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EXERGY ANALYSIS OF A BAKERY STOVE

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Abstract. Exergy analysis of a bakery stove, carried out with the use of exergy balance of this object was presented in the paper. With the use of balance data, assessment of internal and external exergy losses during baking process in the four-chamber cyclometric stove, used for baking a wide assortment of bakery products, was carried out. The obtained calculation results showed that the internal exergy loss constitutes 41.04% of exergy supplied to the system and the external – 58.89%. Those values are the measure of the quality of energy, which may be recovered and used for heating purposes or may be subjected to conversion into other forms of energy. It concerns, as a rule, the loss of external exergy because the internal one was dispersed.

Key words: bakery stove, exergy, internal loss of exergy, external loss of exergy

Introduction

Food industry is one of economy branches included to energy-consuming. These are mainly food processing establishments based on thermal processes. Bakery industry also belongs to them. In bakery and confectionery processes approx. 12.5% of the total energy used by food industry is consumed (Ambroziak and Grabusiński, 1993). In a bakery, bakery stoves, chambers of final fermentation, mixing machines and lines for cutting and packing bread are consumers of energy, which is delivered mainly in the form of heat are (Wojalski, 1992).

Energy balances are mainly used to analyse energy processes (Ho et al., 1986; Krzysztofik and Łapczyńska-Kordon, 2008), which do not allow full assessment of the process, because energy is not consumed but undergoes conversion from one form into another. Therefore, the quality, not the amount of energy, is changed.

Assessment of the energy quality may be carried out with the use of exergy analysis or analysis of the processes. It is based on the second principle of thermodynamics, according to which, macroscopic changes are irreversible. Irreversibility of thermal processes (generating entropy) has a disadvantageous effect on their efficiency. Theoretical quantity determination of this effect is possible with the use of entropy and exergy, which is defined as the "maximum efficiency of the discussed portion of energy for execution of work with the use of heat collected from the surrounding and commonly occurring and independent elements of the surrounding" (Szargut, 2007). Since exergy is not subject to the conservation law, therefore irreversible change results in irrevocable loss of exergy expressed with the Gouy-Stodoli law.

Only few processes of food industry were subjected to exergy analysis. It mainly covered processes of drying agro-food products (Aghbashlo et al., 2013; Akpinar, 2004; Colak and Hepbasli, 2006; Tekin and Bayramoglu, 2001). Those analysis concerned exergy efficiency and losses of internal and external exergy. Their results made selection of proper parameters of the process possible and moreover allowed indication of efficient ways of waste energy management.

Similar analysis for bakery establishments would allow the improvement of energy efficiency of the baking process. The main energy consumer in these establishments is a bakery stove, in which energy is subject to irreversible changes. A considerable part of this energy is introduced to the surrounding and lost irrevocably. Thus, the paper attempts to carry out exergy analysis of the bakery stove on account of internal and external exergy losses and exergy efficiency of a stove.

Research methodology

The analysis was carried out for a bakery stove, which constitutes equipment of "DANEK" bakery in Nowy Sącz. It is a cyclometric four-chamber stove for baking a wide assortment of products.

Energy in the form of heat, supplied to the stove, is obtained through combustion of gas fuel (conversion of chemical energy included in the gas fuel into energy transmitted in the form of heat).

The principle of the stove operation is presented in figure 1.

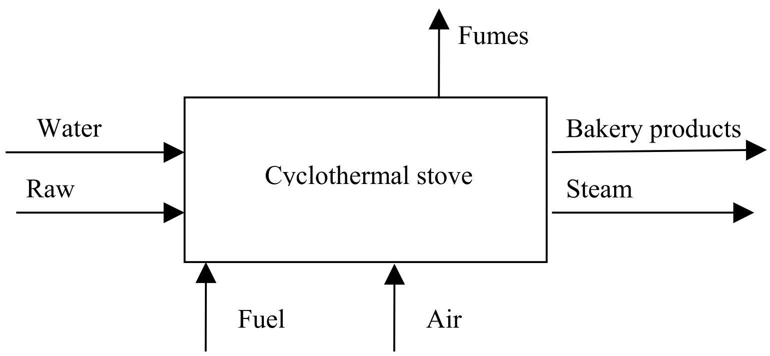

Figure 1. Schematic representation of functioning of a bakery stove as a thermodynamic system

Exergy balance

Thermodynamic system, consisting of four baking chambers of the stove was separated for exergy analysis with the use of balance shield, It was assumed that for simplification of balance calculations, a thermodynamic system is composed of one baking chamber, which replaces four. The remaining elements of the stove equipment were treated as the surrounding.

Exergy is delivered to this system with fuel, air and water, raw material for baking and diverted with bakery products, fumes and steam. It was also assumed that the stove constitutes an open thermodynamic system.

General exergy balance for the separate thermodynamic system is described by the following equation (Szargut, 2007):

$$B_d = B_{wu\dot{z}} + \Delta B_{\dot{z}r} + \delta B_{d-w} + \delta B_z \tag{1}$$

where: B_d – exergy supplied to the system ($J \cdot s^{-1}$).

Exergy is introduced with substances (fuel – 1, air – 2, water – 3, raw materials – 4 which enter the system through the control shield):

$$B_d = \sum_i \dot{m}_i b_{fdi} + \sum_i \dot{m}_i b_{chdi} \tag{2}$$

where:

m_{di} – streams of substances which cut the balance shield ($kg \cdot s^{-1}$),

b_{fdi} – unit physical exergies of substances ($kJ \cdot kg^{-1}$),

$$b_{fdi} = h_{di} - h_{ot} - T_{ot}(s_{di} - s_{ot}) \tag{3}$$

where:

h_{di} – specific physical enthalpy *i*- substances for parameters of the stove operation ($kJ \cdot kg^{-1}$),

h_{di} – specific physical enthalpy *i*- substances for parameters of the surrounding ($kJ \cdot kg^{-1}$),

s_{di} – specific entropy of *i*- substances for parameters of the stove operation ($kJ \cdot kg^{-1} \cdot K^{-1}$),

s_{di} – specific entropy of *i*- substances for parameters of the surrounding ($kJ \cdot kg^{-1} \cdot K^{-1}$),

T_{ot} – temperature of the surrounding (K),

b_{chd} – unit chemical exergy of fuel ($kJ \cdot kg^{-1}$).

$$b_{chd} = \sum_{i=1}^{4} \frac{M_i}{M_m} r_i (b_{chi} + \frac{MR}{M_i} T_n \ln(\frac{M_i}{M_m} r_i)) \tag{4}$$

where:

M_i, M_m – molecular weight of the selected element and mixture (kg·kmol^{-1}),
r_i – volumetric participation of the component (-),
Mb_{chi} – chemical exergy (kJ·kg^{-1}),
MR – universal gas constant, MR=8.315 (kJ·kg^{-1}·K^{-1}),
T_n – temperature in normal conditions (K).

In case of the analysed system, exergy conducted is equal to chemical exergy of fuel. Physical exergy of delivered streams is zero because their temperatures and pressures are equal to the parameters of the surrounding.

$B_{wu\dot{z}}$ – exergy of delivered products (baking):

$$B_{wu\dot{z}} = \dot{m}_{pr} \left(h_{pr} - h_{ot} - T_{ot} \left(s_{pr} - s_{ot} \right) \right) \tag{5}$$

where:

$\dot{m}_{pr}$ – stream of products going out of the stove (kg·s^{-1}),
h_{pr} – unit enthalpy of products (kJ·kg^{-1}),
s_{pr} – unit entropy of a product (kJ·kg^{-1}·K^{-1}),
$\Delta B_{\acute{z}r}$ – increase of exergy of the external source of heat acting at the balance shield of the system:

$$\Delta B_{\acute{z}r} = -\dot{m}_{pal} Q_w \frac{T - T_{ot}}{T} \tag{6}$$

where:

W_u – calorific value (kJ·kg^{-1}),
$\dot{m}_{pr}$ – fuel stream (kg·s^{-1});
$\delta B_{d\text{-}w}$ – internal loss of exergy calculated based on the balance;

$$\delta B_{d-w} = B_d - B_u - \Delta B_{\acute{z}r} - \delta B_z \tag{7}$$

δB_z – external loss of exergy of waste substances (fumes –1, steam – 2):

$$\delta B_z = \sum_i \dot{m}_{wi} b_{fwi} + \dot{m}_{w1} b_{chw1} \quad i=1,2 \tag{8}$$

where:

m_{di} – streams of substances which cut the balance shield (kg·s^{-1}),
b_{fwi} – unit physical exergies of substances (kJkg^{-1}),
b_{chwi} – unit chemical exergy of fumes (kJ·kg^{-1}).

External loss of exergy is a sum of two waste streams: physical exergy of steam and physical and chemical exergy of fumes.

After including the stream of reaching and leaving substances from the separated thermodynamic system and their parameters (tab. 1), balance of stove exergy was described with the following equation:

$$\delta B_w = \dot{m}_1 b_{ch1} - \dot{m}_{pr}\left(h_{pr} - h_{ot} - T_{ot}\left(s_{pr} - s_{ot}\right)\right) - W_u B\frac{T - T_{ot}}{T} - \sum_{i=1,2}\dot{m}_{wi} b_{fwi} - \sum_{i=1,2}\dot{m}_{wi} b_{chwi} \qquad (9)$$

Balance calculations were carried out for data included in table 1. It was assumed that temperature of leaving substances to the thermodynamic system (stove) is equal to the temperature of surrounding.

Table 1
Data for calculating exergy balance

Specification	Symbols	Unit	Value
Baking surface	P w	(m^2)	6
Distribution of bites	q	(szt.m^{-2})	16
Temperature in a stove	T we	(ºC)	270
	T wy	(ºC)	27
Mass of a bite	m_k	(kg)	0.65
Mass of bread	m_{ch}	(kg)	0.57
Specific heat of a stove	c p	(kJ·kg^{-1} ºC^{-1})	1.3
Temperature of bread taken out of the stove	t_{pr}	(ºC)	95
Temperature of a bite when placed in the stove	t_{d4}	(ºC)	27
Specific enthalpy of water	h_{ot}	(kJ·kg^{-1})	246
Specific enthalpy of steam	h_w	(kJ·kg^{-1})	2,793
Water consumption	$\dot{m}_{d3}$	(kg·s^{-1})	0.16
Fuel consumption	$\dot{m}_{pr}$	(m^3·s^{-1})	0.0069
Calorific value of fuel	Q_w	(kJ·kg^{-1})	22.86
Specific heat of gas	c_g	(kJ·kg^{-1} K^{-1})	2.17
Composition of fuel	CH_4	(%)	96.54
	CO_2	(%)	0.04
	N_2	(%)	2.25
	C_2H_4	(%)	1.17
	λ	(–)	1.1
Temperature of fumes	ts	(ºC)	250
Temperature of the surrounding	t_{ot}	(ºC)	27

The remaining parameters, such as chemical entropy, density, specific heat of fuel components and fumes and steam were determined based on thermodynamic charts (Raźnjević, 1966).

Analysis of the calculation results

Calculated values of exergy streams of particular components of balance were presented in table 2.

Table 2

The set of values of particular components of the exergy balance of the baking stove

ENTRANCE (supply of exergy)	($kJ \cdot s^{-1}$)	EXIT (diverting exergy)	($kJ \cdot s^{-1}$)
Exergy supplied to the system	1092.78 (79.9%)	Exergy of diverted products	0.0092 (0.07%)
		Internal loss of exergy	561.07 (41.04%)
Increase of exergy of external heat source	274.46 (20.1%)	External loss of exergy	806.16 (58.89%)

For comparison, exergy streams were presented on the plot: supplied exergy, diverted exergy with products and losses: internal and external fig. 2). The highest values on the outlet from the system obtained exergy losses - internal and external. Exergy of diverted products obtained a slight value in comparison to sizes of other streams, thus it will probably be a very low exergy efficiency of a stove.

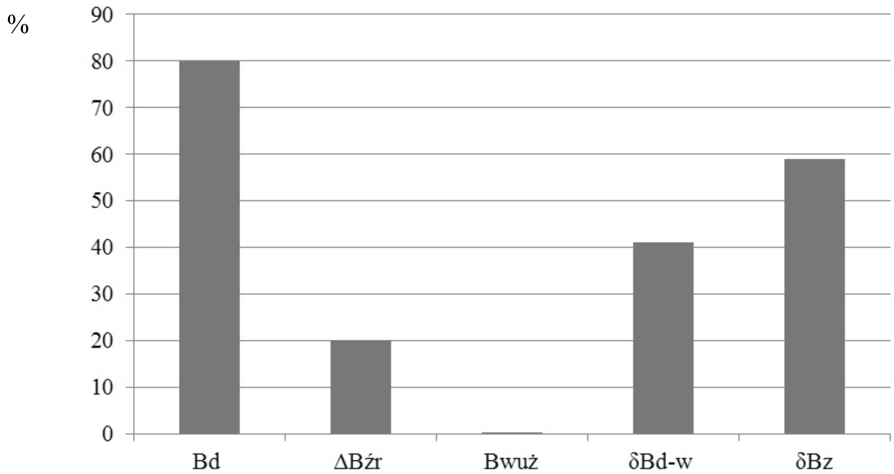

Figure 2. A plot presenting participation of particular balance components for the analysed baking stove

Analysing results of balance calculations it was proved that exergy of diverted products, that is bakings is 0.07%. Change of the exergy of the source with reference to exergy supplied was 20.1%. The highest percentage with reference to exergy supplied to the system constituted: internal loss of exergy – 41.04$ and external loss – 58.89%. With the use of these sizes, assessment of the quality of exergy in the aspect of further usefulness is carried out. Values of these losses may be decreased through the use of energy included in the carriers, which divert from the system (stove).

Decrease of the internal loss of exergy is not easy, because it is related to irreversible changes of energy in the system. Whereas, the size of exergy loss informs on possible uses of energy included in factors diverted from the system. These possibilities may be varied, for example the use of the exchanger system for heating air supplied to the furnace, heating utility water, generating steam.

Summary and conclusions

Exergy analysis of the baking stove allowed assessment of the usefulness of the energy stream, which is subject to changes inside the system and introduced to the surrounding. Internal changes of exergy are difficult to recover due to energy changes which take place inside the system. Whereas, exergy of a stream diverted outside the system, called an external loss of exergy informs on the possibility of recovering energy through ability to perform maximum work by the stream which is its carrier with reference to the parameters of the surrounding. Based on balance calculations it was found out that:

– exergy of baked products was considerably lower than the exergy of internal and external losses,
– internal and external losses were comparable – external losses constituted higher percentage participation,

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ANALIZA EGZERGETYCZNA PIECA PIEKARNICZEGO

Streszczenie. W pracy przedstawiono analizę egzergetyczną pieca piekarniczego, przeprowadzoną za pomocą bilansu egzergetycznego tego obiektu. Wykorzystując dane bilansowe przeprowadzono ocenę strat egzergii wewnętrznej i zewnętrznej podczas procesu wypieku w piecu cyklometrycznym, czterokomorowym, stosowanym do wypieku szerokiego asortymentu produktów piekarniczych. Otrzymane wyniki obliczeń pokazały, że wewnętrzna strata egzergii stanowi 41,04% egzergii doprowadzonej do układu, a zewnętrzna – 58,89%. Wartości te są miarą jakości energii, którą można odzyskać i wykorzystać do celów grzewczych lub poddać konwersji na inne postacie energii. Dotyczy to w zasadzie straty zewnętrznej egzergii, ponieważ wewnętrzna ulega rozproszeniu.

Słowa kluczowe: piec piekarniczy, egzergia, strata wewnętrzna egzergii, strata zewnętrzna egzergii

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