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FUEL ECONOMY AT THE HEAT TREATMENT FURNACES OF STEEL CAST PIECES

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ABSTRACT

The paper presents a study made at the annealing furnaces for homogenization of cast pieces regarding the replacement of marsh gas with blast furnace gas, in a proportion of 100%. In this way an important economy of marsh gas is achieved, representing a special interest because its international deficit and its putting up the price.

KEYWORDS : blast furnace gas, oxygen, fuel economy

1. Introduction

At present, in Mixed Foundry of Mittal Steel Iron and Steel Works at Galati, at the heat treatment furnaces of steel moulded pieces, the marsh gas is used as fuel [1-3] which is, as we know, an expensive and defficitary fuel. On the other hand in many foundries, as is the case of the above mentioned one, there are fuel wastes such as coke gas or furnace gas.

The paper presents a study made at the annealing furnaces of the steel moulded pieces homogenization regarding the replacement of marsh gas with furnace gas in a 100% proportion. Thus an important economy of march gas is obtained. The provision that has to be complied with is that the same amount of heat as in the case of the replaced marsh gas should be obtained in the working space of the furnace, in the different options of fuel utilization. In order to achieve that, in the case of the combustion of the blast furnace gas to a 100% degree, the using of oxygen-enriched air during combustion has to be done. In this paper the concentration of oxygen in the oxygen-enriched air is determined in the case of the hundred percent combustion of furnace gas.

2. Technical characteristics of the annealing furnaces of the steel moulded pieces homogenization

- The furnace capacity (pieces + supports), C=75t;
- The bedstone surface, S_V=32 m^2.
- The maxim piece temperature, t_m=1100 ^{0}C;

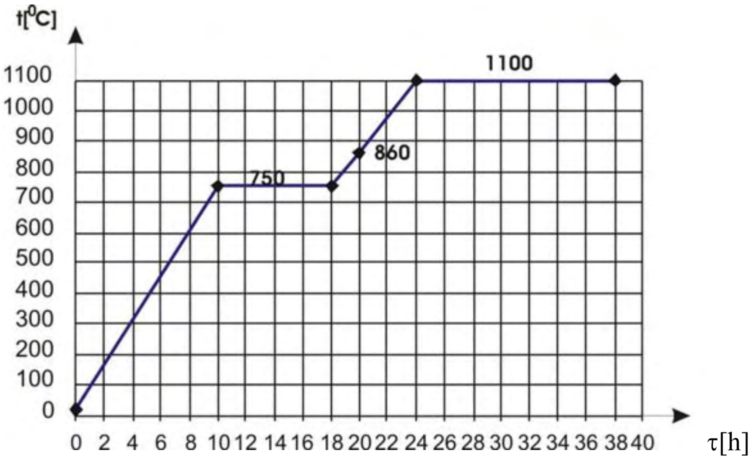

***Fig.1.** The diagram of the steel moulded pieces heating in the homogenizing annealing furnaces*

- The furnace temperature (technological), $t_{tech}=t_m+(100\text{-}150)^0C$;
- The burning unit:
  12 burners x 50 Nm^3/h
  12 burners x 20 Nm^3/h
- Marsh gas consumption, D_{CH_4} =400 Nm^3/h;
- The cycle duration, τ_{cycle}=38h;
- The heating diagram (see fig.1).

3. The calculus of the fuel burning

The burning calculus is made in two varieties, namely marsh gas and furnace gas in a 100% proportion, respectively.

The calculus relations are the following [4]:
- the fuel chemical composition:

$$CH_4+CO+H_2+CO_2+O_2+N_2+H_2O=100\ \%$$
$$[CH_4]+[CO]+[H_2]+[CO_2]+[O_2]+[N_2]+[H_2O]=1Nm^3 \qquad (1)$$

- the inferior calorific power H_i, in [kJ/Nm^3 fuel]:

$$H^i = [CH_4]\cdot H_i^{CH_4} + [CO]\cdot H_i^{CO} + [H_2]\cdot H_i^{H_2} \qquad (2)$$

where:
$[CH_4]$,$[CO]$,$[H_2]$- the quantities of the combustion elements, in [Nm^3/Nm^3 fuel];
$H_i^{CH_4}, H_i^{CO}, H_i^{H_2}$ = inferior calorific powers of the combustion elements, in [kJ/Nm^3];

$$H_i^{CH_4} = 35500\ kJ/Nm^3$$
$$H_i^{CO} = 12740\ kJ/Nm^3$$
$$H_i^{H_2} = 12765\ kJ/Nm^3$$

- the minimum amount of oxygen necessary for the combustion, O_2^{min}, in [Nm^{3}O$_2$/Nm^3 fuel]

$$O_2^{min} = 2[CH_4] + \frac{1}{2}[CO] + \frac{1}{2}[H_2] - [O_2] \qquad (3)$$

-the theoretic air necessary for the combustion, L_0, in [Nm^{3}air/Nm^3 fuel]:

$$L_0 = \frac{100}{21}\cdot O_2^{min} \qquad (4)$$

- the real air used for the combustion, L_r, in [Nm^{3}O$_2$/Nm^3 fuel]:

$$L_r=\lambda L_0$$

where:
λ – the coefficient of excess air; the adopted value: λ=1.05

-the quantity of the burned gases, V_{ga}, in [Nm ga/Nm^3 fuel]:

$$V_{ga} = V_{CO_2} + V_{H_2O_{vap}} + V_{N_2} + V_{O_2excess} \qquad (5)$$

where:

$$V_{CO_2} = [CO_2]+[CH_4]+[CO]$$
$$V_{H_2O_{vap}} = 2[CH_4]+[H_2]+[H_2O]$$
$$V_{N_2} = 0.79L_r+[N_2]$$
$$V_{O_2excess} = 0.21(L_r - L_0)$$

-the participations of the component elements of the burned gases, r_i :

$$r_{CO_2} = \frac{V_{CO_2}}{V_{ga}} \qquad (6)$$
$$r_{H_2O_{vap}} = \frac{V_{H_2O_{vap}}}{V_{ga}}$$
$$r_{N_2} = \frac{V_{N_2}}{V_{ga}}$$
$$r_{O_2excess} = \frac{V_{O_2excess}}{V_{ga}}$$
$$\sum_{i=1}^{4} r_i = 1$$

-the real burning temperature [4], t_r, [^{0}C]:

$$t_r = \eta_{pyr}\frac{0.98\cdot H_i}{V_{ga}\cdot c_{ga}} \qquad (7)$$

where:
η_{pyr} - the pyrometric efficiency; the adopted value η_{pyr}=0.7;
H^i – the inferior calorific power, [kJ/Nm^3 fuel];
V_{ga} – the volume of the burned gases, [Nm^3/Nm^3 fuel],
c_{ga} – the specific heat of the burned gases [kJ/Nm^{3}grd].

-the specific heat of the burned gases c_{ga}, [kj/Nm^{3}grd]:

$$c_{ga} = \sum_{i=1}^{4} c_i \cdot r_i \qquad (8)$$

where:
c_i – the specific heats of the components of the burned gases, which are tabelled as a function of temperature. The adopted value for the temperature of

the burned gases is $t_r = 1000\ ^0C$ and $c_{ga}^{1000\ ^0C}$ can be calculated using the values:

$$c_{CO_2}^{1000\ ^0C} = 2.2035 \text{ kJ/Nm}^3\text{grd}$$

$$c_{H_2O_{vap}}^{1000^0C} = 1.7229 \text{ kJ/Nm}^3\text{grd}$$

$$c_{N_2}^{1000^0C} = 1.3917 \text{ kJ/Nm}^3\text{grd}$$

$$c_{O_2}^{1000^0C} = 1.4775 \text{ kJ/Nm}^3\text{grd}$$

It results:

3.1. The burning of the marsh gas

$$c_{ga}^{1000^0C} = 0.091 \cdot 2.2035 + \\ + 0.182 \cdot 1.7229 + 0.717 \cdot 1.3917 + \\ + 0.01 \cdot 1.4775$$

$$c_{ga}^{1000^0C} = 1.529 \text{ kJ/Nm}^3\text{grd}$$

$$t_r = \frac{0.7 \cdot 0.98 \cdot 35500}{11 \cdot 1.529} = 1447.9\ ^oC \cong 1448\ ^oC$$

$$error = \frac{t'_r - t_r}{t'_r} 100 = \\ = \frac{1448 - 1000}{1448} 100 = 30.9\% >> 5\%$$

With the admitted error of 5%, $c_{ga}^{1448^0C}$ is calculated, by determining the specific heats of the components by interpolation, as a function of their values at the temperatures of 1400 ^{0}C and 1500 ^{0}C.

$$c_{CO_2}^{1448^0C} = 2.3136 + \frac{48 \cdot 0.0218}{100} = 2.324$$

$$c_{H_2O}^{1448^0C} = 1.828 + \frac{48 \cdot 0.0247}{100} = 1.8398$$

$$c_{N_2}^{1448^0C} = 1.4348 + \frac{48 \cdot 0.0092}{100} = 1.4392$$

$$c_{O_2}^{1448^0C} = 1.5203 + \frac{48 \cdot 0.0091}{100} = 1.5246$$

$$c_{ga}^{1448^0C} = 0.091 \cdot 2.324 + 0.182 \cdot 1.8398 + \\ + 0.717 \cdot 1.4392 + 0.01 \cdot 1.5246$$

$$c_{ga}^{1448^0C} = 1.593 \text{ kJ/Nm}^3\text{grd}$$

$$t''_r = \frac{0.7 \cdot 0.98 \cdot 35500}{11 \cdot 1.593} = 1389.7 \cong 1390^0C$$

$$error = \frac{1390 - 1448}{1390} 100 = -4\% < -5\%$$

$$t_r^{CH_4} = 1390\ ^oC$$

3.2. The burning of the furnace gas

$$c_{ga}^{1000^0C} = 0.2571 \cdot 2.2035 + 0.056 \cdot 1.7229 + \\ + 0.6824 \cdot 1.3917 + 0.0045 \cdot 1.4775 = 1.619$$

$$t'_r = \frac{0.7 \cdot 0.98 \cdot 3716}{1.581 \cdot 1.619} = 995.9 \cong 996^oC$$

$$error = \frac{996 - 1000}{996} 100 = -0.4\%$$

$$t_r^{GF} = 996^oC$$

The thermodynamic parameters at the burning with atmospheric air of the marsh gas or furnace gas respectively, and the chemical composition of the fuel are given in Tables 1 and 2.

The thermodynamic parameters at the burning with atmospheric air

Table 1

Fuel	The chemical composition of the fuel [%]								The calorific power, H_i [kJ/Nm^3]	O_2^{min} [Nm^3/ Nm^3 fuel]
	CH_4	CO	H_2	CO_2	O_2	N_2	H_2O	Tot.		
Marsh gas	100	-	-	-	-	-	-	100	35500	2
Furnace gas	0.20	22.45	6.15	18.00	0.20	50.70	2.30	100	3716	0.145

Table 2

Fuel	L_0 [Nm^3/Nm^3 fuel]	L_r [Nm^3/Nm^{3}fuel]	V_{ga} [Nm^3/Nm^3 fuel]					Participations in the burned gases, r_i					Burning temp.
			V_{CO_2}	V_{H_2O}	V_{N_2}	$V_{O_{2ex}}$	Tot.	r_{CO_2}	r_{H_2O}	r_{N_2}	$r_{O_2\,ex}$	Tot.	
Marsh gas	9.52	9.996	1	2	7.89	0.1	11	0.091	0.182	0.717	0.01	1	1390
Funace gas	0.690	0.724	0.4065	0.0885	0.0789	0.0071	1.581	0.2571	0.0560	0.6824	0.0045	1	996

4. Study regarding the utilization of the furnace gas in a proportion of a hundred percent at burning

As it results from § 3.2. the burning temperature of the furnace gas with atmospheric air is 996 ^{0}C. The technological process of the homogenizing annealing furnace neccessitates an optimal temperature in the working space of 1200-1250 ^{0}C.

A method to increase the burning temperature is the utilization, at burning, of the oxygen enriched air.

The oxygen concentration in the enriched air (fig. 2) is calculated with the relation [5]:

$$x=\frac{\lambda\left\{\frac{1}{2}[CO]+\frac{1}{2}[H_2]+2[CH_4]-[O_2]\right\}}{\frac{\eta_{pyr}\cdot 0.98\cdot H_i}{t_f\cdot c_{ga}}-\frac{1}{2}[CO]-[CH_4]-[CO_2]-[H_2O]-[N_2]-\frac{1}{2}[H_2]-[O_2]} \qquad (9)$$

considering $t_f = t_m+150=1250\ ^0C$.

$c_{ga}^{1250^0C}$ is calculated as follows,

$$c_{ga}^{1250^0C}=\sum_{i=1}^{4} r_i\cdot c_i$$

using the values:

$$c_{CO_2}^{1250^0C}=2.2768$$

$$c_{H_2Ovap}^{1250^0C}=1.7898$$

$$c_{N_2}^{1250^0C}=1.4197$$

$$c_{O_2}^{1250^0C}=1.5055$$

$$c_{ga}^{1250^0C}=0.2571\cdot 2.2768+0.056\cdot 1.7898+0.6824\cdot 1.4197+0.0045\cdot 1.5055=1.661$$

$$x=\frac{1.05\left(\frac{1}{2}0.2245+\frac{1}{2}0.0615+2\cdot 0.002-0.002\right)}{\frac{0.7\cdot 0.98\cdot 3716}{1250\cdot 1.661}-\frac{1}{2}0.2245-0.002-0.18-0.023-0.507-\frac{1}{2}0.0615-0.002}$$

$$x=\frac{1.050\cdot 0.145}{1.2277-0.857}=0{,}41$$

For $t_f = t_m+100=1200\ ^0C$

$$c_{CO_2}^{1200^0C}=2.2638$$

$$c_{H_2Ovap}^{1200^0C}=1.7769$$

$$c_{N_2}^{1200^0C}=1.4143$$

$$c_{O_2}^{1200^0C}=1.5005$$

$$c_{ga}^{1200^0C}=0.2571\cdot 2.2638+0.056\cdot 1.7769+$$
$$+0.6824\cdot 1.4143+0.0045\cdot 1.5005=1.652$$

and

$$x=\frac{1.05\cdot 0.145}{1.285-0.857}=0.355$$

For $t_m = 860\ ^0C$, $t_f = 860+150=1010\ ^0C$

$$x = \frac{1.05 \cdot 0.145}{1.558 - 0.857} = 0.217$$

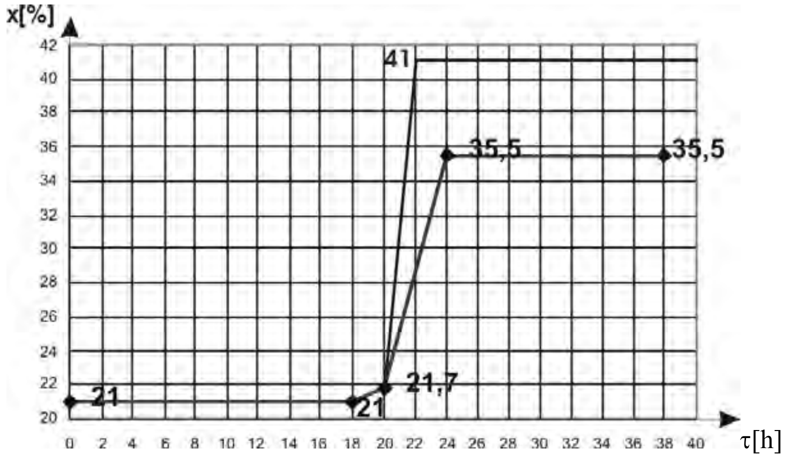

Fig.2. *The oxygen concentration in the enriched air in the case of the furnace gas burning.*

5. Economic efficiency

The costs are the following:

CH_4 = 189.18 USD/1000 Nm^3
GF = 13.55 USD/1000 Nm^3
Oxygen = 86.15 USD/1000 Nm^3
Air = 7.68 USD/1000 Nm^3

5.1. The case of the marsh gas burning

Using the values of the average flowrates of marsh gas taken from Fig. 3, the costs are calculated as following:

a) during the period τ_1=(0-10) h

D_{CH_4} = 135 Nm^3/h

$D_{air} = L_r\, D_{CH_4}$

$$D_{air} = 9.996 \cdot 135 = 1349.5 \text{ Nm}^3/\text{h}$$

$$C_1 = 135 \cdot \frac{189.18}{1000} + 1349.5\frac{7.68}{1000} = \\ = 35.9 \text{ USD/h}$$

b) during the period τ_2=(10-14) h

D_{CH_4} = 245 Nm^3/h

$$D_{air} = 9.996 \cdot 245 = 2449 \text{ Nm}^3/\text{h}$$

$$C_2 = 245 \cdot \frac{189.18}{1000} + 2449\frac{7.68}{1000} = 65.15 \text{ USD/h}$$

c) during the period τ_3=(14-24) h

D_{CH_4} = 330 Nm^3/h

$$D_{air} = 9.996 \cdot 330 = 3298.7 \text{ Nm}^3/\text{h}$$

$$C_3 = 330 \cdot \frac{189.18}{1000} + 3298.7\frac{7.68}{1000} = \\ = 87.76 \text{ USD/h}$$

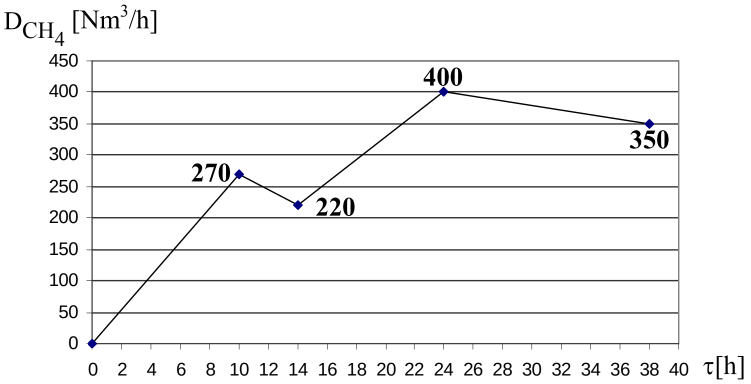

Fig.3. *The variation of the marsh gas flowrate as a function of the treatment duration, in conformity with the exploitation data.*

d) during the period τ_4=(24-38) h

D_{CH_4} = 375 Nm^3/h

$$D_{air} = 9.996 \cdot 375 = 3748.5 \text{ Nm}^3/\text{h}$$

$$C_4 = 375 \cdot \frac{189.18}{1000} + 3748.5 \frac{7.68}{1000} =$$
$$= 99.72 \text{ USD/h}$$

The total cost is:

$$C_{CH_4} = \sum_{i=1}^{4} C_i \tau_i$$

$$C_{CH_4} = 35.9 \cdot 10 + 65.15 \cdot 4 + 87.76 \cdot 10 + 99.72 \cdot 14 =$$
$$= 2893.28 \text{ USD/cycle}$$

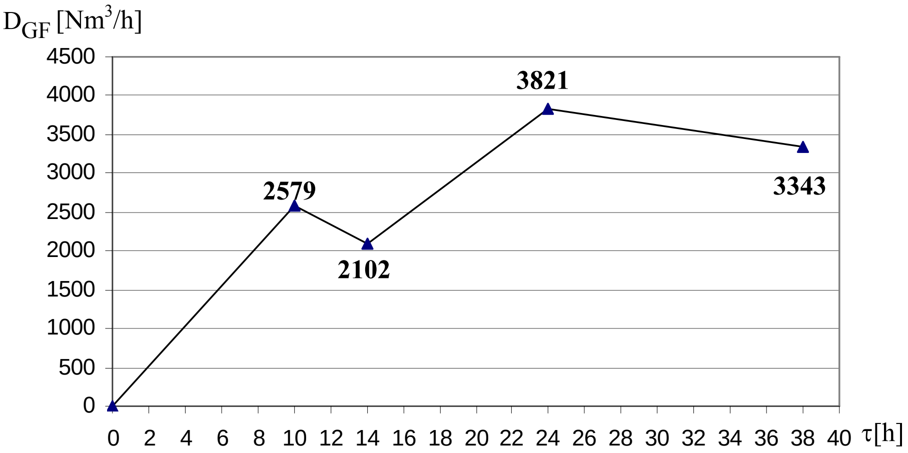

Fig.4. *The variation of the furnace gas flowrate as a function of the treatment duration, determined from the calculations.*

5.2. The case of the furnace gas burning

The values of the furnace gas flowrates in Fig. 4 have been calculated with the relation [6]:

$$D_{GF} = D_{CH_4} \frac{H_i^{CH^4}}{H_i^{GF}} \qquad (10)$$

where:

D_{GF}, D_{CH_4} - the flowrates of the marsh gas and the furnace gas, respectively, in[Nm^3/h];

$H_i^{CH^4}, H_i^{GF}$ -the calorific powers, [kJ/Nm^3].

a) For τ_1=18h burning of the furnace gas with atmospheric air, the average flowrate of furnace gas, calculated in conformity with Fig. 4, is:

$$D_{GF} = 1780 \frac{Nm^3}{h}$$

and using the value

L_r=0.724 Nm^{3}air/Nm^{3}GF

the cost is:

$$C_1 = \left(1780 \frac{13.55}{1000} + 0.724 \cdot 1780 \frac{7.68}{1000}\right) 18 =$$
$$= 612.16 \text{ USD}$$

b) In the case of the furnace gas burning with oxygen enriched air:

- the oxygen enriched air L’$_r$,[Nm^3/Nm^3 fuel] is:

$$L_r' = \frac{100}{x} O_2^{min} \qquad (11)$$

where x is oxygen concentration [%];

- the flowrate of the oxygen enriched air, D'_{air}, in [Nm^3/Nm^3 fuel] is [6]:

$$D'_{air} = D_{GF} L'_r \qquad (12)$$

$$\begin{cases} D'_{air} = D_{O_2} + D_{air} \\ x = \dfrac{D_{O_2} + 0.21 \cdot D_{air}}{D_{O_2} + D_{air}} \end{cases} \qquad (13)$$

It results:

$$\begin{cases} D_{air} = \dfrac{D'_{air}(1-x)}{0.79} \\ D_{O_2} = \left(\dfrac{x - 0.21}{0.79}\right) D'_{air} \end{cases} \qquad (14)$$

- For the range τ_2=(18-24)h, it is considering an average oxygen concentration in air x=30%, and an average value for the furnace gas flowrate of

$$D_{GF} = 3305.3 \text{ Nm}^3/\text{h}$$

taken from Fig. 4, resulting:

$$L'_r = \frac{100}{30} 0.145 = 0.483 \frac{Nm^3}{Nm^3 \text{ fuel}}$$

$$D'_{air} = 3305.3 \cdot 0.483 = 1596.5 \text{ Nm}^3/\text{h}$$

$$D_{air} = \frac{1596.5(1-0.3)}{0.79} = 1414.6\,\mathrm{Nm^3/h}$$

$$D_{O_2} = \frac{0.3-0.21}{0.79}\cdot 1596.5 = 181.88\,\frac{\mathrm{Nm^3}}{\mathrm{h}}$$

• For the range τ_3 = (24-38)h, it is considering an average oxygen concentration in air x= 37%, and an average value for the furnace gas flowrate of

$$D_{GF} = 3582\,\mathrm{Nm^3/h}$$

taken from Fig. 4, resulting:

$$L'_r = \frac{100}{37}0.145 = 0.392\mathrm{Nm^3/Nm^3}\ \text{fuel}$$

$$D'_{air} = 3582\cdot 0.392 = 1404.1\,\mathrm{Nm^3/h}$$

$$D_{air} = \frac{1404.1(1-0.37)}{0.79} = 1119.7\,\mathrm{Nm^3/h}$$

$$D_{O_2} = \frac{0.37-0.21}{0.79}1119.7 = 226.7\,\mathrm{Nm^3/h}$$

$$C_3 = \left(3582\frac{13.55}{1000} + 1119.7\frac{7.68}{1000} + 226.7\frac{86.15}{1000}\right)14$$

C_3 =1073.3 USD

$C_{GF} = C_1+C_2+C_3$ = 2113.36 USD/cycle

$$\boxed{\begin{array}{l}\text{Economy} = C_{CH_4} - C_{GF} = \\ = 779.92\ \text{USD/cycle}\end{array}}$$

6. Conclusion

In the case of burning of the furnace gas with atmospheric air, a burning temperature of 996 ^{0}C has resulted. This burning temperature assures the heating of the pieces from the homogenizing annealing furnace in the first period of the 18 hours cycle. Forward, in order to increase the burning temperature of the furnace gas, oxygen enriched air is used, reaching an average oxygen concentration in air of approx. 37%.

$$C_2 = \left(3305.3\frac{13.55}{1000} + 1414.6\cdot\frac{7.68}{1000} + 181.88\frac{86.15}{1000}\right)6$$

C_2 = 427.9 USD

Calculating the costs for the two varieties, first burning of the furnace gas with atmospherican oxigen enriched air and second burning of the marsh gas with atmospheric air, respectively, a smaller cost has resulted in the case of burning the furnace gas than in the case of the marsh gas, the economy being of 779.92 USD/cycle.

The economy of marsh gas, achieved by the utilization of the furnace gas, presents a special interest because of the deficit of the marsh gas on the global market and its putting up the price.

References

[1]. Vlădea I., *Tratat de termodinamică tehnică şi transmitere a căldurii*, Editura Didactică şi Pedagogică, Bucureşti, 1974.

[2]. Popa B., *Transferul de căldură în procesele industriale*, Editura Dacia, Cluj, 1975.

[3]. Brunklaus J., *Cuptoare industriale*, Editura Tehnică, Bucureşti, 1977.

[4]. Ivanescu L., *Raţionalizarea consumului de combustibil la agregatele termice metalurgice*, Editura Fundaţiei Universitare ”Dunarea de Jos”, Galaţi, 2002.

[5]. Ivanescu, L., Ivanescu, A., Cananau, N., Neacsu. M, *Procedeu de ardere a combustibililor cu puteri calorice mici,* Brevet inventie Nr.a 200300313, Oficiul de stat pentru inventii şi mărci, Bucureşti, 2005.

[6]. Ivanescu, L., Ivanescu, A., Cananau, N., *Cercetari privind utilizarea gazului de furnal în proporţie de sută la sută*, Contract cercetare Nr. 328, Galaţi, 2003.