ENERGY EFFICIENCY ANALYSIS FOR A COMPRESSED AIR INSTALLATION

BUZATU G.C., MIRCEA P.M., MIRCEA I., STAN IVAN F.E.
University of Craiova, Faculty of Electrical Engineering,
cosmin.buzatu@yahoo.com, mmircea@elth.ucv.ro ,
imircea@elth.ucv.ro, ely_felicia@yahoo.com,

Abstract: The energy performance of compressed air consumers aims to identify points in the process, on the basis of actual consumption of compressed air or electricity for its production, operation of the plant allows to obtain good results, as close to the nominal values for which it was designed.
Establishing energy performance is achieved after performing (development) of real energy balance, based on measurements of specific energy consumption of energy facilities
In this paper, the authors present the results of an energy analysis for an industrial transmission and distribution network of compressed air.

Keywords: energy performance, installation, compressed air, energy balance.

1. INTRODUCTION

Compressed air production occupies a very important place for the energy consumers in the industry. In Romania, the high share of industry participation in energy consumption, 18 percent return of compressed air production.

Compressed air is an expensive form of energy but with technological qualities to the consumer. .All the interventions related to the production, distribution and use of compressed air has a direct effect on energy consumption. Professionals must be very careful at the fact that their compressed air system should provide, by using less energy use as the air quantity, pressure and appropriate quality. Simple energy balance optimized and real, established by the beneficiary units of the investment objectives with a technological nature covering the equipments and installations, stations, factories and enterprises.

The main types of energy balance are [2], [4]: the balance sheet project, which uses as calculation energy elements the adopted values through project; approval balance sheet, which has the aim to confirm the effective power and technological parameters set out in project; Reception balance sheet prepared in terms of achieving concrete technological scheme, the raw material, fuels and real "utilities"; real balance, is compiled in order to confirm that the technological and energetically parameters of equipment are maintained over time and highlight the causes of deviations and any actions that need to be taken; the optimized balance is established whenever it is develops the real balance.

The upper error, whatever the form of the balance sheet is will not exceed: ±2,5% for the balances in which the main sizes are determined by measurements; ±5% for the balances where some sizes can not be measured directly, but those can be deduced accurately by measuring other quantities.

2. COMPRESSED AIR INSTALLATIONS PRESENTATION

In this paper is analysed in terms of energy efficiency, the compressed air system, within an industrial enterprise aimed at the production of car wheels. To highlight the energy efficiency of compressed air consumer, below are presented the energy indicators for the analysed installation (Figure 1, 2 and 3).

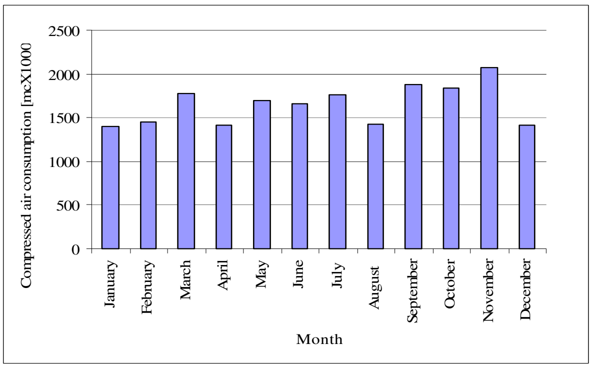

Fig. 1. Compressed air consumption monthly variation 2014

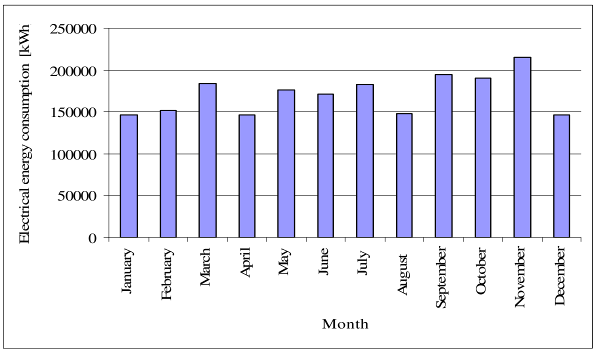

Fig. 2. Electrical energy consumption for compressed air consumption monthly variation 2014

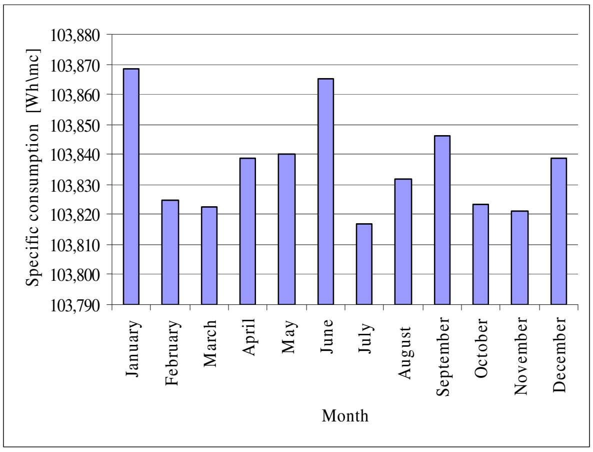

Fig. 3. Specific consumption monthly variation 2014

The enterprise produces and use in technological purpose compressed air at approximately 19 mil.Cubic meters / year.

There is a compressor station consists of four compressors and compressed air production is used in: manufacturing workshop rings, vascular workshop, direction quality primer-paint shop, press multiple station, Coventry line, the line L2, disc manufacturing workshop, manufacturing workshop wheels, depurator.

The pipe work is made of steel pipe with diameters between 32 and 114 mm DN and the pressure networking is about. 6 bar.

The technical characteristics of the four compressors are shown in Table 1; the geometric and physical properties of the analyzed compressed air circuit are shown in Table 2.

Table 1. Technical characteristics of the 4 compressors

Equipment	Characteristic	Symbol	Measurement unit	Value			
				COMP1	COMP2	COMP3	COMP4
Compressor	Inlet Air Flow	Q_{an}	m^3/min	22,5	22,5	22,5	22,5
	yield	h_n		0,8	0,8	0,8	0,8
	Discharge pressure	P_r	bar	6	6	6	6
	nominal power	P_n	kW	132	132	132	132
Engine	Power supply	U	kV	3*0,4	3*0,4	3*0,4	3*0,4
	rated current	I	A	247	232	222	247
	The nominal power factor			0,83	0,87	0,91	0,83
	nominal yield	h_n		0,9	0,9	0,9	0,9
	The speed of rotation	n_n	rot/min	1470	2960	2975	1470
The coupling K	nominal yield	h_K		0,9	0,9	0,9	0,9
Power cable	Section	s	mm^2	1*150	1*150	1*150	1*150
	Length	l	m	25	40	35	50

Table 2. Geometric and physical characteristics of the circuit analyzed

Section title	L_{echiv}	d	
	[m]	[mm]	[m]
T1-2	18	114	0,114
T2-3	2	114	0,114
T3-4	2	114	0,114
T4-5	12	114	0,114
T5-6	4,5	114	0,114
T6-8	7	114	0,114
T7-8	2	114	0,114
T8-9	5	114	0,114
T9-10	6	114	0,114
T10-11	6	114	0,114
T11-12	6	114	0,114
T12-13	54	114	0,114
T13-14	6	114	0,114
T14-11	54	114	0,114
T15-10	54	114	0,114
T16-9	54	114	0,114
T16-17	7	114	0,114
T17-8	54	114	0,114
T17-18	6	114	0,114
T18-24	53,5	114	0,114
T18-19	12	114	0,114
T19-22	41	114	0,114
T19-20	13	114	0,114
T20-21	41	114	0,114
T21-22	13	114	0,114
T22-23	13	114	0,114
T23-24	12	114	0,114

Section title	L_{echiv}	d	
	[m]	[mm]	[m]
T24-7	6	114	0,114
T1-25	0,5	60	0,06
T25-26	3	60	0,06
T26-27	45	60	0,06
T27-28	5	60	0,06
T28-29	45	60	0,06
T29-1	5	60	0,06
T1-30	5	60	0,06
T30-31	15	60	0,06
T31-32	6	60	0,06
T32-33	12	60	0,06
T33-34	5	60	0,06
T34-35	12	60	0,06
T35-32	5	60	0,06
T33-36	12	32	0,032
T36-37	0,5	32	0,032
T37-38	2	32	0,032
T39-40	6	60	0,06
T40-41	3	60	0,06
T41-42	6	60	0,06
T42-43	12	60	0,06
T43-44	12	32	0,032
T44-45	4	32	0,032
T43-46	6	60	0,06
T47-48	0,5	32	0,032
T48-49	3	32	0,032
T49-50	5	32	0,032
T51-52	5	32	0,032

Sections nominal debt rating was based on catalogue values for all consumers of compressed air.

3. METHODOLOGY OF THE REAL ENERGY BALANCE

3.1. Compressors real electrical balance

Energy balance equation zone is:

$$P_A = \Delta P_{RE} + \Delta P_{cf} + \Delta P_m + \Delta P_K + \Delta P_C + P_u \quad (1)$$

where: P_A=active hourly energy taker from the grid;
ΔP_{RE}=hourly energy loses in alimentation cable;
ΔP_{cf} =hourly energy loses in frequency converter;
ΔP_M=hourly energy loses in electrical motor;
ΔP_k=hourly energy loses in coupling motor-compressor;
ΔP_C=hourly energy loses in air compressor;
P_u= useful hourly energy .

Useful energy calculation

PC power required for air compression in the inlet pressure (pa) to its compressor, the discharge pressure (pr) is calculated using the formula:

$$P_C = \frac{Q_a \cdot \lambda_a \cdot L_{pol}}{102} \quad (2)$$

where:

Q - flow rate (the compressor suction Nm^3/min);

λ_a - specific weight of the air at input of the compressor [kg / m^3];

$$\lambda_a = 1{,}293 \cdot \frac{273}{T_a} \cdot \frac{1}{p_a} \quad (3)$$

where:

T_a - intake air temperature [K]

L_{pol} - the work of air compression polytrophic 1 kgf, defined by the expression**:**

$$L_{pol} = \frac{i \cdot n}{n-1} \cdot R \cdot T_a \cdot \left[\left(\frac{p_r}{p_a} \right)^{\frac{n-1}{i \cdot n}} - 1 \right] \quad (4)$$

where: n – compression polytropic index ($1{,}2 \div 1{,}3$); (is taken as n=1,25)

R – the specific gas constant;

$$R = \frac{\Re}{M}$$

$\Re$ - universal gas constant;

$\Re = 8314 kJ / kmd \cdot K$;

M – kilo molar mass of gas

M_{aer}=28 kmol/kg;

Calculation of energy losses

Hourly energy transmitted to the compressor (CAP), taking into account the yield is:

$$P_{AC} = \frac{P_C}{\eta_n} \quad (5)$$

Hourly energy losses in the compressor (ΔP_C) are:

$$\Delta P_C = P_{AC} - P_C \quad (6)$$

Hourly electrical energy to the motor shaft (WFP), taking into account the coupling efficiency (K) motor - compressor is:

$$P_{aM} = \frac{P_{AC}}{\eta_K} \quad (7)$$

Energy losses (ΔP_K), in the coupling zones (K) are:

$$\Delta P_K = P_{aM} - P_{AC} \quad (8)$$

Power consumption (PAM) of the engine (M) ise:

$$P_{AM} = \frac{P_{aM}}{\eta_M} \quad (9)$$

Hourly energy losses (ΔP_M) in the drive motor are:

$$\Delta P_M = P_{AM} - P_{aM} \quad (10)$$

3.2. Real energy balance on the compressed air system

The calculation of load loss

The methodology used for pressure loss calculations for each segment is as follows:

a) Calculate the flow rate on the section:

$$V = \frac{4Q}{\pi d^2} \quad (11)$$

where:

Q - flow on the section, [m^3 / s];

d - diameter section [m].

b) Calculate the Reynolds number:

$$Re = \frac{v \quad d}{\nu} \quad (12)$$

where:

V section flow velocity [m / s];

d - diameter section [m].

υ - the cinematic viscosity of the compressed air υ = 14, 61·10-6 [m / s] (13.5)

c) Depending on the Reynolds number is established if the regime flow is whether laminar or turbulent and it is calculate the coefficient of linear losses λ.

d) Calculate the hydraulic gradient:

$$j = \frac{\lambda \quad v^2}{2gd} \qquad (13)$$

where:

λ - the coefficient of linear losses;
v - section flow velocity [m / s];
g - acceleration of gravity [m / s];
d – section diameter [m].

e) Calculate the load losses:

$$h_r = j \cdot l \qquad (14)$$

where:

j - hydraulic slope;
l - the length of the section [m];

f) Calculate the pressure drop:

$$\Delta P = \gamma \cdot h_r \qquad (15)$$

where:

γ - specific gravity compressed air $\gamma = 12,01$ N/m^3;
hr - load loss on the section, [m].

Calculation of pressure at the consumers

a) Consumers pressure:

$$p = p_{nc} - \Sigma \Delta p \qquad (16)$$

where: p = 8-1.51 = 6.49 [bar]

The power consumed to cover losses hydraulic network

Power losses due to hydraulic losses in the compressed air network are calculated with the relationship:

$$\Delta P_{pr} = \Delta pt_{pr} \cdot Q_{nt} \qquad (17)$$

where:

Δpt_{pr} - pressure loss on the section
Q_{nt} - nominal flow on the section.

The results obtained by applying this calculation methodology are presented in the following tables:

Table 3. Useful energy calculation

Parameter	**Symbol**	**Measurement unit**	**Value**			
			COMP1	**COMP2**	**COMP3**	**COMP4**
Specific gravity air	λ_a	kgf/m^3	0,143	0,143	0,143	0,143
The work polytrophic	L_{pol}	kgfm/kgfaer	2668,125	2853,733	2439,428	2668,125
Power output	P_u	kW/h	84,275	90,137	77,051	84,275

Table 4. Calculation of energy losses

Size	**Symbol**	**U.M.**	**Value**			
			COMP1	**COMP2**	**COMP3**	**COMP4**
Energy transmitted hourly to the compressor	P_{AC}	kW/h	105,343	112,672	96,314	105,343
Hourly energy losses in the compressor	ΔP_C	kW/h	21,069	22,534	19,263	21,069
Hourly energy to the motor shaft	P_{aM}	kW/h	117,048	125,191	107,016	117,048
Energy losses in the coupling zones (K)	ΔP_K	kW/h	11,705	12,519	10,702	11,705
Power absorbed by the engine (M)	P_{AM}	kW/h	130,054	139,101	118,906	130,054
Hourly energy losses in the drive motor	ΔP_M	kW/h	13,005	13,910	11,891	13,005
Hourly energy absorbed by the plant from the network	P_A	kW/h	130,054	139,101	118,906	130,054

Table 5. Compressors real hourly electric balance on the compressor station

Incoming energy			**Outgoing energy**		
Size	**Value**		**Size**	**Value**	
	[kWh]	**%**		**[kWh]**	**%**
The energy absorbed from network	518,114	100	Useful energy	335,738	64,80
			Total useful energy	***335,738***	***64,80***
			Losses in the compressor	83,935	16,20
			Losses coupling	46,630	9,00
			Losses in the motor	51,811	10,00
			Total losses	***182,376***	***35,20***
Total energy entered into the contour	**518,114**	**100**	**Total energy out of the contour**	**518,114**	**100**

Table 6. Power losses hourly calculation of the analised consumer

Name	V	Re	λ	J	hr	Δ p		Δp	ΔPpr
	[m/s]				[m]	[N/m2]	[N/m2]	[kW]	[bar]
T1-2	101,457	791656,2	0,03	138,064	2485,157	29846,737	0,29847	29846,737	30,89286
T2-3	101,457	791656,2	0,03	138,064	276,129	3316,304	0,03316	3316,304	3,432541
T3-4	101,457	791656,2	0,03	138,064	276,129	3316,304	0,03316	3316,304	3,432541
T4-5	101,457	791656,2	0,03	138,064	1656,771	19897,824	0,19898	19897,824	20,59524
T5-6	101,457	791656,2	0,03	138,064	621,289	7461,684	0,07462	7461,684	7,723216
T6-8	101,457	791656,2	0,03	138,064	966,450	11607,064	0,11607	11607,064	12,01389
T7-8	101,457	791656,2	0,03	138,064	276,129	3316,304	0,03316	3316,304	3,432541
T8-9	101,457	791656,2	0,03	138,064	690,321	8290,760	0,08291	8290,760	8,581351
T9-10	101,457	791656,2	0,03	138,064	828,386	9948,912	0,09949	9948,912	10,29762
T10-11	101,457	791656,2	0,03	138,064	828,386	9948,912	0,09949	9948,912	10,29762
T11-12	101,457	791656,2	0,03	138,064	828,386	9948,912	0,09949	9948,912	10,29762
T12-13	6,976	54431,7	0,03	0,653	35,246	423,300	0,00423	423,300	0,030125
T13-14	36,758	286818,1	0,03	18,123	108,736	1305,917	0,01306	1305,917	0,489719
T14-11	6,976	54431,7	0,03	0,653	35,246	423,300	0,00423	423,300	0,030125
T15-10	6,976	54431,7	0,03	0,653	35,246	423,300	0,00423	423,300	0,030125
T16-9	6,976	54431,7	0,03	0,653	35,246	423,300	0,00423	423,300	0,030125
T16-17	36,758	286818,1	0,03	18,123	126,858	1523,569	0,01524	1523,569	0,571339
T17-8	20,663	161230	0,03	5,727	309,239	3713,955	0,03714	3713,955	0,782902
T17-18	36,758	286818,1	0,03	18,123	108,736	1305,917	0,01306	1305,917	0,489719
T18-24	5,329	41582,25	0,03	0,381	20,379	244,749	0,00245	244,749	0,013306
T18-19	36,758	286818,1	0,03	18,123	217,472	2611,833	0,02612	2611,833	0,979438
T19-22	8,299	64757,15	0,03	0,924	37,876	454,894	0,00455	454,894	0,038514
T19-20	36,758	286818,1	0,03	18,123	235,594	2829,486	0,02829	2829,486	1,061057
T20-21	8,008	62488,1	0,03	0,860	35,268	423,574	0,00424	423,574	0,034606
T21-22	101,452	791617,9	0,03	138,051	1794,662	21553,894	0,21554	21553,894	22,30828
T22-23	101,452	791617,9	0,03	138,051	1794,662	21553,894	0,21554	21553,894	22,30828
T23-24	101,452	791617,9	0,03	138,051	1656,611	19895,902	0,19896	19895,902	20,59226
T24-7	101,452	791617,9	0,03	138,051	828,306	9947,951	0,09948	9947,951	10,29613
T1-25	21,821	89614,72	0,03	12,135	6,067	72,869	0,00073	72,869	0,004494
T25-26	21,821	89614,72	0,03	12,135	36,404	437,212	0,00437	437,212	0,026961
T26-27	21,821	89614,72	0,03	12,135	546,060	6558,177	0,06558	6558,177	0,404421
T27-28	21,821	89614,72	0,03	12,135	60,673	728,686	0,00729	728,686	0,044936
T28-29	21,821	89614,72	0,03	12,135	546,060	6558,177	0,06558	6558,177	0,404421
T29-1	21,821	89614,72	0,03	12,135	60,673	728,686	0,00729	728,686	0,044936
T1-30	168,082	690275,5	0,03	719,969	3599,846	43234,149	0,43234	43234,149	20,53622
T30-31	168,082	690275,5	0,03	719,969	10799,538	129702,448	1,29702	129702,448	61,60866
T31-32	21,821	89614,72	0,03	12,135	72,808	874,424	0,00874	874,424	0,053923
T32-33	21,821	89614,72	0,03	12,135	145,616	1748,847	0,01749	1748,847	0,107846
T33-34	21,821	89614,72	0,03	12,135	60,673	728,686	0,00729	728,686	0,044936
T34-35	21,821	89614,72	0,03	12,135	145,616	1748,847	0,01749	1748,847	0,107846
T35-32	21,821	89614,72	0,03	12,135	60,673	728,686	0,00729	728,686	0,044936
T33-36	3,939	8628,444	0,03	0,742	8,899	106,872	0,00107	106,872	0,000338
T36-37	3,939	8628,444	0,03	0,742	0,371	4,453	0,00004	4,453	1,41E-05
T37-38	3,939	8628,444	0,03	0,742	1,483	17,812	0,00018	17,812	5,64E-05
T39-40	21,821	89614,72	0,03	12,135	72,808	874,424	0,00874	874,424	0,053923
T40-41	21,821	89614,72	0,03	12,135	36,404	437,212	0,00437	437,212	0,026961
T41-42	21,821	89614,72	0,03	12,135	72,808	874,424	0,00874	874,424	0,053923
T42-43	21,821	89614,72	0,03	12,135	145,616	1748,847	0,01749	1748,847	0,107846
T43-44	3,939	8628,444	0,03	0,742	8,899	106,872	0,00107	106,872	0,000338
T44-45	3,939	8628,444	0,03	0,742	2,966	35,624	0,00036	35,624	0,000113
T43-46	21,821	89614,72	0,03	12,135	72,808	874,424	0,00874	874,424	0,053923
T47-48	3,939	8628,444	0,03	0,742	0,371	4,453	0,00004	4,453	1,41E-05
T48-49	3,939	8628,444	0,03	0,742	2,225	26,718	0,00027	26,718	8,46E-05
T49-50	3,939	8628,444	0,03	0,742	3,708	44,530	0,00045	44,530	0,000141
T51-52	3,939	8628,444	0,03	0,742	3,708	44,530	0,00045	44,530	0,000141
						405009,544	**4,0501**	**405009,544**	**284,8155**

Table 7. Real energy balance timetable for the transmission and distribution of the compressed air

Entered energy			Outgoing energy		
Size	Value		Size	Value	
	[kWh/h]	%		[kWh/h]	%
The energy provided by compressors in the Network	620,558	100	Consumer useful energy or handling compressed air	335,738	54,10
			Total useful energy	***335,738***	***54,10***
			Hydraulic losses in network	284,82	45,90
			Total losses	***284,82***	***45,90***
Total energy entered into the contour	**620,558**	**100**	**Total energy out of the contour**	**620,558**	**100**

Calculation of energy transformation efficiency indicators

Transform energy efficiency indicators are:

➢ installation net energy yield:

$$\eta_{ne/a\ pr} = \frac{P_u}{P_A} \times 100$$

where:
P_u – useful output power for consumer's compressed air;
P_A – total power entered into shape.

$$\eta_{ne/a\ pr} = \frac{P_u}{P_A} \times 100 = \frac{335{,}738}{518{,}738} \times 100 = 64{,}72\%$$

➢ net specific consumption of electricity transmission and distribution project for compressed air.

$$C_{ne/a\ pr} = \frac{P_A}{Q_{an}}$$

where:
P_A – total electrical energy entered in the contour;
Q_{an} – the flow of compressed air.

$$C_{ne/a\ pr} = \frac{518{,}738}{4 \cdot 22.5 \cdot 60} = 0{,}096 \quad kWh/Nm^3$$

4. RESULTS INTERPRETATION AND CONCLUSIONS

The compressed air losses are relatively greater of about 45,90%.

The use of a larger diameter for the pipelines would lead to obtain a laminar flow regime, for larger distances, and potentially reducing pressure losses.

If a pipe diameter is 1% lower than the nominal, real pressure loss is 5% higher than the calculated one.

The decrease in pressure of only 0.5 bar causes a reduction of 12-15% of the power output of pneumatic equipment.

Generally we can say that the power output of pneumatic equipment decreases with the square of absolute pressure compressed air.

In order to reduce power losses and increase efficiency of the plant, it suggests the following actions:

- purchasing a variable speed compressor
- location of measuring flow and pressure of the compressed air network segment;
- insulation of pipes mounted in outdoor air, to avoid air cooling and increased consumption volume;
- to perform periodic tests for tightness.

5. ECONOMIC EFFICIENCY CALCULATION

Based on actual consumption of existing equipment, calculations are made considering that the lifespan of the compressor is about 14020 hours / year

Energy consumption*:*

Total energy consumed:

E_{tot}= 1830170.8 kWh/an

Current energy costs:

The annual costs for electricity consumed by the compressors are:

Ec_{comp}= 1830170.8 x 0.455= 823576.86 RON/an

The total costs are:

E_c= 823576.86 RON/an

The financial analysis is proposed

The total investment for a compressor with variable speed drive will be:

I=180000RON≈40000EURO

The annual energy savings is:

Ec_{comp}=96999.052 kWh/an

Financial economics energy is:

E_c=96999.052 x 0.455 = 44134.56 RON/an

Total annual saving will be in this case:

E_{cfin}= 44134.56 RON (≈9699.9EURO)

Payback period is:

T_r= 4.28 years

- Annual saving: 9699.9 Euro
- Total investment cost: 40000 Euro
- Project internal rate of return: 12 %
- Net updated: 138,783.19 RON
- Investment payback period: 4.28year

REFERENCES

[1]. Carabogdan, I. Gh., ş.a., - Bilanţuri energetice. Probleme şi aplicaţii pentru ingineri, Editura Tehnică, Bucureşti, 1986.

[2]. Ionescu, C. D., ş.a., - Monitorizarea şi evaluarea continuă a eficienţei energetice, Editura Agir, Bucureşti, 2001.

[3] Laza I., s.a., - Utilizarea eficienta a energiei. Ns pentru manageri energetici, Editura Orizonturi Universitare, Timisoara, 2004.

[4]. Mereuţă, C., - Măsuri practice generale pentru economisirea energiei electrice în industrie, Editura Tehnică, Bucureşti, 1985.

[5] Mills David., -Pneumatic conveying design guide. Second edition. Elsevier, 2004.

[6]. Mircea, I., Ruieneanu, L., Dinu, R.C., - Producerea energiei electrice şi termice, Îndrumar de laborator, vol.I, Reprografia Universităţii din Craiova, 2001.

[7]. Mircea, P.M., Buzatu, G.C., Mircea, I., Analysis and Monitoring of the Compressed Air Facilities, ICATE 2014.

[7]. Răducanu, C., ş.a., - Audit energetic, Editura Agir, Bucureşti, 2000.

[8]. Vuc, Gh., - Managementul energiei electrice, Editura Agir, Bucureşti, 2001.

[9] Takats Peter, Alup compressoren GmbH, ‚Manual tehnic de aer comprimat: probleme energetice si de functionare", Editura Enesis, Baia-Mare, Editia 2006.

[10]. ***PE 902/1996 - Normativul pentru întocmirea şi analiza bilanţurilor energetice., Bucureşti, CIDE.

[11]. ***Normativ privind metodica de întocmire şi analiza bilanţurilor energetice în întreprinderile industriale, ICEMENERG, Bucureşti, 2000.

[12] *** Manual tehnic DS 300, VA 400, CS Instruments GmbH.