defined in 5.4.2.4.

5.4.2.2 Energy required for drying and evaporation ($E_{pr,ev}$)

This classification is for energy required for drying and evaporation in the thermo processing.

5.4.2.3 Energy required for endothermic reaction for heated material (product) ($E_{pr,re}$)

This classification is for energy required for chemical reaction for heated material in the thermo processing. The energy is absorbed energy by chemical reactions, e.g. $CaCO_3 + E_{pr,re} \rightarrow CaO + CO_2$.

5.4.2.4 Enthalpy change in product ($E_{pr,en}$)

This classification is for the amount of change in the enthalpy of a product in the boundary.

Calculate enthalpy change in a product using Formula (3):

$$E_{pr,en} = E_{p2} - E_{p1} \tag{3}$$

Calculate enthalpy of a product at the time of the loading into the boundary per tonne (E_{p1}) according to ISO 13579-1:2013, 9.3.1.1.2.1.

Calculate enthalpy of a product at the time of extraction from the boundary per tonne (E_{p2}) according to ISO 13579-1:2013, 9.3.1.1.2.2.

5.4.3 Sensible heat of exhaust gas at the outlet of combustion chamber

5.4.3.1 Sensible heat of exhaust gas from fuel ($E_{ex,oc}$)

This classification is for sensible heat of exhaust gas from fuel at the outlet of combustion chamber.

Calculate sensible heat of exhaust gas according to ISO 13579-1:2013, 9.3.1.4, if applicable.

5.4.3.2 Sensible heat of exhaust gas from raw materials ($E_{exrm,oc}$)

This classification is for sensible heat of exhaust gas from raw materials at the outlet of combustion chamber.

Calculate sensible heat of exhaust gas according to ISO 13579-1:2013, 9.3.1.4, if applicable.

5.4.4 Sensible heat of exhaust gas at the outlet of heat recovery equipment

5.4.4.1 Sensible heat of exhaust gas from fuel ($E_{ex,or}$)

This classification is for sensible heat of exhaust gas at the outlet of heat recovery equipment. In this case, the heat recovery equipment is integrally structured within the combustion chamber. Indication that describes the structure of the heat recovery equipment is necessary.

Calculate sensible heat of exhaust gas according to ISO 13579-1:2013, 9.3.1.4, if applicable.

5.4.4.2 Sensible heat of exhaust gas from raw materials ($E_{exrm,or}$)

This classification is for sensible heat of exhaust gas at the outlet of heat recovery equipment. In this case, the heat recovery equipment is integrally structured with the combustion chamber. An indication that describes the structure of the heat recovery equipment is necessary.

Calculate sensible heat of exhaust gas according to ISO 13579-1:2013, 9.3.1.4, if applicable.

5.4.5 Sensible heat of exhaust gas at the inlet of heat recovery equipment

5.4.5.1 Sensible heat of exhaust gas from fuel ($E_{ex,ir}$)

This classification is for sensible heat of exhaust gas at the inlet of heat recovery equipment which is located well apart from combustion chamber. This classification is used for evaluation of the heat recovery equipment unit.

Calculate sensible heat of exhaust gas according to ISO 13579-1:2013, 9.3.1.4, if applicable.

5.4.5.2 Sensible heat of exhaust gas from raw materials ($E_{exrm,ir}$)

This classification is for sensible heat of exhaust gas at the inlet of heat recovery equipment which is located well apart from combustion chamber. This classification is used for evaluation of the heat recovery equipment unit.

Calculate sensible heat of exhaust gas according to ISO 13579-1:2013, 9.3.1.4, if applicable.

5.4.6 Recovery heat ($E_{h,re}$)

5.4.6.1 General

This classification is for available recovery heat which is recovered from exhaust energy (e.g. heat of exhaust gas). Recovery heat is used for preheating of fuel, combustion air and/or product provided to the boundary.

5.4.6.2 Recovery heat from sensible heat of exhaust gas ($E_{h,reex}$)

This classification is for available recovery heat which is recovered from exhaust gas.

5.4.6.3 Recovery heat from sensible heat of product ($E_{h,repr}$)

This classification is for available recovery heat which is recovered from product.

5.4.7 Thermal energy loss (E_l)

5.4.7.1 General

Thermal energy loss (E_l) is summation of any combination of the following six classifications of energy:

- energy loss by uncombusted content ($E_{l,uc}$), as defined in 5.4.7.2;
- energy required for heating jigs and other substance ($E_{l,j}$), as defined in 5.4.7.3;
- energy loss from furnace structure ($E_{l,fs}$), as defined in 5.4.7.4;
- energy required for heat storage of furnace structure ($E_{l,hs}$), as defined in 5.4.7.5;
- energy loss by atmosphere gas ($E_{l,atm}$), as defined in 5.4.7.6;
- energy loss by exhaust gas from raw materials ($E_{l,exrm}$), as defined in 5.4.7.7;
- other energy loss ($E_{l,other}$), as defined in 5.4.7.8.

5.4.7.2 Energy loss by uncombusted content ($E_{l,uc}$)

This classification is for energy loss by calorific value of exhaust gas.

5.4.7.3 Energy required for heating jigs and other substance ($E_{l,j}$)

This classification is for the amount of change in enthalpy of jigs, carriages and cars which are intended for use in the transfer of product and other substance such as oxidized substances derived from the product.

NOTE This item, which is generally treated as heat loss, can be added as part of specific energy output, depending on the condition of the energy evaluation.

Calculate energy loss by jigs/carriage according to ISO 13579-1:2013, 9.3.1.2, if applicable.

5.4.7.4 Energy loss from furnace structure ($E_{l,fs}$)

Calculate energy loss from furnace structure per tonne of product using Formula (4):

$$E_{l,fs} = \sum E_{l,\,fs\,i} \tag{4}$$

where $E_{l,fs\,i}$ is the individual applicable energy loss from furnace structure per tonne of product, e.g. loss by furnace walls, loss by cooling water, loss from furnace opening, etc.

NOTE This item, which is generally treated as heat loss, can be added as part of specific energy output, depending on the condition of the energy evaluation.

References for calculations of each energy losses are listed as the following:

- ISO 13579-1:2013, 9.3.1.7 for loss by furnace wall;
- ISO 13579-1:2013, 9.3.1.11 for loss by cooling water;
- ISO 13579-1:2013, 9.3.1.9 for loss from furnace opening;
- ISO 13579-1:2013, 9.3.1.10 for loss from furnace parts installed through furnace wall.

5.4.7.5 Energy required for heat storage of furnace structure ($E_{l,hs}$)

This classification is for the amount of heat energy that is stored in batch-type furnace wall in its preheating process.

NOTE This item, which is generally treated as heat loss, can be added as part of specific energy output, depending on the condition of the energy evaluation.

Calculate energy required for heat storage of furnace structure according to ISO 13579-1:2013, 9.3.1.5, if applicable.

5.4.7.6 Energy loss by atmosphere gas ($E_{l,atm}$)

This classification is for energy loss as amount of change in enthalpy of special atmosphere gas when the gas is used in indirect heating TPE.

NOTE This item, which is generally treated as heat loss, can be added as part of specific energy output, depending on the condition of the energy evaluation.

Calculate energy loss by atmosphere gas according to ISO 13579-1:2013, 9.3.1.6, if applicable.

5.4.7.7 Energy loss by exhaust gas from raw materials ($E_{l,exrm}$)

This classification is for energy loss as amount of sensible heat of exhaust gas from raw materials.

NOTE This item, which is generally treated as heat loss, can be added as part of specific energy output, depending on the condition of the energy evaluation.

5.4.7.8 Other energy loss ($E_{l,other}$)

This classification is for energy losses which are calculated as residual term of energy balance.

It is necessary to examine the accuracy of measurement when the result of calculation takes the term as negative value.

For definition, see ISO 13579-1:2013, 3.1.5.13.

5.4.8 Electrical energy loss in electroheating ($E_{l,eh}$)

This classification is for electrical energy loss in electroheating, e.g. energy loss in transformers, rectifiers and conductors. When these energies are not measured, they fall into other energy losses specified in 5.4.7.8.

5.4.9 Energy consumed in auxiliary equipment (E_{aux})

This classification is for energy consumption by auxiliary equipment (e.g. pumps, blowers, fans, compressors, vacuum pumps).

Calculate energy consumption by auxiliary equipment per tonne of product using Formula (5):

$$E_{aux} = \sum E_{aux\ i} \tag{5}$$

where $E_{aux\ i}$ is the energy consumption by each auxiliary equipment per tonne of product.

Calculate energy consumption by each auxiliary equipment according to ISO 13579-1:2013, 9.3.2, if applicable.

NOTE In ISO 13579-1, the symbol for energy consumption by auxiliary equipment is E_{aux}.

5.4.10 Energy consumed in generation of utilities ($E_{u,gen}$)

This classification is for energy used in generation of utilities (e.g. special atmosphere gas, nitrogen, oxygen, compressed air, steam).

Calculate energy consumed in generation of utilities per tonne of product using Formula (6):

$$E_{u,gen} = \sum E_{u,gen\ i} \tag{6}$$

where $E_{u,gen\ i}$ is the energy consumption by generation of each utility per tonne of product.

NOTE Energy for generation of utilities can be calculated with the amount of utilities and specific energy consumption for generation.

Calculate energy consumption by generation of utilities according to ISO 13579-1:2013, 9.3.3, if applicable.

5.4.11 Electrical generation loss ($E_{l,eg}$)

This classification is for energy loss in electrical generation.

Calculate electrical generation loss according to ISO 13579-1:2013, 9.3.4, if applicable.

5.4.12 Fuel equivalent energy of electricity ($E_{fe,el}$)

This classification is for aggregate of fuel equivalent energy of electricity converted from each occurrence of electrical energy consumptions in the boundary.

Calculate fuel equivalent energy according to ISO 13579-1:2013, 9.3.4, if applicable.

5.4.13 Recycled energy (E_{rcy})

This classification is for energy which is recovered from heat loss from TPE and to use outside TPE.

Conversion to fuel equivalent energy is necessary, depending on the condition of the energy evaluation.

6 Efficiency based on enthalpy

6.1 General formula

Formula (7) is the general formula for the calculation of specific energy efficiency of enthalpy:

$$\eta = \frac{E_{sp\text{-}out}}{E_{sp\text{-}in}} \tag{7}$$

Specific energy input ($E_{sp\text{-}in}$) or specific energy output ($E_{sp\text{-}out}$) consists of one or any combination of classifications of energy specified in 5.3.

6.2 Examples of typical efficiencies

6.2.1 General

Examples of typical efficiencies are specified using the symbols defined in Table 2.

6.2.2 Overall efficiency in accordance with ISO 13579-1

Formula (8) is for the calculation of overall efficiency according to ISO 13579-1:

$$\eta_1 = \frac{E_{\mathrm{pr}}}{E_{\mathrm{h}} - E_{\mathrm{rcy}}} \tag{8}$$

This efficiency is typically applicable to boundary “EB1”.

6.2.3 Heat efficiency on the whole calorific value basis

Formula (9) is for the calculation of heat efficiency on the whole calorific value basis:

$$\eta_2 = \frac{E_{\mathrm{pr}}}{E_{\mathrm{h}} + E_{\mathrm{h,re}}} \tag{9}$$

This efficiency is typically applicable to boundary “EB3a”.

6.2.4 Heat efficiency on the supplied calorific value basis

Formula (10) is for the calculation of heat efficiency on the supplied calorific value basis:

$$\eta_3 = \frac{E_{\mathrm{pr}}}{E_{\mathrm{h}}} \tag{10}$$

This efficiency is typically applicable to boundary “EB2a”.

6.2.5 Available heat ratio

Formula (11) is for the calculation of available heat:

$$E_{\mathrm{available}} = E_{\mathrm{pr}} + E_{\mathrm{l}} \tag{11}$$

Formula (12) is for the calculation of available heat ratio:

$$\eta^{*} = \frac{E_{\mathrm{available}}}{E_{\mathrm{h,fuel}}} \tag{12}$$

NOTE See 3.1.7 for the definition of available heat.

NOTE See Annex C for details about the application of available heat ratio.

6.2.6 Combustion efficiency

Formula (13) is for the calculation of ratio of combusted fuel to supplied fuel:

$$\eta_5 = \frac{E_{\mathrm{h,fuel}} - E_{\mathrm{l,uc}}}{E_{\mathrm{h,fuel}}} \tag{13}$$

6.2.7 Effective waste heat recovery ratio in combustion furnace

Formula (14) is for the calculation of effective ratio of waste heat recovery in combustion furnace:

$$\eta_R = \frac{E_{h,re}}{E_{ex,oc}} \quad (14)$$

This efficiency is typically applicable to boundary "EB2" or "EB3".

NOTE Increasing the ratio defined in 6.2.7 leads to improvement of the degree of energy-saving effectiveness. Since the effect is related to the available heat ratio defined in 6.2.3, the example of calculation of the heat recovery ratio is also provided in Annex A and Annex B.

6.2.8 Waste heat recovery ratio as performance indicator of heat recovery equipment

Formula (15) is for the calculation of ratio of waste heat recovery as performance indicator of heat recovery equipment:

$$\eta_7 = \frac{E_{h,re}}{E_{ex,ir}} \quad (15)$$

This efficiency is typically applicable to boundary "EB4".

6.2.9 Ratio of waste heat of combustion exhaust gas to calorific value of fuel

Formula (16) is for the calculation of ratio of waste heat of combustion exhaust gas to calorific value of fuel.

$$\eta_{exh} = \frac{E_{ex,oc}}{E_{h,fuel}} \quad (16)$$

This efficiency is typically applicable to boundary "EB3" or "EB2".

6.2.10 Converted available heat ratio where waste heat recovery is not considered

Formula (17) is for the calculation of converted available heat ratio where waste heat recovery is not considered:

$$\eta^*_0 = 1 - \eta_{exh} \quad (17)$$

7 Efficiency based on exergy

7.1 General

This clause provides definitions of exergy as an option of energy efficiency evaluation of TPE. Each definition corresponds to enthalpy efficiency defined in Clause 6. This document does not cover entropy increase in each process.

7.2 Boundary

Electrical generation is inherently excluded from the boundary of exergy efficiency.

7.3 Classification of exergy

Classification of exergy types and symbols specified in Table 3 apply.

The basic unit of exergy specified in Table 3 is 1 kJ/t of product, unless otherwise specified.

Calculations of energy are defined in 7.4.

Table 3 — Classification of exergy

Classification		Symbol	Description
Exergy input to the heating chamber	exergy input from electrical source	$EX_{h,el}$	7.4.1
	exergy of fuel	$EX_{h,fuel}$	7.4.2
	exergy of exothermic reaction	$EX_{react, exo}$	7.4.3
	exergy of sensible heat of fluid at the inlet	$EX_{s,fluid}$	7.4.4
Exergy in energy required for a product	exergy in energy required for drying and evaporation	$EX_{pr,ev}$	7.4.5
	exergy required for endothermic reaction for heated material	$EX_{pr,re}$	7.4.6
	exergy in given enthalpy to product	$EX_{pr,en}$	7.4.7
Exergy of exhaust gas	at the outlet of combustion chamber	$EX_{ex,oc}$	
	at the outlet of heat recovery equipment	$EX_{ex,or}$	7.4.8
	at the inlet of heat recovery equipment	$EX_{ex,ir}$	
Recovery exergy	recovery exergy	$EX_{h,re}$	7.4.9
Thermal energy losses	exergy in required for heating jigs and other substance	$EX_{l,j}$	7.4.10
	exergy in heat loss from furnace structure	$EX_{l,fs}$	7.4.11
	exergy in Energy required for heat storage of furnace structure	$EX_{l,hs}$	7.4.12
	exergy given in enthalpy to atmosphere gas	$EX_{l,atm}$	7.4.13
Electrical energy loss in electroheating	exergy loss in electroheating	$EX_{l,eh}$	7.4.14
Energy consumed indirectly	exergy consumed in auxiliary equipment	EX_{aux}	7.4.15
	exergy consumed in generation of utilities	$EX_{u,gen}$	7.4.16
Energy to be used outside of TPE	exergy of recycled energy	EX_{rcy}	7.4.17

7.4 Calculation of exergy

7.4.1 Exergy input from electrical source ($EX_{h,el}$)

This classification is for the amount of exergy required to apply specific heat by electroheating.

Exergy input from electrical source is equivalent to energy input from electrical source. See Formula (18):

$$EX_{h,el} = E_{h,el} \tag{18}$$

7.4.2 Exergy of fuel ($EX_{h,fuel}$)

7.4.2.1 Gaseous fuel

Calculate exergy of gaseous fuel by summing up exergy of each component using Formula (19):

$$EX_{\text{h,fuel}} = \left(\sum x_i e^{\circ}_{c,i} + RT_0 \sum x_i \ln x_i \right) \times V_{\text{f}} \quad (19)$$

7.4.2.2 Liquid fuel

7.4.2.2.1 General

Calculate exergy of liquid fuel using Rant's approximation specified in 7.4.2.2.2 or using Nobusawa's formula specified in 7.4.2.2.3.

7.4.2.2.2 Rant's approximation

Calculate exergy using Formula (20):

$$EX_{\text{h,fuel}} = 0{,}975 H_{\text{h}} \times V_{\text{f}} \quad (20)$$

NOTE H_h is used instead of H_l in this formula.

7.4.2.2.3 Nobusawa's formula

Calculate exergy using Formula (21):

$$EX_{\text{h,fuel}} = H_l \left(1{,}003\,8 + 0{,}136\,5 \frac{h}{c} + 0{,}030\,8 \frac{o}{c} + 0{,}010\,4 \frac{s}{c} \right) \times V_{\text{f}} \quad (21)$$

NOTE Formula (21) is used if *h, o, s* and *c* are known. If not, use Formula (20).

7.4.3 Exergy of exothermic reaction ($EX_{react,exo}$)

Exergy of exothermic reaction is equivalent to heat of exothermic reaction defined in 5.4.1.4. See Formula (22):

$$EX_{\text{react,exo}} = E_{\text{react,exo}} \quad (22)$$

7.4.4 Exergy of sensible heat of fluid at the inlet ($EX_{s,fluid}$)

7.4.4.1 General

Calculate exergy of sensible heat of fluid per tonne of product using Formula (23):

$$EX_{\text{s, fluid}} = \sum EX_{\text{s, fluid i}} \quad (23)$$

where $EX_{\text{s, fluid i}}$ is the individual applicable exergy of sensible heat of fluid per tonne of product, e.g. exergy of sensible heat of

— fuel (see 7.4.4.2),

— combustion air (see 7.4.4.2),

— infiltration air (see 7.4.4.2), and

— atomization agent (see 7.4.4.3).

7.4.4.2 Exergy of sensible heat of fuel and air

Convert sensible heat of fuel or air to exergy using Formula (24) and Formula (25):

$$EX_{\text{s,fuid}} = \Delta H - T_0 \Delta S \tag{24}$$

$$\Delta S = m_{\text{fl}} c_{\text{pm},fl} \ln \frac{T_{\text{fl}}}{T_0} \tag{25}$$

7.4.4.3 Exergy of steam (atomization agent)

Convert sensible heat of steam (atomization agent) using Formula (24) and Formula (26):

$$\Delta S = m_{\text{v1}} \left\{ c_{\text{pm,w}} \ln \frac{373,15}{T_0} + \frac{L}{373,15} + c_{\text{pm,v}} \ln \frac{T_{\text{v1}}}{373,15} \right\} \tag{26}$$

7.4.5 Exergy in energy required for drying and evaporation ($EX_{\text{pr,ev}}$)

This classification is for exergy in energy required for drying and evaporation in the thermo processing.

Calculate exergy in given enthalpy to the product using Formula (27):

$$EX_{\text{pr,ev}} = E_{\text{pr,ev}} \left(1 - \frac{T_0}{T_{\text{fc}}} \right) \tag{27}$$

7.4.6 Exergy required for endothermic reaction for heated material ($EX_{\text{pr,re}}$)

This classification is for exergy in energy required for chemical reaction for heated material in the thermo processing.

Calculate exergy in given enthalpy to the product using Formula (28):

$$EX_{\text{pr,re}} = E_{\text{pr,re}} \left(1 - \frac{T_0}{T_{\text{fc}}} \right) \tag{28}$$

7.4.7 Exergy in given enthalpy to product ($EX_{\text{pr,en}}$)

This classification is for amount of exergy in the heat transferred to the product.

Calculate exergy in given enthalpy to the product using Formula (29):

$$EX_{\text{pr,en}} = E_{\text{pr,en}} \left(1 - \frac{T_0}{T_{\text{fc}}} \right) \tag{29}$$

7.4.8 Exergy of exhaust gas ($EX_{\text{ex,oc}}$, $EX_{\text{ex,or}}$, $EX_{\text{ex,ir}}$)

Convert sensible heat of exhaust gas to exergy using Formulae (30) and (31) or Formulae (32) and (33), as appropriate:

$$EX_{\text{ex,oc}} = E_{\text{ex,oc}} - T_0 \Delta S \tag{30}$$

$$EX_{\text{ex,or}} = E_{\text{ex,or}} - T_0 \Delta S \tag{31}$$

$$EX_{\text{ex,ir}} = E_{\text{ex,ir}} - T_0 \Delta S \tag{32}$$

where

$$\Delta S = m_{\text{ex}} c_{\text{pm,ex}} \ln \frac{T_{\text{ex}}}{T_0} \tag{33}$$

7.4.9 Recovery exergy ($EX_{\text{h,re}}$)

Convert sensible heat of preheated item (e.g. product, fluid) to exergy using Formula (34) and Formula (36):

$$EX_{\text{h,re}} = E_{\text{h,re}} - T_0 \Delta S \tag{34}$$

$$\Delta S = m_{\text{ph}} c_{\text{pm,ph}} \ln \frac{T_{\text{ph}}}{T_0} \tag{35}$$

See also 7.4.4.2 for recovery exergy of sensible heat of fuel and air.

7.4.10 Exergy in required for heating jigs and other substance ($EX_{\text{l,j}}$)

Calculate exergy in given enthalpy to jigs/carriage using Formula (36):

$$EX_{\text{l,j}} = E_{\text{l,j}} \left(1 - \frac{T_0}{T_{\text{fc}}} \right) \tag{36}$$

7.4.11 Exergy in heat loss from furnace structure ($EX_{\text{l,fs}}$)

Calculate exergy in heat loss from furnace structure using Formula (37):

$$EX_{\text{l,fs}} = E_{\text{l,fs}} \left(1 - \frac{T_0}{T_{\text{fc}}} \right) \tag{37}$$

7.4.12 Exergy in energy required for heat storage of furnace structure ($EX_{\text{l,hs}}$)

Calculate exergy in energy required for heat storage of furnace structure using Formula (38):

$$EX_{\text{l,hs}} = E_{\text{l,hs}} \left(1 - \frac{T_0}{T_{\text{fc}}} \right) \tag{38}$$

7.4.13 Exergy in given enthalpy to atmosphere gas ($EX_{\text{l,atm}}$)

Calculate exergy in energy required for heat storage of furnace structure using Formula (39):

$$EX_{\text{l,atm}} = E_{\text{l,atm}} \left(1 - \frac{T_0}{T_{\text{fc}}} \right) \tag{39}$$

7.4.14 Exergy consumed in electroheating ($EX_{\text{l,eh}}$)

Exergy consumed in electroheating is equivalent to the value of exergy of electrical loss in electroheating defined in 5.4.8. See Formula (40):

$$EX_{\text{l,eh}} = E_{\text{l,eh}} \tag{40}$$

7.4.15 Exergy consumed in auxiliary equipment (EX_{aux})

Exergy consumed in auxiliary equipment is equivalent to the value of energy consumption by auxiliary equipment defined in 5.4.9. See Formula (41):

$$EX_{aux} = E_{aux} \tag{41}$$

7.4.16 Exergy consumed in generation of utilities ($EX_{u,gen}$)

Exergy consumed in generation of utilities is equivalent to the value of energy consumed in generation of utilities defined in 5.4.10 when it is by electrical energy. See Formula (42):

$$EX_{u,gen} = E_{u,gen} \tag{42}$$

When energy consumed in generation of utilities is by fuel, apply the formulae specified in 7.4.2, while fuel consumption per tonne of product (V_f) means fuel consumption in generation of utilities per tonne of product.

7.4.17 Exergy of recycled energy (EX_{rcy})

This classification is for exergy of recycled energy which is recovered from heat loss from TPE and to use outside of TPE. Conversion from recycled energy (E_{rcy}) varies depending on the mode of energy transformation in recycling energy.

Calculate exergy of recycled energy when the form of recycled energy is steam using Formula (43) and Formula (44):

$$EX_{rcy} = E_{rcy} - T_0 \Delta S \tag{43}$$

$$\Delta S = m_{v2} \left\{ c_{pm,w} \ln \frac{373,15}{T_0} + \frac{L}{373,15} + c_{pm,v} \ln \frac{T_{v2}}{373,15} \right\} \tag{44}$$

7.5 Efficiency

7.5.1 General formula

Formula (45) is the general formula for the calculation of specific exergy efficiency:

$$\eta_{ex} = \frac{EX_{sp\text{-}out}}{EX_{sp\text{-}in}} \tag{45}$$

7.5.2 Examples of typical efficiencies

7.5.2.1 General

Examples of typical efficiencies are specified using the symbols defined in Table 3.

7.5.2.2 Overall exergy efficiency in accordance with ISO 13579-1

Formula (46) is for the calculation of overall exergy efficiency according to ISO 13579-1 using Gibbs free energy of fuel:

$$\eta_{ex1} = \frac{EX_{pr,ev} + EX_{pr,re} + EX_{pr,en}}{EX_{h,el} + EX_{h,fuel} + EX_{react,exo} + EX_{s,fluid} - EX_{rcy}} \tag{46}$$

7.5.2.3 Heat exergy efficiency on the whole calorific value basis

Formula (47) is for the calculation of heat efficiency on the whole calorific value basis using Gibbs free energy of fuel:

$$\eta_{ex2} = \frac{EX_{pr,ev} + EX_{pr,re} + EX_{pr,en}}{EX_{h,el} + EX_{h,fuel} + EX_{react,exo} + EX_{s,fluid} + EX_{h,re}} \tag{47}$$

7.5.2.4 Ratio of exergy in available heat to the input exergy

Formula (48) is for the calculation of exergy in available heat:

$$EX_{available} = \left(EX_{pr,ev} + EX_{pr,re} + EX_{pr,en}\right) + \left(EX_{l,j} + EX_{l,fs} + EX_{l,hs} + EX_{l,atm} + EX_{l,other}\right) \tag{48}$$

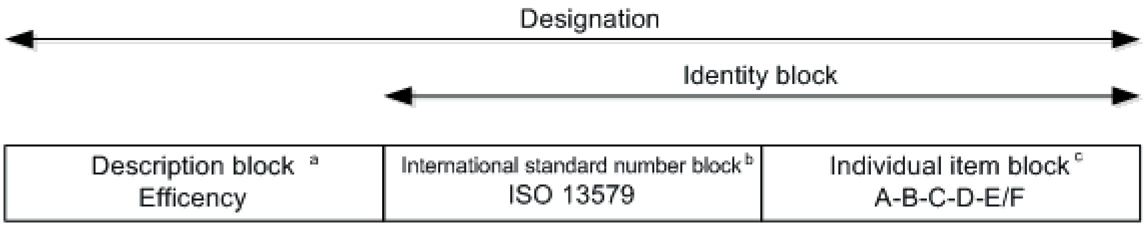
Formula (49) is for the calculation of ratio of exergy in available heat to the input exergy:

$$\eta_{ex}{}^{*} = \frac{EX_{available}}{EX_{h,fuel}} \tag{49}$$

8 Designation

8.1 General

Codes for the description block and the international standard block are specified in Figure 2.



a “Efficiency” is assigned as the description block.

b “ISO 13579” is assigned as the international standard number block.

c For individual item block, see 8.2.

Figure 2 — Structure of designation system

8.2 Individual item block

Individual item block of efficiency of TPE according to ISO 13579 is formed as follows:

A-B-C-D-E/F

In this item block, the elements are defined as:

A symbol for the type of operation which is specified in 8.3;

B symbol for the energy source which is specified in 8.4;

C symbol for the boundary for the evaluation of energy efficiency of TPE which is specified in 5.2;

D symbol for the energy type (EN: enthalpy or EX: exergy);

E symbol for the specific energy output;

F symbol for the specific energy input.

When a specific symbol is not necessarily assigned, an asterisk (*) is used as its substitute.

8.3 Type of operation

The following symbols for each type of operation apply.

Symbol	Type of operation
COD	direct heating continuous furnace
BAD	direct heating batch-type furnace
D	direct heating furnace
COI	indirect heating continuous furnace
BAI	indirect heating batch-type furnace
I	indirect heating furnace

NOTE 1 Batch-type furnace entails energy required for heat storage of furnace wall.

NOTE 2 Energy loss by atmosphere gas is considered in indirect heating operation, if applicable.

8.4 Energy source

The following codes for each energy source apply.

Symbol	Energy source
E	electricity only
F	combustion only
M	electricity and combustion
EC	electricity only with fuel equivalent energy conversion
MC	electricity and combustion with fuel equivalent energy conversion

8.5 Example

Examples for the designation of efficiency of TPE according to ISO 13579 are provided in Table 4.

Table 4 — Examples for the designation of efficiency of TPE

Description	Designation	Relevant clause
Overall efficiency in accordance with ISO 13579	Efficiency ISO 13579 D-MC-EB1-EN — $E_{pr}/(E_h - E_{rcy})$	6.2.2
Heat efficiency on the whole calorific value basis	Efficiency ISO 13579 D-M-EB2B-EN — $E_{pr}/(E_h + E_{h,re})$	6.2.3
Heat efficiency on the supplied calorific value basis	Efficiency ISO 13579 D-M-EB2S-EN — E_{pr}/E_h	6.2.4
Available heat ratio	Efficiency ISO 13579 COD-F-EB2B-EN — $E_{available}/E_{h,fuel}$	6.2.5
Combustion efficiency	Efficiency ISO 13579 *-F-EB2B-EN — $(E_{h,fuel}-E_{l,uc})/E_{h,fuel}$	6.2.6
Effective waste heat recovery ratio in combustion furnace	Efficiency ISO 13579 COD-F-EB2-EN — $E_{h,re}/E_{ex,oc}$	6.2.7
Waste heat recovery ratio as performance indicator of heat recovery equipment	Efficiency ISO 13579 *-*-EB4A-EN — $E_{h,re}/E_{ex,ir}$	6.2.8

9 Measurement

The measurement method specified in ISO 13579-1:2013, Clause 8 applies, as necessary.

10 Evaluation report

For the evaluation report of evaluation of TPE efficiency, ISO 13579-1:2013, Clause 10 applies.

The designation specified in this document shall be added if necessary.

Annex A
(informative)

Example of energy efficiency evaluation

A.1 General

This annex provides an example for making an energy balance table and its transformation for a good presentation of useful indexes of energy efficiency of two types of TPE.

A.2 Example of a continuous reheating furnace for steel

A.2.1 TPE overview

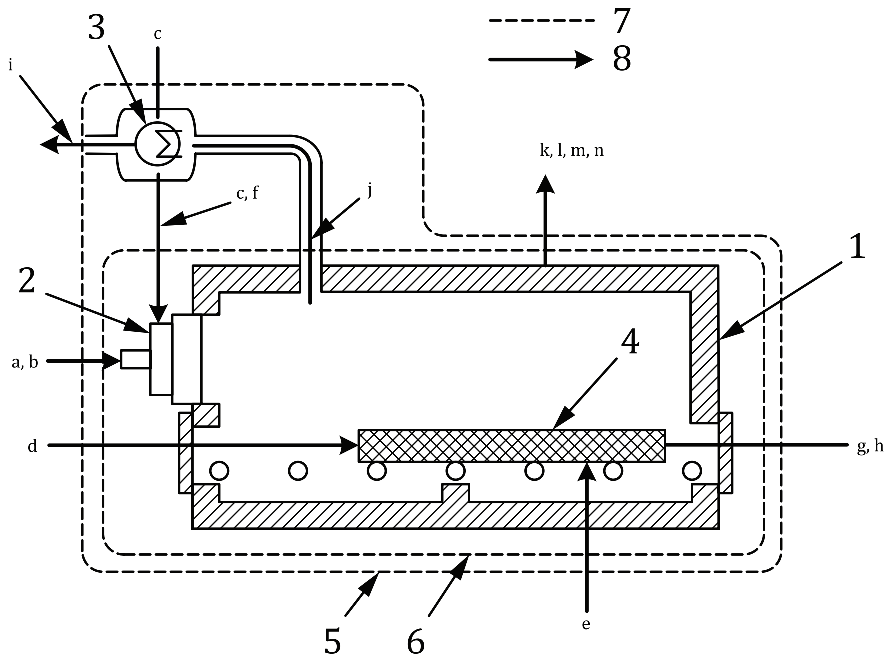
A brief overview of TPE for the example efficiency evaluation is indicated in Table A.1.

Table A.1 — Brief overview of TPE

Type	Continuous reheating furnace for steel
Nominal capacity	300 t/h
Type of burners	Burners with general heat recovery equipment
Material of product	Carbon steel slab

A.2.2 Boundary

Figure A.1 shows the boundary of the efficiency evaluation.



Key

1 heating chamber
2 burner
3 heat exchanger
4 product
5 boundary EB2a (see Table 1)
6 boundary EB3a (see Table 1)
a Calorific value of fuel, $E_{h,fuel}$.
b Sensible heat of fuel, $E_{s,fuel}$.
c Sensible heat of combustion air, $E_{s,air}$.
d Enthalpy of product at inlet, E_{p1}.
e Heat of exothermic reaction, $E_{react,exo}$.
f Recovery heat from exhaust gas, $E_{h,reex}$.
g Enthalpy of product at the time of extraction from the boundary, E_{p2}.
h Sensible heat of oxidized substance, $E_{l,j}$.
i Sensible heat of exhaust gas (at the outlet of heat recovery), $E_{ex,or}$.
j Sensible heat of exhaust gas (at the outlet of combustion chamber), $E_{ex,oc}$.
k Wall loss, $E_{l,fs(1)}$
l Heat loss of radiation from furnace opening, $E_{l,fs(2)}$.
m Cooling water loss, $E_{l,fs(3)}$.
n Other energy losses, $E_{l,other}$.

Figure A.1 — Boundaries of efficiency evaluation for the example continuous reheating furnace for steel

A.2.3 Measurement data

Table A.2 shows measurement data.

Table A.2 — Measurement data

Production rate	300 t/h		
Loading temperature of the product	20 °C		
Extraction temperature of the product	1 250 °C		
Ambient temperature	20 °C		
Atmosphere pressure	101,2 kPa		
Relative humidity	60 %		
Fuel	Type	COG (coke oven gas)	
	CO_2	2,38 %	
	C_2H_2	2,42 %	
	O_2	0,1 %	
	CO	7,06 %	
	H_2	57,39 %	
	CH_4	24,55 %	
	N_2	6,1 %	
	Calorific value	17,23 MJ/m^3(n)	
	Flow rate	22 809 m^3(n)/h	
	Supply temperature	20 °C	
Atomization agent		None	
Combustion air	Volume	Air ratio, *m* = 1,15, is obtained by calculation.	
	Temperature	20 °C at the inlet of heat recovery equipment	
	Temperature	750 °C at the inlet of burner	
Oxygen enrichment		None	
Infiltration air		None	
Atmosphere gas		None	
Exhaust gas	Temperature	900 °C	At the exit of furnace chamber
	Air ratio	1,15	
Furnace outer wall	Position	Temperature	Surface area
	Side	110 °C	612 m^2
	Top	120 °C	820 m^2
	Bottom	120 °C	612 m^2
	Front/Back	110 °C	186 m^2

NOTE 1 The data provided in this table are based on ISO 13579-2.

NOTE 2 Fume may be taken into account, if necessary.

Table A.2 *(continued)*

Cooling water	Indirect	Supply temp.	35 °C
		Discharge temp.	49 °C
		Volume	300 t/h
		Supply pressure	0,5 MPa
	Direct	Supply temp.	35 °C
		Discharge temp.	49 °C
		Volume	70 t/h
		Supply pressure	0,5 MPa
	Supply piping	500 DN (diameter 0,5 m)	
NOTE 1 The data provided in this table are based on ISO 13579-2.			
NOTE 2 Fume may be taken into account, if necessary.			

A.2.4 Variations in energy balance table and various kind of efficiency

Table A.3 shows examples of transformation of energy balance table to obtain various kind of efficiency using data provided in Table A.2.

Table A.3 — Example of transformation of thermal energy balance table and various kind of efficiency

Measurements in MJ/t

Type of energy, symbols		**Boundary**				
		1	**2**	**3**	**4**	**5**
		EB2a[a]	EB3a[b]	EB2a[c]	EB3a[d]	EB3a[e]
Thermal energy input	Calorific value of fuel, $E_{h,fuel}$	1 310	1 310	1 310	1 310	1 310
	Sensible heat of fuel, $E_{s,fuel}$	2	2	2	2	2
	Sensible heat of combustion air, $E_{s,air}$	9	9	9	9	9
	Enthalpy of product at inlet, E_{p1}	15	15			
	Heat of exothermic reaction, $E_{react,exo}$	28	28	28	28	
	Sensible heat of infiltration air, $E_{s,infilt}$	0	0	0	0	0
	Recovery heat from exhaust gas, $E_{h,reex}$		210		210	210
	Total	**1 364**	**1 574**	**1 349**	**1 559**	**1 531**

NOTE 1 Source: ISO 13579-2:2013, Annex B.

NOTE 2 If heat content of the skid cooling water/steam is used outside the system of an industrial furnace, that will be considered by ISO 13579-1 (refer to Reference [3]).

[a] Boundary of EB2a which includes heating chamber and heat recovery equipment. Recovery heat does not appear in the balance table. Values of enthalpy of product at the inlet (E_{p1}) and outlet (E_{p2}) are split to energy input and output.

[b] Boundary of EB3a which includes only heating chamber. Recovery heat is specified. Values of enthalpy of product at the inlet (E_{p1}) and outlet (E_{p2}) are split to energy input and output.

[c] Boundary of EB2a which includes heating chamber and heat recovery equipment.

[d] Boundary of EB3a which includes only heating chamber.

[e] Boundary of EB3a which includes only heating chamber. The value of heat of exothermic reaction is subtracted on both input and output energy.

[f] See 6.2.4. $E_{pr,ev} = 0$, $E_{pr,re} = 0$.

[g] See 6.2.3. $E_{pr,ev} = 0$, $E_{pr,re} = 0$.

Table A.3 *(continued)*

Type of energy, symbols		Boundary				
		1	2	3	4	5
		EB2a[a]	EB3a[b]	EB2a[c]	EB3a[d]	EB3a[e]
Thermal energy output	Enthalpy of product at the time of extraction from the boundary, E_{p2}	850	850			
	Enthalpy change in product, $E_{pr,en} = (E_{p2} - E_{p1})$			835	835	
	$E_{pr,en} - E_{react,exo}$					807
	Sensible heat of oxidized substance, $E_{l,j}$	7	7	7	7	7
	Sensible heat of exhaust gas (at the outlet of heat recovery), $E_{ex,or}$	177		177		
	Sensible heat of exhaust gas (at the outlet of the combustion chamber), $E_{ex,oc}$		562		562	562
	Wall loss, $E_{l,fs(1)}$	42	42	42	42	42
	Heat loss of radiation from furnace opening, $E_{l,fs(2)}$	8	8	8	8	8
	Cooling water loss, $E_{l,fs(3)}$	102	102	102	102	102
	Other energy loss, $E_{l,other}$	3	3	3	3	3
	Total	**1 364**	**1 574**	**1 349**	**1 559**	**1 531**
Efficiencies	Heat efficiency on the supplied calorific value basis, η_3 [f]			0,619		
	Heat efficiency on the whole calorific value basis, η_2 [g]				0,536	
	$(E_{pr,en} - E_{react,exo}) / [E_{h,fuel} + E_{s,fluid} + E_{h,re} + (E_{h,el})]$					0,554

NOTE 1 Source: ISO 13579-2:2013, Annex B.

NOTE 2 If heat content of the skid cooling water/steam is used outside the system of an industrial furnace, that will be considered by ISO 13579-1 (refer to Reference [3]).

[a] Boundary of EB2a which includes heating chamber and heat recovery equipment. Recovery heat does not appear in the balance table. Values of enthalpy of product at the inlet (E_{p1}) and outlet (E_{p2}) are split to energy input and output.

[b] Boundary of EB3a which includes only heating chamber. Recovery heat is specified. Values of enthalpy of product at the inlet (E_{p1}) and outlet (E_{p2}) are split to energy input and output.

[c] Boundary of EB2a which includes heating chamber and heat recovery equipment.

[d] Boundary of EB3a which includes only heating chamber.

[e] Boundary of EB3a which includes only heating chamber. The value of heat of exothermic reaction is subtracted on both input and output energy.

[f] See 6.2.4. $E_{pr,ev} = 0$, $E_{pr,re} = 0$.

[g] See 6.2.3. $E_{pr,ev} = 0$, $E_{pr,re} = 0$.

A.2.5 Energy balance table of available heat

By transforming energy balance of Boundary 4 of Table A.3, create Table A.4 for evaluating available heat.

Table A.4 — Energy balance table of available heat

Measurements in MJ/t

Type of energy, symbols		
Thermal energy input	Calorific value of fuel, $E_{h,fuel}$	1 310
	Recovery heat from exhaust gas, $E_{h,re}$	210
	Total	**1 520**
Thermal energy output	Available heat, $E_{available}$	958
	Exhaust gas (at the outlet of combustion chamber), $E_{ex,oc}$	562
	Total	**1 520**
Efficiencies	Effective waste heat recovery ratio in combustion chamber, η_R [a]	0,374
	Ratio of waste heat of combustion exhaust gas to calorific value of fuel, η_{exh} [b]	0,429
	Converted available heat ratio where waste heat recovery is not considered η^*_0 [c]	0,571
	Available heat ratio, η^* [d]	0,731

a See 6.2.7.

b See 6.2.9.

c See 6.2.10.

d See 6.2.5.

NOTE 1 Calorific value of fuel ($E_{h,fuel}$) can be estimated by calculating available heat ($E_{available}$) and available heat ratio (η^*).

NOTE 2 See Formula (C.3) for the relation of η^*, η_R and η^*_0.

A.3 Example of a cement kiln

A.3.1 TPE overview

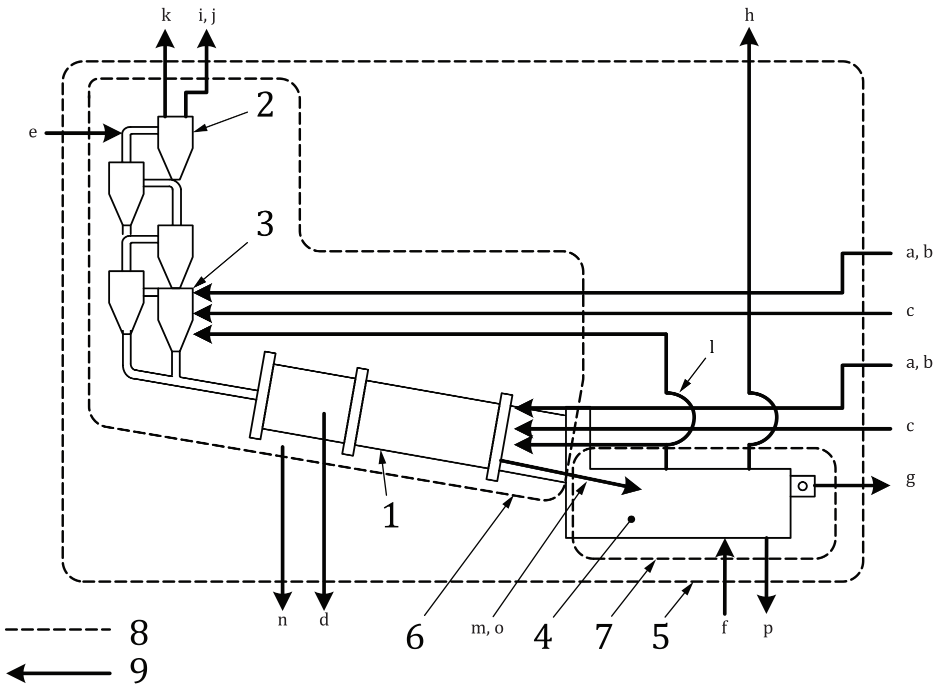
A brief overview of TPE for the example efficiency evaluation is indicated in Table A.5.

Table A.5 — Brief overview of TPE

Type	Suspension preheater kiln	
Kiln	Inner diameter:	5,2 m
	Length:	84 m
	Effective volume	1 784 m^3
Suspension heater	Number of stage	4

A.3.2 Boundary

Figure A.2 shows the boundary of the efficiency evaluation.



Key

1 kiln

2 suspension preheater

3 precalciner vessel

4 cooler

5 boundary 1 (EB2b, TPE)

6 boundary 2 (EB3b, preheater, precalciner and kiln)

7 boundary 3 (EB4, cooler)

a Calorific value of fuel, $E_{\mathrm{h,fuel}}$.

b Sensible heat of fuel, $E_{\mathrm{s,fuel}}$.

c Sensible heat of combustion air, $E_{\mathrm{s,air}}$.

d Heat of reaction (endothermic reaction of raw material), $E_{\mathrm{pr,re}}$.

e Sensible heat of product (raw materials) at inlet, $E_{\mathrm{p1\,(1)}}$.

f Sensible heat of cooling air to cooler.

g Enthalpy of product (clinker) at the outlet of cooler, $E_{\mathrm{p2\,(1)}}$.

h Sensible heat of air discharged from cooler.

i Sensible heat of exhaust gas derived from product (raw material), $E_{\mathrm{ex,oc\,(1)}}$.

j Sensible heat of exhaust gas derived from combustion of fuel, $E_{\mathrm{ex,oc\,(2)}}$.

k Sensible heat of discharged dust, $E_{\mathrm{ex,oc\,(3)}}$.

l Sensible heat of preheated combustion air, $E_{\mathrm{h,re}}$.

m Sensible heat of product (clinker) at the outlet of kiln.

n Other energy losses (radiations, etc.), $E_{\mathrm{l,other\,(2)}}$.

o Sensible heat of product (clinker) at the inlet of cooler.

p Other energy losses from cooler, $E_{\mathrm{l,other\,(3)}}$.

Figure A.2 — Boundaries of efficiency evaluation for the cement kiln

A.3.3 Measurement data

Table A.6 shows the measurement data.

Table A.6 — Measurement data

Item			Measurement data	Unit
Clinker	Production rate		202,6	t/h
	SiO_2		22,4	%
	Al_2O_3		5,5	%
	Fe_2O_3		3,3	%
	CaO		66,0	%
	MgO		1,2	%
	Lime saturation ratio (LSD)		0,92	
	Temperature at the inlet of cooler		1 350	°C
	Temperature at the outlet of cooler		110	°C
Exhaust gas derived from dry raw materials	Rate of water vapour		24[a]	m^3(n)/t[b]
	Rate of carbon acid gas		271[a]	m^3(n)/t[b]
Raw materials	Input rate		1 558[a]	kg/t[b]
	Moisture content		0,0	%
	Temperature		70	°C
Fuel	Type: heavy oil			
	Gross calorific value		43 535	kJ/kg
	Net calorific value		40 814	kJ/kg
	Temperature		110	°C
	Consumption (kiln)		32,6	kg/t[b]
	Consumption (precalciner)		48,7	kg/t[b]
Combustion air (non-preheated)	Kiln	Volume	35,2	m^3(n)/t[b]
		Temperature	20	°C
	Precalciner	Volume	52,6	m^3(n)/t[b]
		Temperature	20	°C
Combustion air (preheated)	Kiln	Volume	321[a]	m^3(n)/t[b]
		Temperature	891[a]	°C
	Precalciner	Volume	501	m^3(n)/t[b]
		Temperature	700	°C
Exhaust gas from kiln	Volume		452	m^3(n)/t[b]
	Temperature		1 150	°C
	CO_2		23,2	%
	O_2		2,0	%
	CO		0,0	%
	N_2		74,8	%
	Air ratio		1,11 [a]	

[a] Calculated values.

[b] Per tonne of clinker output.

Table A.6 *(continued)*

Item		Measurement data	Unit
Exhaust gas at the outlet of preheater	Volume	1 486	m^3(n)/t[b]
	Temperature	391	°C
	CO_2	30,4	%
	O_2	4,0	%
	CO	0,0	%
	N_2	65,0	%
	Air ratio	1,30 [a]	
Cooling air	Volume	2 387	m^3(n)/t[b]
	Temperature	30	°C
Air discharged from the cooler	Volume	1 565	m^3(n)/t[b]
	Temperature	230	°C
Discharged dust at the outlet of the preheater/kiln	Mass	0,13	t/t[b]
	Temperature	391	°C

a Calculated values.

b Per tonne of clinker output.

A.3.4 Variations in energy balance table and various kind of efficiency

Table A.7 shows examples of transformation of the energy balance table and various kind of efficiency using data provided in Table A.6.

Table A.7 — Example of thermal energy balance table

Measurements in MJ/t

Type of energy, symbols		Boundary		
		1[a]	**2**[b]	**3**[c]
Thermal energy input	Calorific value of fuel, $E_{h,fuel}$	3 318	3 318	
	Sensible heat of fuel, $E_{s,fuel}$	14	14	
	Sensible heat of combustion air, $E_{s,air}$	0	0	
	Heat of combustion of raw materials, $E_{react,exo}$	0	0	
	Sensible heat of product (raw materials) at the inlet of preheater, $E_{p1\ (1)}$	65	65	
	Sensible heat of non-preheated combustion air, $E_{s,air}$	0		
	Sensible heat of product (clinker) at the inlet of cooler, $E_{p1\ (2)}$			1 437
	Sensible heat of air at the inlet of the cooler	16		16
	Recovery heat from the cooler, $E_{h,re}$		857	
	Total	**3 413**	**4 254**	**1 453**

NOTE Source: JIS Z 9202–1991, Annex 5.

a Boundary 1: Boundary of EB2b (see Figure A.2).

b Boundary 2: Boundary of EB3b (see Figure A.2).

c Boundary 3: Boundary of EB4 (see Figure A.2).

d $E_{pr} = E_{pr,re}$.

e $E_{pr} = E_{pr,re}$.

f Waste heat recovery ratio: $E_{h,re}$ / $E_{p1(2)}$.

Table A.7 *(continued)*

Type of energy, symbols		Boundary		
		1[a]	**2**[b]	**3**[c]
Thermal energy output	Energy required for endothermic reaction of clinker (reaction, evaporation), $E_{pr,re}$	1 809	1 809	
	Sensible heat of product (clinker) at the outlet of cooler, $E_{p2\ (1)}$	71		71
	Sensible heat of product (clinker) at the outlet of kiln, $E_{p2\ (2)}$		1 437	
	Sensible heat of air discharged from the cooler	431		431
	Sensible heat of exhaust gas derived from product (raw materials), $E_{ex,oc\ (1)}$	208	208	
	Sensible heat of exhaust gas derived from combustion of fuel, $E_{ex,oc\ (2)}$	631	631	
	Sensible heat of discharged dust	44	44	
	Recovery heat from the cooler, $E_{h,re}$			857
	Other energy losses (TPE), $E_{l,other\ (1)}$	219		
	Other energy losses (preheater, precalciner and kiln), $E_{l,other\ (2)}$		125	
	Other energy losses (cooler), $E_{l,other\ (3)}$			94
	Total	**3 413**	**4 254**	**1 453**
Efficiencies	Heat efficiency on the supplied calorific value basis, η_3 [d]	0,530		
	Heat efficiency on the whole calorific value basis, η_2 [e]		0,425	
	Waste heat recovery ratio: $E_{h,re}/E_{p1\ (2)}$ [f]			0,596

NOTE Source: JIS Z 9202–1991, Annex 5.

a Boundary 1: Boundary of EB2b (see Figure A.2).

b Boundary 2: Boundary of EB3b (see Figure A.2).

c Boundary 3: Boundary of EB4 (see Figure A.2).

d $E_{pr} = E_{pr,re}$.

e $E_{pr} = E_{pr,re}$.

f Waste heat recovery ratio: $E_{h,re} / E_{p1(2)}$.

Annex B
(informative)

Comparison of enthalpy efficiency and exergy efficiency of continuous reheating furnaces

B.1 Summary of the calculation

This annex provides comparison of enthalpy efficiency and exergy efficiency using data of a continuous reheating furnace given in Table B.1 where three forms of heat recovery are considered [see also Figure B.1 a), b) and c)].

Table B.1 — Energy balance tables of reheating furnace for steel sorted by form of heat recovery

Furnace summary:					
Capacity: 130 t/h [usual operation base where the data of this table is measured (max. 200 t/h)]					
Type: Walking beam (double line loading)					
Temperature of furnace: 1 250 °C max.					
Slab temp: 20 °C (loading)					
Case a) No heat recovery is performed [see Figure B.1 a)]					
Energy input item	×10^3 kJ/t	**Remarks**	**Energy output item**	×10^3 kJ/t	**Remarks**
Calorific value of fuel	1 884,96		Sensible heat of the product	834,27	
Sensible heat of fuel	3,77		Sensible heat of exhaust gas	923,43	approx. 950 °C
Sensible heat of atomization agent	33,91		Sensible heat of scale	15,07	
Sensible heat of combustion air	18,42	20 °C	Cooling water loss	112,18	
Sensible heat of the product	13,40	20 °C	Furnace wall loss	126,42	
Heat of exothermic reaction (scale)	56,93		Other loss	0,00	
Total	**2 011,37**		**Total**	**2 011,37**	

Table B.1 *(continued)*

Case b) Heat recovery with recuperators [see Figure B.1 b)]					
Energy input item	×10³ kJ/t	**Remarks**	**Energy output item**	×10³ kJ/t	**Remarks**
Calorific value of fuel	1 509,47		Sensible heat of the product	834,27	
Sensible heat of fuel	2,93		Sensible heat of exhaust gas	724,60	approx. 900 °C
Sensible heat of atomization agent	27,21		Sensible heat of scale	15,07	
Sensible heat of combustion air	202,60	approx. 400 °C	Cooling water loss	112,18	
Sensible heat of the product	13,40		Furnace wall loss	126,42	
Heat of exothermic reaction (scale)	56,93		Other loss	0,00	
Total	**1 812,54**		**Total**	**1 812,54**	
Case c) Regenerative burner system [see Figure B.1 c) and the table footnote]					
Energy input item	×10³ kJ/t	**Remarks**	**Energy output item**	×10³ kJ/t	**Remarks**
Calorific value of fuel	1 147,80		Sensible heat of the product	834,27	
Sensible heat of fuel	2,09		Sensible heat of exhaust gas	619,95	
Sensible heat of atomization agent	20,93		Sensible heat of scale	15,07	
Sensible heat of combustion air	466,74		Cooling water loss	112,18	
Sensible heat of the product	13,40		Furnace wall loss	126,42	
Heat of exothermic reaction (scale)	56,93		Other loss	0,00	
Total	**1 707,89**		**Total**	**1 707,89**	

NOTE For regenerative burner system:

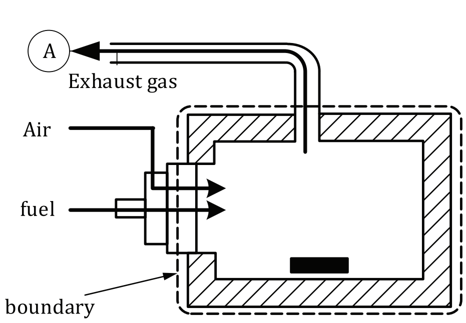
— Preheating temperature: 1 050°C;

— Temperature of exhaust gas at the inlet: 1 200°C;

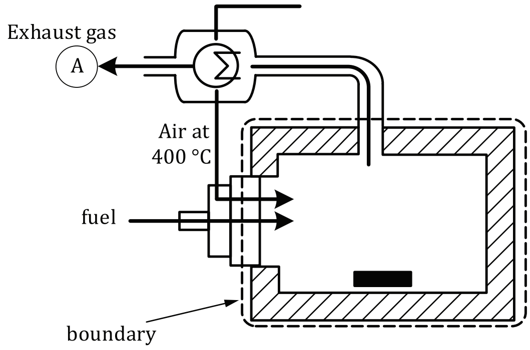
— Temperature of exhaust gas at the outlet: 300 °C;

— Temperature at the furnace end (escape): 900 °C;

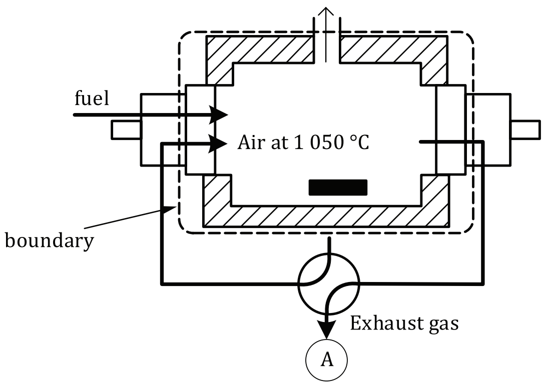
— Ratio of escaping exhaust gas: 20 %.



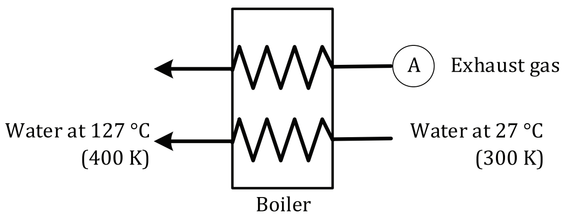
a) Case a) No waste heat is recovered



b) Case b) Waste heat is recovered with recuperator



c) Case c) Waste heat is recovered with regenerative burner system



d) Additional: Steam generation using exhaust gas

Figure B.1 — Forms of heat recovery

Additionally, steam generation using exhaust gas is considered for each form of heat recovery [see Figure B.1 d)].

Table B.2 provides symbols of efficiency that apply according to the combination of classes.

Table B.2 — Symbols used for efficiency of each type

Symbol of efficiency	Description	Class 1	Class 2
η	Specific enthalpy efficiency	I	a
η_{ex}	Specific exergy efficiency		
η^*	Enthalpy based available heat ratio	I	b
η_{ex}^*	Exergy based available heat ratio		
η'	Specific enthalpy efficiency	II	a
η_{ex}'	Specific exergy efficiency		
$\eta^{*\prime}$	Enthalpy based available heat ratio	II	b
$\eta_{ex}^{*\prime}$	Exergy based available heat ratio		

NOTE 1 For Class 1, the following apply:

I Case where heat recovery by generation of steam is NOT performed;

II Case where additional heat recovery by generation of steam is performed.

NOTE 2 For Class 2, the following types of energy as specific energy output ($E_{sp\text{-}out}$) apply:

a Enthalpy change in product ($E_{pr,en}$);

b Available heat as specified in 6.2.5 ($E_{available}$).

B.2 Result of calculation

Tables B.3 and B.4 provide the result of calculation based on the data in Table B.5. Symbols used in these tables are referred to symbols given in the body texts of this document as much as possible.

As shown in Table B.4, in the case where no heat recovery is performed [Case a)], the values of efficiency are η = 41,86 % and η_{ex} = 37,47 %, indicating the lowest value compared to the other forms of heat recovery. In addition, the absolute value of these enthalpy efficiency (η) and exergy efficiency (η_{ex}) are relatively close to each other. The same pattern can be observed in available heat ratio (η^* and η_{ex}^*).

However, in the case of efficiencies including steam generation, there is a significant difference between enthalpy efficiency (η') and exergy efficiency (η_{ex}'). Namely, the efficiency of η' has an improvement of 30 % or larger by the inclusion of steam generation; whereas, the efficiency of η_{ex}' has only an improvement of 6 %. The same observation can be applied to the relation of $\eta^{*\prime}$ and $\eta^{*\prime}$_ex. Therefore, although significant improvement can be observed in terms of enthalpy-based efficiency, it is found that it does not give very large effect when the efficiency is evaluated based on exergy.

Secondly, values of η' are almost the same in three cases [Case a): η' = 75,88 %, Case b): η' = 75,64 % and Case c): η' = 74,99 %]. On the other hand, the efficiency of η_{ex}' gradually increases as it becomes Case b), then Case c) [Case a): η_{ex}' = 44,12 %, Case b): η_{ex}' = 51,08 % and Case c): η_{ex}' = 61,82 %]. Namely, it can be observed that heat recovery by preheating combustion air is very effective to the exergy efficiency.

When Table B.1 is observed, significant decrease in fuel energy consumption is found as the form of heat recovery changes from Case a) to Case b), then Case b) to Case c). Therefore, it can be concluded that evaluation based on exergy can indicate values which reflect more actual situation in energy conservation measures because enthalpy efficiency is unable to express the decrease in fuel energy consumption when waste heat recovery by generation of steam is included. Whereas, exergy efficiency shows values that correspond to the changes of the fuel energy consumption regardless of the situation whether heat recovery by steam generation is used or not.

Table B.3 — Result of calculation (1/2)

Measurements in kJ/t

Input		a) No waste heat recovery is performed		b) Heat recovery with recuperators		c) Regenerative burner system	
		Enthalpy	Exergy	Enthalpy	Exergy	Enthalpy	Exergy
Calorific value of fuel	$E_{h,fuel}$	1 884,06	1 733,33	1 508,75	1 388,05	1 147,25	1 055,47
Sensible heat of fuel	$E_{s,fuel}$	3,77	0,12	2,93	0,10	2,09	0,07
Sensible heat of atomizing heat	$E_{s,fluid}$	33,89	5,97	27,20	4,79	20,92	3,69
Sensible heat of combustion air	$E_{s,air}$	18,41	0,60	202,51	72,64	466,52	266,41
Sensible heat of product	E_{p1}	13,39	0,64	13,39	0,64	13,39	0,64
Heat of exothermic reaction (scale)	$E_{react,exo}$	56,90	56,90	56,90	56,90	56,90	56,90
Total		**2 010,41**	**1 797,56**	**1 811,67**	**1 523,12**	**1 707,07**	**1 383,18**
Output		**Enthalpy**	**Exergy**	**Enthalpy**	**Exergy**	**Enthalpy**	**Exergy**
Sensible heat of product	E_{p2}	833,87	673,38	833,87	673,38	833,87	673,38
Sensible heat of exhaust gas	$E_{ex,oc}$	922,99	742,99	724,25	583,00	619,65	498,80
Sensible heat of scale	$E_{l,j}$	15,06	12,12	15,06	12,12	15,06	12,12
Cooling water loss	$E_{l,fs(1)}$	112,13	90,26	112,13	90,26	112,13	90,26
Furnace wall loss	$E_{l,fs(2)}$	126,36	101,71	126,36	101,71	126,36	101,71
Other loss	$E_{l,other}$	0,00	0,00	0,00	0,00	0,00	0,00
Total		**2 010,41**	**1 620,47**	**1 811,67**	**1 460,49**	**1 707,07**	**1 376,29**
NOTE Calculations are based on data in Table B.5.							

Table B.4 — Result of calculation (2/2)

Items	Symbols		a) No waste heat recovery is performed		b) Heat recovery with recuperators		c) Regenerative burner system	
	Enthalpy	Exergy	Enthalpy	Exergy	Enthalpy	Exergy	Enthalpy	Exergy
Input (kJ/t)	$E_{sp\text{-}in}$	$EX_{sp\text{-}in}$	1 992,00	1 796,96	1 609,17	1 450,48	1 240,56	1 116,77
Output without steam recycle (kJ/t)	$E_{sp\text{-}out}$	$EX_{sp\text{-}out}$	833,87	673,38	833,87	673,38	833,87	673,38
Output without steam recycle, available (kJ/t)	$E_{available}$	$EX_{available}$	1087,42	878,13	1087,42	878,13	1087,42	878,13
Output with steam recycle (kJ/t)	$E'_{sp\text{-}out}$	$EX'_{sp\text{-}out}$	1511,58	792,78	1217,19	740,91	930,31	690,37
Output with steam recycle, available (kJ/t)	$E'_{available}$	$EX'_{available}$	1 765,13	997,53	1 470,74	945,66	1 183,86	895,12
Specific efficiency (%)	η	η_{ex}	41,86	37,47	51,82	46,42	67,22	60,30
Available heat ratio (%)	η^*	η_{ex}^*	54,59	48,87	67,58	60,54	87,66	78,63

Table B.4 *(continued)*

Items	Symbols		a) No waste heat recovery is performed		b) Heat recovery with recuperators		c) Regenerative burner system	
	Enthalpy	Exergy	Enthalpy	Exergy	Enthalpy	Exergy	Enthalpy	Exergy
Specific efficiency incl. steam generation (%)	η'	η_{ex}'	75,88	44,12	75,64	51,08	74,99	61,82
Available heat ratio incl. steam generation (%)	$\eta^{*\prime}$	$\eta_{ex}{}^{*\prime}$	88,61	55,51	91,40	65,20	95,43	80,15
NOTE Calculations are based on data in Table B.5.								

B.3 Detailed logics and assumptions for calculating exergy efficiency

B.3.1 Input of energy and exergy

B.3.1.1 Fuel

Enthalpy of fuel is calculated using higher calorific value. The value can be provided from the difference of formation energy between reactant and product material.

Calculations are performed under assumption that

— fuel is methane, and

— exergy is assumed as E = 0,92 HH (higher calorific value) based on approximate formula of Rant.

Therefore, Formula (B.1) is applied:

$$E_{\text{h,fuel}} \times 0{,}92 = EX_{\text{h,fuel}} \tag{B.1}$$

NOTE This value can also be obtained from the Gibbs free energy formula, as specified in 7.5.2.2.

Formulae for the calculation of the enthalpy and exergy are specified in 5.4 and 7.4, respectively.

In addition, exergy loss by mixing of fuel and air is excluded in the calculation.

Pressure at the time of energy input (e.g. atmosphere pressure) is equivalent to the ambient atmosphere pressure.

B.3.1.2 Enthalpy and exergy input other than fuel

Concerning the input items ($E_{\text{sp-in}}$ and $EX_{\text{sp-in}}$) other than fuel, the following items are included:

— sensible heat of fuel;

— sensible heat of atomization agent;

— sensible heat of product;

— heat of exothermic reaction.

Sensible heat of combustion air is not included since it is considered that sensible heat of combustion air is always provided via heat recovery from exhaust gas.

Formulae for the calculation of the enthalpy and exergy are specified in 5.4 and 7.3, respectively.

B.3.2 Condition of items as output

B.3.2.1 General

Items as output are listed as the following (as explained in B.1):

a) recovered energy (and exergy) as steam generated from exhaust heat;

b) thermal energy (and exergy) which is received in product material;

c) thermal losses (and exergy included in these losses) dissipated via furnace walls and cooling water.

The calculation methods for these items are explained in B.3.2.2 to B.3.2.4.

B.3.2.2 Recovery of enthalpy and exergy by generation of steam

B.3.2.2.1 Recovery of enthalpy

Recovered enthalpy by generation of steam is calculated using Formula (B.2):

$$H_{\mathrm{v}} = \eta_{\mathrm{rcy,steam}} E_{\mathrm{ex,oc}} \left(1 - \eta_{\mathrm{R}}\right) \tag{B.2}$$

and mass of generated steam is calculated as Formula (B.3):

$$m_{\mathrm{v2}} = \frac{H_{\mathrm{v}}}{c_{\mathrm{pm,w}} \left(373{,}15 - T_0\right) + L + c_{\mathrm{pm,v}} \left(T_{\mathrm{v2}} - 373{,}15\right)} \tag{B.3}$$

where

$\eta_{\mathrm{rcy,steam}}$ = 0,75 is assumed here;

η_{rcy} = 0,95 is assumed here.

B.3.2.2.2 Recovered exergy

Recovery of exergy as steam is calculated using Formulae (B.4) and (B.5):

$$EX_{\mathrm{v}} = H_{\mathrm{v}} - T_0 \Delta S \tag{B.4}$$

$$\Delta S = m_{\mathrm{v2}} \left\{ c_{\mathrm{pm,w}} \ln \frac{373{,}15}{T_0} + \frac{L}{373{,}15} + c_{\mathrm{pm,v}} \ln \frac{T_{\mathrm{v2}}}{373{,}15} \right\} \tag{B.5}$$

B.3.2.3 Enthalpy and exergy received by the product material

For specific energy output per tonne of product, received enthalpy is calculated using Formula (B.6):

$$E_{\text{sp-out}} = E_{\mathrm{p2}} \tag{B.6}$$

For specific exergy output per tonne of product, received of exergy is calculated using Formula (B.7):

$$EX_{\text{sp-out}} = E_{\mathrm{p2}} \left(1 - \frac{T}{T_{\mathrm{fc}}}\right) \tag{B.7}$$

where T_{fc} = 1 250 °C is assumed here.

B.3.2.4 Enthalpy and exergy which include wall loss, cooling water loss, scale loss and enthalpy/exergy received in product material

B.3.2.4.1 Received enthalpy

Received enthalpy is calculated using Formula (B.8):

$$E_{\text{available}} = E_{\text{p2}} + E_{\text{l}} \tag{B.8}$$

B.3.2.4.2 Received exergy

Received enthalpy is calculated using Formula (B.9):

$$EX_{\text{available}} = E_{\text{available}}\left(1 - \frac{T}{T_{\text{fc}}}\right) \tag{B.9}$$

where T_{fc} = 1 250° C is assumed here.

B.3.3 Calculation of specific enthalpy efficiency and specific exergy efficiency

Formulae (B.10), (B.11), (B.12) and (B.13) describe enthalpy efficiency:

$$\eta = \frac{E_{\text{sp-out}}}{E_{\text{sp-in}}} = \frac{E_{\text{p2}}}{E_{\text{h,fuel}} + E_{\text{s,fuel}} + E_{\text{s,atomize}} + E_{\text{p2}} + E_{\text{react,exo}}} \tag{B.10}$$

$$\eta^* = \frac{E_{\text{available}}}{E_{\text{sp-in}}} = \frac{E_{\text{p2}} + E_{\text{l}}}{E_{\text{h,fuel}} + E_{\text{s,fuel}} + E_{\text{s,atomize}} + E_{\text{p2}} + E_{\text{react,exo}}} \tag{B.11}$$

$$\eta' = \frac{E'_{\text{sp-out}}}{E_{\text{sp-in}}} = \frac{E_{\text{p2}} + H_{\text{v}}}{E_{\text{h,fuel}} + E_{\text{s,fuel}} + E_{\text{s,atomize}} + E_{\text{p2}} + E_{\text{react,exo}}} \tag{B.12}$$

$$\eta^{*\prime} = \frac{E'_{\text{available}}}{E_{\text{sp-in}}} = \frac{E_{\text{p2}} + E_{\text{l}} + H_{\text{v}}}{E_{\text{h,fuel}} + E_{\text{s,fuel}} + E_{\text{s,atomize}} + E_{\text{p2}} + E_{\text{react,exo}}} \tag{B.13}$$

Formulae (B.14), (B.15), (B.16) and (B.17) describe exergy efficiency:

$$\eta_{\text{ex}} = \frac{EX_{\text{sp-out}}}{EX_{\text{sp-in}}} = \frac{EX_{\text{p2}}}{EX_{\text{h,fuel}} + EX_{\text{s,fuel}} + EX_{\text{s,atomize}} + EX_{\text{p2}} + EX_{\text{react,exo}}} \tag{B.14}$$

$$\eta_{\text{ex}}^* = \frac{EX_{\text{available}}}{EX_{\text{sp-in}}} = \frac{EX_{\text{available}}}{EX_{\text{h,fuel}} + EX_{\text{s,fuel}} + EX_{\text{s,atomize}} + EX_{\text{p2}} + EX_{\text{react,exo}}} \tag{B.15}$$

$$\eta_{\text{ex}}' = \frac{EX'_{\text{sp-out}}}{EX_{\text{sp-in}}} = \frac{EX_{\text{p2}} + EX_{\text{v}}}{EX_{\text{h,fuel}} + EX_{\text{s,fuel}} + EX_{\text{s,atomize}} + EX_{\text{p2}} + EX_{\text{react,exo}}} \tag{B.16}$$

$$\eta^{*\prime} = \frac{EX'_{\text{available}}}{EX_{\text{sp-in}}} = \frac{EX_{\text{available}} + EX_{\text{v}}}{EX_{\text{h,fuel}} + EX_{\text{s,fuel}} + EX_{\text{s,atomize}} + EX_{\text{p2}} + EX_{\text{react,exo}}} \tag{B.17}$$

Table B.5 — Summary of initial condition and property values of materials

Item	Symbol	a) No waste heat recovery is performed	b) Heat recovery with recuperators	c) Regenerative burner system
Temp. of product (extracted)	$T_{prod,ex}$ (K)	1 503,15	1 503,15	1 503,15
Temp. of product (loaded)	$T_{prod,lo}$ (K)	322,90	322,90	322,90
Ambient temp	T_0 (K)	293,15	293,15	293,15
Specific heat of product	$c_{p,prod}$ (kJ/kgK)	0,45	0,45	0,45
Temp. of furnace	$T_{furnace}$ (K)	1 523,15	1 523,15	1 523,15
Temp. of fuel (initial)	T_{fuel} (K)	313,15	313,15	313,15
Specific heat of fuel (2,2 at methane)	$c_{p,fuel}$ (kJ/kgK)	2,20	2,20	2,20
Mass of fuel (per kg of product)	m_{fuel} (kg)	0,09	0,07	0,05
Temp. of combustion air	T_{air} (K)	313,15	673,15	1 323,15
Specific heat of air	$c_{p,air}$ (kJ/kgK)	1,30	1,30	1,30
Mass of air (per kg of product)	m_{air} (kg)	0,71	0,41	0,35
Efficiency of steam recycle	$\eta_{rcy,steam}$	0,75	0,75	0,75
Temp. of vapour steam	T_{vap} (K)	400,00	400,00	400,00
Specific heat of water, liquid	$c_{p,wl}$ (kJ/kgK)	4,19	4,19	4,19
Specific heat of water, 400 K vapour	$c_{p,wv}$ (kJ/kgK)	4,26	4,26	4,26
Latent heat of water	L (kJ/kg)	334,00	334,00	334,00
Heat capacity of water, 297 K liquid to 400 K vapour	C_{water} (kJ/kgK)	783,34	783,34	783,34
Mass of vapour steam for atomizing (per kg of product)	m_{vap} (kg)	0,04	0,03	0,03
Mass of vapour steam for recycle (per kg of product)	m_{vap} (kg)	0,87	0,49	0,12
Efficiency of each recycling system (recuperator, regenerator, etc.)	η_{rcy}	0,95	0,95	0,95
Enthalpy of steam recycle	H_{vap}	677,71	383,31	96,44
Entropy change of steam recycle	ΔS_{vap}	1,90	1,08	0,27
Exergy of steam recycle	Ex_{vap}	119,39	67,53	16,99

Annex C
(informative)

Procedure for estimation of energy saving effect of combustion furnaces

C.1 General

Calorific value of fuel ($E_{h,fuel}$) consumed in combustion TPE is defined as Formula (C.1):

$$E_{h,fuel} = E_{available} / \eta^* \quad (C.1)$$

NOTE For definition of available heat and available heat ratio, see 6.2.5.

Energy input from electrical source ($E_{h,el}$) is calculated using Formula (C.2), considering it does not entail loss of exhaust gas [i.e. η^* (available heat ratio) = 1]:

$$E_{h,el} = E_{available} \quad (C.2)$$

Therefore, it is necessary to analyse two factors (available heat and available heat ratio) when addressing energy saving effect of combustion TPE. Whereas, only the analysis of available heat should suffice when electrical heating equipment is evaluated.

C.2 Determination of boundary and making an energy balance table

It is necessary to evaluate the energy balance table of heating chamber for the estimation of energy saving effect.

Make an energy balance table with boundary EB3a then calculate:

— effective waste heat recovery ratio in combustion furnace, η_R, as defined in 6.2.7;

— ratio of waste heat of combustion exhaust gas to calorific value of fuel, η_{exh}, as defined in 6.2.9;

— converted available heat ratio where waste heat recovery is not considered η^*_0, as defined in 6.2.10;

— available heat ratio, η^*, as defined in 6.2.5.

C.3 Estimation of energy saving effect

C.3.1 General formula

Relations of each index of efficiency are described as Formula (C.3):

$$\eta^* = \eta^*_0 + \left(1 - \eta^*_0\right) \cdot \eta_R \tag{C.3}$$

Estimate energy saving ratio using Formula (C.4):

$$\begin{aligned}\alpha_{es} &= \left(1 - E_{h,fuel\,II} / E_{h,fuel\,I}\right) \times 100 \\ &= \left(1 - \frac{E_{available\,II}}{E_{available\,I}} \times \frac{\eta^*_I}{\eta^*_{II}}\right) \times 100\end{aligned} \tag{C.4}$$

When the available heat is constant, the energy saving ratio is described as Formula (C.5):

$$\alpha_{es} = \left(1 - \eta^*_I / \eta^*_{II}\right) \tag{C.5}$$

C.3.2 Estimation of available heat ratio

In the case where heat recovery is performed by preheating of combustion air, available heat ratio can be approximately calculated using temperature of combustion air and exhaust gas, and air ratio is calculated from analysis of exhaust gas using Formula (C.6), while not depending on detailed measurement.

$$\eta^* = \left(E_{h,fuel} + E_{h,re} - E_{ex,oc}\right) / E_{h,fuel} \tag{C.6}$$

The calorific value of fuel ($E_{h,fuel}$), the recovery heat ($E_{h,re}$) and the sensible heat of exhaust gas at the outlet of combustion chamber ($E_{ex,oc}$) are calculated using Formulae (C.7), (C.8) and (C.9):

$$E_{h,fuel} = H_l \times V_f \tag{C.7}$$

$$E_{h,re} = H_r \times V_f \tag{C.8}$$

$$E_{ex,oc} = H_{ex} \times V_f \tag{C.9}$$

The sensible heat of preheated combustion air per unit fuel consumption (H_r) is calculated using Formula (C.10):

$$H_r = t_a \times C_a \times m \times A_0 \tag{C.10}$$

where the sensible heat of exhaust gas at the outlet of combustion chamber per unit fuel consumption (H_{ex}) is calculated using Formula (C.11):

$$H_{ex} = t_{gout} \times C_g \times \left[G_0 + \left(m - 1\right) A_0\right] \tag{C.11}$$

C.3.3 Estimation by individual parameters

C.3.3.1 Effect of waste heat recovery

When available heat is constant and there is no change in fuel rate, air ratio and the temperature of exhaust gas at the outlet of the furnace chamber, calculate the energy saving ratio according to change in effective waste heat recovery ratio using Formula (C.12):

$$\alpha_{es} = \frac{(\eta_{RII} - \eta_{RI}) \times (1 - \eta^*_0)}{\eta^*_0 + \eta_{RII}(1 - \eta^*_0)} \times 100 \qquad (C.12)$$

NOTE See 6.2.7 for the definition of effective waste heat recovery ration in combustion furnace.

C.3.3.2 Effect of improvement in air ratio

Energy saving ratio by improvement in air ratio is defined as Formula (C.13):

$$\alpha_{es} = \frac{(1 - \eta_R) \times t_{gout} \times C_g \times (m_I - m_{II}) \times A_0}{H_l - (1 - \eta_R) \times t_{gout} \times C_g \times \left[G_0 + (m_{II} - 1) \times A_0\right]} \times 100 \qquad (C.13)$$

C.3.4 Example of estimation of energy saving ratio

C.3.4.1 General

In this example

— a model of continuous reheating furnace for steel given in A.2 is used,

— the boundary is determined as EB2a specified in Figure A.1, and

— the energy balance table and efficiencies given in Table A.4 is used as the baseline.

C.3.4.2 Improvement in waste heat recovery

See Table C.1.

Table C.1 — Effect of improvement in waste heat recovery to energy saving ratio

η_R	η^*	α_{es}	**Notes**
0	0,570	Baseline	No heat recovery: Reference condition
0,20	0,656	13,1 %	
0,40	0,742	23,2 %	
0,60	0,828	31,2 %	
0,637	0,843	32,5 %	

C.3.4.3 Improvement in air ratio

Table C.2 shows estimated change in energy saving ratio when air ratio varies from 1,15 to 1,05 and 1,25.

Table C.2 — Effect of change in air ratio to energy saving ratio

Air ratio (m)	1,15	1,05	1,25
H_l	17,23	17,23	17,23
A_0	4,176	4,176	4,176
G_0	4,828	4,828	4,828
C_g	1,511	1,511	1,511
t_{gout}	900	900	900
η_R	0,673	0,637	0,637
α_{es}	Baseline	8 %	−7,7 %

C.3.4.4 Preheating product

Table C.3 shows estimated change in energy saving ratio when preheating of product is performed by waste heat recovery.

Table C.3 — Effect of preheating product to energy saving ratio

Temp. of the product at the inlet (°C)	30	100	200	300	400
$E_{pr,en}$ (MJ/t)	835	801	743	682	607
$E_{available}$ (MJ/t)	958	924	866	805	730
$E_{h,fuel}$ (MJ/t)	1 136	1 095	1 026	954	865
α_{es}	Baseline	3,6 %	9,7 %	16,0 %	23,9 %

C.3.4.5 Example of effect of reducing in heat losses

When the sum of $E_{l,fs\text{-}1}$ and $E_{l,fs\text{-}3}$ in Table A.3 were reduced by half by improving insulation, the available heat reduces to 922 MJ/t from 958 MJ/t. Therefore, required calorific value of fuel ($E_{h,fuel}$) can be calculated using the definition of Formula (C.1) as Formula (C.14):

$$E_{h,fuel} = E_{available} / \eta^* = 922/0{,}843 = 1\,093 \text{ MJ/t} \quad (C.14)$$

NOTE Since the estimation is on the premise of constant production rate, reduction ratio of fuel input rate and fuel consumption rate per unit production are common.

C.4 Examples of energy saving estimation by simplified models of typical furnaces

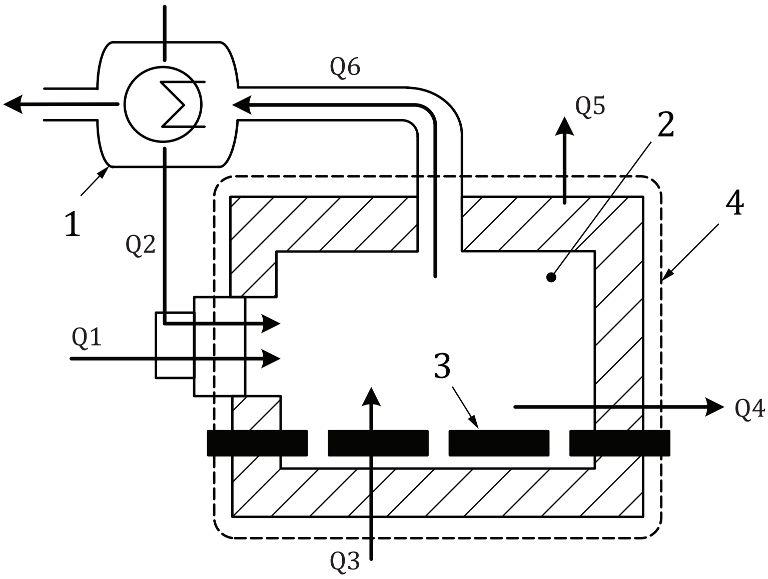
C.4.1 Continuous reheating furnace

C.4.1.1 Heat balance of boundary EB3a

Relation of types of enthalpy in regards to continuous reheating furnace is described as Formula (C.15):

$$E_{h,fuel} + E_{h,reex} = E_{pr,en} + E_{ex,oc} - E_{react,exo} \quad (C.15)$$

For basic configuration of continuous reheating furnace, see Figure C.1.



Key

1	exhaust gas heat recovery equipment	Q1	calorific value of fuel ($E_{h,fuel}$)
2	heating chamber	Q2	recovery heat from exhaust gas ($E_{h,reex}$)
3	product	Q3	heat of oxidization ($E_{react,exo}$)
4	boundary (EB3a)	Q4	enthalpy change in product ($E_{pr,en}$)
		Q5	thermal energy loss (E_l)
		Q6	sensible heat of exhaust gas from fuel ($E_{ex,oc}$)

Figure C.1 — Example of simplified configuration of continuous reheating furnace

Calculate thermal energy loss (Q5) using Formula (C.16):

$$Q5 = Q51 + Q52 \tag{C.16}$$

where

Q51 is energy loss from furnace structure ($E_{l,fs}$);

Q52 is other energy loss ($E_{l,other}$).

C.4.1.2 Formulae for energy saving

a) Available heat ratio

Calculate available heat ratio using Formula (C.17):

$$\eta^* = \left(E_{h,fuel} + E_{h,reex} - E_{ex,oc}\right) / E_{h,fuel} \tag{C.17}$$

Calculate converted available heat ratio using Formula (C.18):

$$\eta_0^* = \left(E_{h,fuel} - E_{ex,oc}\right) / E_{h,fuel} \tag{C.18}$$

b) Effective waste heat recovery ratio

Calculate effective waste heat recovery ratio of sensible heat of exhaust gas from fuel ($E_{ex,oc}$) using Formula (C.19):

$$\eta_R = E_{h,reex} / E_{ex,oc} \quad \text{(C.19)}$$

c) Available heat

Calculate available heat using Formula (C.20):

$$E_{available} = E_{pr,en} + E_l - E_{react,exo} \quad \text{(C.20)}$$

d) Calculation formula of calorific value of fuel ($E_{h,fuel}$)

Calculate calorific value of fuel using Formula (C.21):

$$E_{h,fuel} = E_{available} / \eta^* \quad \text{(C.21)}$$

e) Energy saving ratio (α_{es})

Calculate energy saving ratio using Formula (C.22):

$$\alpha_{es} = \left(1 - \frac{E_{h,fuel\,II}}{E_{h,fuel\,I}} \right) \quad \text{(C.22)}$$

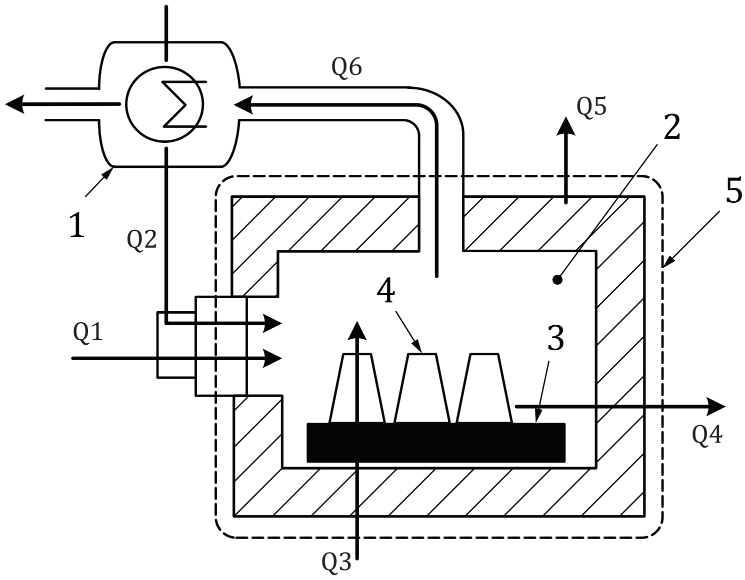
C.4.2 Batch-type heating furnace

C.4.2.1 Heat balance of boundary EB3a

Relation of types of enthalpy in regards to batch-type heating furnace is described as Formula (C.23):

$$E_{h,fuel} + E_{h,reex} = E_{pr,en} + E_{ex,oc} - E_{react,exo} \quad \text{(C.23)}$$

For basic configuration of continuous reheating furnace, see Figure C.2.



Key

1	exhaust gas heat recovery equipment	Q1	calorific value of fuel ($E_{h,fuel}$)
2	heating chamber	Q2	recovery heat from exhaust gas ($E_{h,reex}$)
3	cars, jigs and so on	Q3	heat of oxidization ($E_{react,exo}$)
4	product	Q4	enthalpy change in product ($E_{pr,en}$)
5	boundary (EB3a)	Q5	thermal energy loss (E_l)
		Q6	sensible heat of exhaust gas from fuel ($E_{ex,oc}$)

Figure C.2 — Example of simplified configuration of batch-type heating furnace

Calculate thermal energy loss (Q5) using Formula (C.24):

$$Q5 = Q51 + Q52 + Q53 + Q54 \tag{C.24}$$

where

Q51 is energy loss from furnace structure ($E_{l,fs}$);

Q52 is energy required for heating jigs and other substance ($E_{l,j}$);

Q53 is energy required for heat storage of furnace structure ($E_{l,hs}$);

Q54 is other energy loss ($E_{l,other}$).

C.4.2.2 Formulae for energy saving

a) Available heat ratio

Calculate available heat ratio using Formula (C.25):

$$\eta^* = \left(E_{h,fuel} + E_{h,reex} - E_{ex,oc}\right) / E_{h,fuel} \tag{C.25}$$

Calculate converted available heat ratio using Formula (C.26):

$$\eta_0^* = \left(E_{\text{h,fuel}} - E_{\text{ex,oc}}\right) / E_{\text{h,fuel}} \tag{C.26}$$

b) Effective waste heat recovery ratio

Calculate effective waste heat recovery ratio of sensible heat of exhaust gas from fuel ($E_{\text{ex,oc}}$) using Formula (C.27):

$$\eta_{\text{R}} = E_{\text{h,reex}} / E_{\text{ex,oc}} \tag{C.27}$$

c) Available heat

Calculate available heat using Formula (C.28):

$$E_{\text{available}} = E_{\text{pr,en}} + E_{\text{l}} - E_{\text{react,exo}} \tag{C.28}$$

d) Calculation formula of calorific value of fuel

Calculate calorific value of fuel using Formula (C.29):

$$E_{h,\,fuel} = E_{available} / \eta^* \tag{C.29}$$

e) Energy saving ratio

Calculate energy saving ratio using Formula (C.30):

$$\alpha_{\text{es}} = \left(1 - \frac{E_{\text{h,fuel II}}}{E_{\text{h,fuel I}}}\right) \tag{C.30}$$

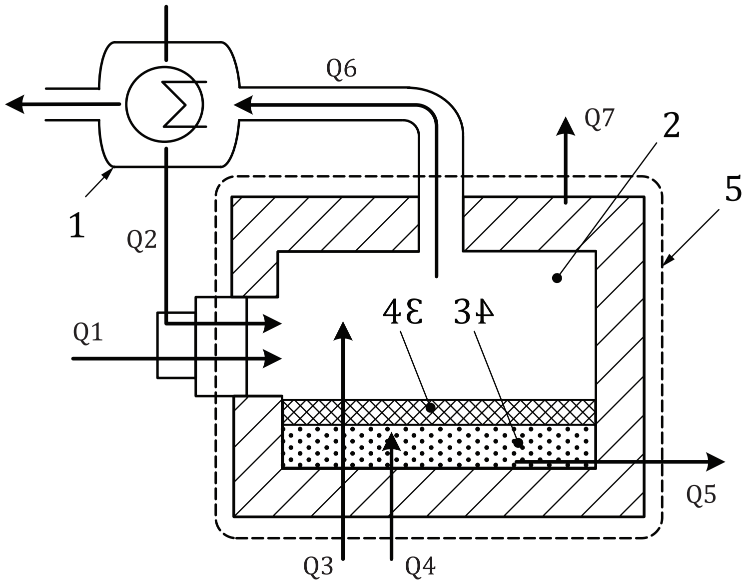
C.4.3 Batch-type melting furnace

C.4.3.1 Heat balance of boundary EB3a

Relation of types of enthalpy in regards to batch-type melting furnace is described as Formula (C.31):

$$E_{\text{h,fuel}} + E_{\text{h,reex}} = E_{\text{pr,en}} + E_{\text{l}} + E_{\text{ex,oc}} - E_{\text{react,exo}(1)} - E_{\text{react,exo}(2)} \tag{C.31}$$

For basic configuration of continuous batch-type melting furnace, see Figure C.3.



Key

1 exhaust gas heat recovery equipment
2 heating chamber
3 product (molten metal)
4 slag
5 boundary (EB3a)

Q1 calorific value of fuel ($E_{h,fuel}$)
Q2 recovery heat from exhaust gas ($E_{h,reex}$)
Q3 heat of oxidization ($E_{react,exo(1)}$)
Q4 combustion heat of waste ($E_{react,exo(2)}$)
Q5 enthalpy change in product ($E_{pr,en}$)
Q6 sensible heat of exhaust gas from fuel ($E_{ex,oc}$)
Q7 thermal energy loss (E_l)

Figure C.3 — Example of simplified configuration of batch-type melting furnace

Calculate thermal energy loss (Q7) using Formula (C.32):

$$Q7 = Q71 + Q72 + Q73 + Q74 \qquad \text{(C.32)}$$

where

Q71 is energy loss from furnace structure ($E_{l,fs}$);

Q72 is energy required for heating jigs and other substance ($E_{l,j(1)}$);

Q73 is energy loss by sensible heat of slag ($E_{l,j(2)}$);

Q54 is other energy loss ($E_{l,other}$).

C.4.3.2 Formulae for energy saving

a) Available heat ratio

Calculate available heat ratio using Formula (C.33):

$$\eta^* = \left(E_{h,fuel} + E_{h,reex} - E_{ex,oc}\right) / E_{h,fuel} \qquad \text{(C.33)}$$

Calculate converted available heat ratio using Formula (C.34):

$$\eta_0^* = \left(E_{\text{h,fuel}} - E_{\text{ex,oc}}\right) / E_{\text{h,fuel}} \tag{C.34}$$

b) Effective waste heat recovery ratio

Calculate effective waste heat recovery ratio of sensible heat of exhaust gas from fuel ($E_{\text{ex,oc}}$) using Formula (C.35):

$$\eta_{\text{R}} = E_{\text{h,reex}} / E_{\text{ex,oc}} \tag{C.35}$$

c) Available heat

Calculate available heat using Formula (C.36):

$$E_{\text{available}} = E_{\text{pr,en}} + E_{\text{l}} - E_{\text{react,exo(1)}} - E_{\text{react,exo(2)}} \tag{C.36}$$

d) Calculation formula of calorific value of fuel

Calculate calorific value of fuel using Formula (C.37):

$$E_{\text{h,fuel}} = E_{\text{available}} / \eta^* \tag{C.37}$$

e) Energy saving ratio

Calculate energy saving ratio using Formula (C.38):

$$\alpha_{\text{es}} = \left(1 - \frac{E_{\text{h,fuel II}}}{E_{\text{h,fuel I}}}\right) \tag{C.38}$$

f) Calculation formula of calorific value of fuel

Calculate calorific value of fuel using Formula (C.39):

$$E_{\text{h,fuel}} = E_{\text{available}} / \eta^* \tag{C.39}$$

g) Energy saving ratio (α_{es})

Calculate energy saving ratio using Formula (C.40):

$$\alpha_{\text{es}} = \left(1 - \frac{E_{\text{h,fuel II}}}{E_{\text{h,fuel I}}}\right) \tag{C.40}$$

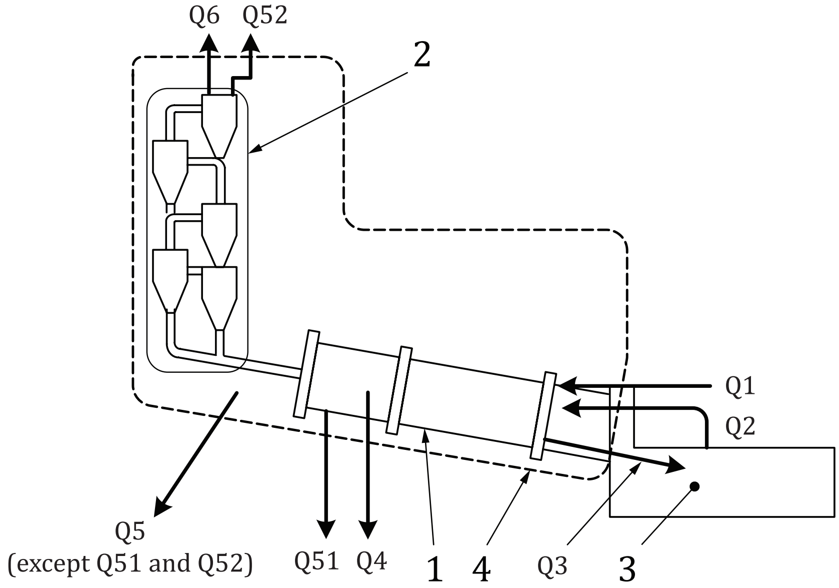
C.4.4 Cement kiln

C.4.4.1 Heat balance of boundary EB3a

Relation of types of enthalpy in regards to cement kiln is described as Formula (C.41):

$$E_{\text{h,fuel}} = E_{\text{pr,en}} + E_{\text{pr,re}} + E_{\text{l}} + E_{\text{ex,oc}} - E_{\text{h,repr}} \tag{C.41}$$

For basic configuration of cement kiln, see Figure C.4:



Key

1	kiln	Q4	energy required for endothermic reaction for heated product ($E_{pr,re}$)
2	preheater of raw material	Q5	thermal energy loss (E_l)
3	cooler of product	Q51	energy loss from furnace structure ($E_{l,fl}$)
4	boundary (EB3a)	Q52	sensible heat of exhaust gas from raw material ($E_{exrm,oc}$)
Q1	calorific value of fuel ($E_{h,fuel}$)	Q6	sensible heat of exhaust gas from fuel ($E_{ex,oc}$)
Q2	recovery heat from product ($E_{h,repr}$)		
Q3	enthalpy change in product ($E_{pr,en}$)		

Figure C.4 — Example of simplified cement kiln

Calculate thermal energy loss (Q5) using Formula (C.42):

$$Q5 = Q51 + Q52 + Q53 \tag{C.42}$$

where

Q51 is energy loss from furnace structure ($E_{l,fs}$);

Q52 is sensible heat of exhaust gas from raw material ($E_{exrm,oc}$);

Q53 is other energy loss ($E_{l,other}$).

C.4.4.2 Formulae for energy saving

a) Available heat ratio

Calculate available heat ratio and converted available heat ratio using Formula (C.43):

$$\eta^* = \eta_0^* = \left(E_{h,fuel} - E_{ex,oc}\right) / E_{h,fuel} \tag{C.43}$$

b) Recovery ratio of sensible heat of product

Calculate recovery ratio of sensible heat of product (η_{rp}) using Formula (C.44):

$$\eta_{\mathrm{rp}} = E_{\mathrm{h,repr}} / E_{\mathrm{pr,en}} \tag{C.44}$$

c) Available heat

Calculate available heat using Formula (C.45):

$$E_{\mathrm{available}} = E_{\mathrm{pr,en}} + E_{\mathrm{l}} - E_{\mathrm{react,exo(1)}} - E_{\mathrm{react,exo(2)}} \tag{C.45}$$

d) Calculation formula of calorific value of fuel

Calculate calorific value of fuel using Formula (C.46):

$$E_{\mathrm{h,fuel}} = E_{\mathrm{available}} / \eta^{*} \tag{C.46}$$

e) Energy saving ratio

Calculate energy saving ratio using Formula (C.47):

$$\alpha_{\mathrm{es}} = \left(1 - \frac{E_{\mathrm{h,fuel\,II}}}{E_{\mathrm{h,fuel\,I}}}\right) \tag{C.47}$$

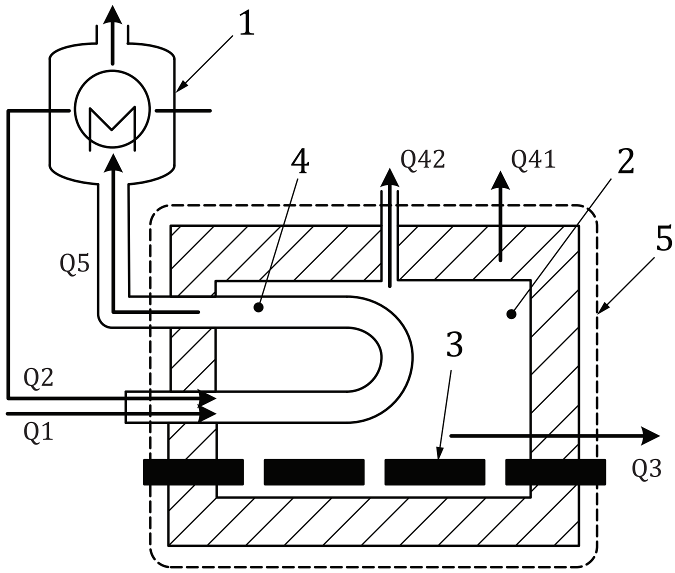
C.4.5 Indirect heating heat treatment furnace

C.4.5.1 Heat balance of boundary EB3a

Relation of types of enthalpy in regards to cement kiln is described as Formula (C.48):

$$E_{\mathrm{h,fuel}} + E_{\mathrm{h,reex}} = E_{\mathrm{pr,en}} + E_{\mathrm{l}} + E_{\mathrm{ex,oc}} \tag{C.48}$$

For basic configuration of indirect heating heat treatment furnace see Figure C.5.



Key

1	exhaust gas heat recovery equipment	Q1	calorific value of fuel ($E_{h,fuel}$)
2	heating chamber	Q2	recovery heat from exhaust gas ($E_{h,reex}$)
3	product	Q3	enthalpy change in product ($E_{pr,en}$)
4	indirect heating equipment (radiant tube)	Q4	thermal energy loss (E_l)
5	boundary (EB3a)	Q41	energy loss from furnace structure ($E_{l,fl}$)
		Q42	energy loss by atmosphere gas ($E_{l,atm}$)
		Q5	sensible heat of exhaust gas from fuel ($E_{ex,oc}$)

Figure C.5 — Example of simplified indirect heating heat treatment furnace

Calculate thermal energy loss (Q4) using Formula (C.49):

$$Q4 = Q41 + Q42 + Q43 \qquad \text{(C.49)}$$

where

Q41 is energy loss from furnace structure ($E_{l,fs}$);

Q42 is energy loss by atmosphere gas ($E_{l,atm}$);

Q43 is other energy loss ($E_{l,other}$).

C.4.5.2 Formulae for energy saving

a) Available heat ratio

Calculate available heat ratio using Formula (C.50):

$$\eta^* = \left(E_{h,fuel} + E_{h,reex} - E_{ex,oc}\right) / E_{h,fuel} \qquad \text{(C.50)}$$

Calculate converted available heat ratio using Formula (C.51):

$$\eta_0^* = \left(E_{h,fuel} - E_{ex,oc}\right) / E_{h,fuel} \qquad \text{(C.51)}$$

b) Effective waste heat recovery ratio

Calculate effective waste heat recovery ratio of sensible heat of exhaust gas from fuel ($E_{ex,oc}$) using Formula (C.52):

$$\eta_R = E_{h,reex} / E_{ex,oc} \tag{C.52}$$

c) Available heat

Calculate available heat using Formula (C.53):

$$E_{available} = E_{pr,en} + E_l \tag{C.53}$$

d) Calculation formula of calorific value of fuel ($E_{h,fuel}$)

Calculate calorific value of fuel using Formula (C.54):

$$E_{h,fuel} = E_{available} / \eta^* \tag{C.54}$$

e) Energy saving ratio (α_{es})

Calculate energy saving ratio using Formula (C.55):

$$\alpha_{es} = \left(1 - \frac{E_{h,fuel\,II}}{E_{h,fuel\,I}} \right) \tag{C.55}$$

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