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MONITORING OF ENERGY EFFICIENCY IN INDUSTRIAL PNEUMATIC MACHINES

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Abstract: *About 10 % of total industrial energy consumption in Europe is spent for generation of compressed air, which can be found in almost all manufacturing industries. Compressed air is very expensive energy source, thus big attention should be paid to the structure and condition of the compressed air system and to its energy consumption. Implementing energy saving measures with high monitoring level of compressed air system can significantly reduce factory energy consumption. Wireless Sensor Network (WSN) based monitoring solution for industrial pneumatic machines was developed. Sample tool kit system for production environment monitoring was also created. Monitoring of pneumatic system's condition by online wireless senor network allows forecasting technical, managerial and maintenance problems in larger supply chain.*
Keywords: *compressed air system, energy efficiency, energy savings, condition monitoring system, wireless sensor network*

1. INTRODUCTION

Use of compressed air in mechanization and automation of manufacturing processes was started just in the middle of the 20th century. At the moment compressed air systems are widely used in almost all manufacturing industries due to advantages of the compressed air, such as its availability, cleanness, high reliability of the components, insensitivity to external influences and ease of use. However, compressed air has a big disadvantage comparing to other available energy sources – very high energy costs, only 10-15% of the energy, consumed for production of compressed air, can be converted into work by end-users [1, 2]. In practice the expensiveness of compressed air very often is not taken into account, which leads to big energy losses in the factories.

The EU is aiming for a 20% cut in Europe's annual primary energy consumption by 2020. The Commission has proposed several measures to increase efficiency at all stages of the energy chain: generation, transformation, distribution and final consumption. About 20% of the EU's primary energy consumption is accounted for by industry [3, 4]. According to the SAVE Programme, 10% of industrial consumption of electricity is used for generation of compressed air (in certain industries up to 30%). Case studies carried out within the SAVE Programme showed, that efficiency of many compressed air systems is low and savings in the range from 5% to 50% are possible[5].

Increasing energy efficiency of compressed air systems gives not only reduced energy costs and thus money savings, but also ensures other significant benefits for the enterprise. Energy saving measures implies high monitoring level of compressed air system and appropriate maintenance, which leads to decreased breakdowns of production equipment, avoiding the loss of raw materials or other inputs, longer life cycle of pneumatics devices and higher reliability of compressed air systems [6].

Energy savings in compressed air systems can be achieved through implementing a row of technical measures such as:

1. improvement of compressors drives and control;
2. lowering intake air temperature;
3. minimizing and prevention of leaks;
4. minimization of inappropriate uses of compressed air;
5. minimization of pressure drop in the system;
6. minimization of system pressure;
7. waste heat recovery [5-14].

The applicability of measures will vary depending on individual features of sites and industries, but demand-side improvements have usually higher level of implementation, lower capital costs and shorter payback period, than supply-based improvements [5, 9, 13].

1.1 Improvement of compressors drives and control

There are three main cost factors influencing life cycle costs of compressed air system: equipment costs, maintenance cost and energy costs. The proportions between these factors in total life cycle costs vary depending on motor efficiency, energy cost, operating hours, lifetime etc., but for the typical compressed air system energy costs amount to 75% and more of the total costs (Fig.1) [2, 9]. Therefore the efficiency of compressor drive will have a big influence on the energy consumption of the whole compressed air system.

One of the opportunities to improve the compressor drive is use of the high-efficiency motors. These motors are 2-8% more efficient comparing to the standard ones due to improved design and manufacturing process, better materials used and due to reduced losses in the motor [5, 7, 9]. Another opportunity is energy saving through using of variable speed drives. Each compressed air system has its unique air usage profile. Many compressed-air systems are designed to operate at maximum-load conditions. However, most of the

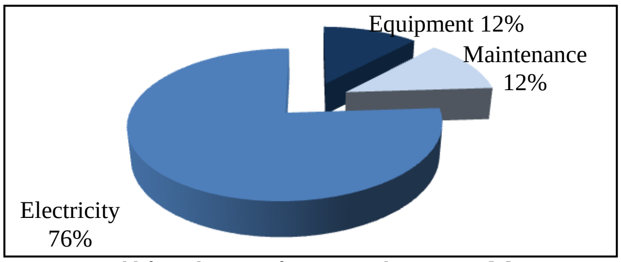

Fig. 1. Typical life cycle costs of compressed air system [2]

systems operate at their full load only for short periods of time. This often results in energy inefficiency of compressed air system during the rest of the time. Such systems can be improved by using variable speed drive for the compressor to match its output to the system demand [5, 9]. Energy savings for sophisticated controls can be up to 12% [11].

It should be also controlled, that motor power is chosen according to the actual need. Running at part load causes low efficiency of the electric motor. These motors should be replaced with the suitable-capacity motors to improve the efficiency of the system [9].

1.2 Lowering intake air temperature

Higher temperature intake air is less dense, resulting in less compressed air volume being produced. Therefore additional compressor work is needed to achieve the system demand requirements. For each 3 °C rise in air intake temperature (above the compressor design temperature) the compressor efficiency is decreased by 1%. In many cases the intake air temperature can be lowered by using cool outside air, and thus the efficiency of the compressor can be improved [7, 9, 10].

1.3 Minimizing and prevention of leaks

Leaks can be a significant source of wasted energy in an industrial compressed air system, sometimes wasting 20%-50% of a compressor's output. In addition, leaks cause a drop in system pressure, which can make air tools less efficient and adversely affect production. By forcing the equipment to run longer, leaks shorten the life of system equipment, lead to additional maintenance requirements and increased downtime [7-9, 11-13].

The amount of wasted air (and wasted energy) is proportional to the line pressure and to the area of leak (Table 1). Therefore reduced system pressure will result in reduced leakage amounts and reduced energy losses [8].

Leaks occur most often at the joints, connections, elbows, reducing bushes, sudden expansions, valve systems, hoses, tubes, filters, check valves, relief valves, extensions, and the equipment connected to the compressed air lines. Although total elimination of air leaks is impractical, regular leak repair and maintenance can reduce energy wastes to less than 10% of compressor's output [7-9].

Hole diameter (mm)	Leakage amount (m^3/min (ANR))	Energy loss (kW)
1	0.068	0.44
2	0.271	1.76
3	0.611	3.97
4	1.086	7.06
5	1.696	11.03

Tab. 1.Wasted air and energy for different leak sizes at 0.7 MPa (g), compressor specific power 6.5 kW/m^3/min (ANR)

A simple way to detect large leaks is to apply soapy water to suspect areas, or to use a plastic bag to monitor the velocity of the air filling the bag, although this may be time consuming. The best way to detect leaks is to use an ultrasonic acoustic detector, which can recognize the high frequency hissing sounds associated with air leaks. This equipment facilitates identification of even the smallest leak regardless of the baseline ambient noise level in an industrial plant [7, 9]. Even after leakage detection and repair some part of compressed air still will be wasted through the undetected and small leaks. New leaks can also occur. Therefore non-operating equipment should be isolated from the compressed air system with the solenoid valves to prevent possible leakages during non-working period [7, 10].

1.4 Minimization of inappropriate uses of compressed air

Many operations can be done more economically and more efficiently using energy sources other than compressed air. For example, it is almost always more efficient to install local air blowers where there is a requirement for large volumes of low pressure air that does not need to be dried or filtered. Users should always consider more cost-effective solutions before considering compressed air [7, 10, 11].

1.5 Minimization of pressure drop in the system

Properly designed and installed compressed air systems have a pressure drop less than 10% of the compressors discharge pressure. Excessive pressure drop will result in poor system performance and excessive energy consumption. Minimizing pressure drop requires a systems approach in design and maintenance. Air treatment components should be selected with the lowest possible pressure drop at specified maximum operating conditions and best performance. Manufacturers' recommendations for maintenance should be followed, particularly in air filtering and drying equipment, which can have damaging moisture effects like pipe corrosion. Air should be treated accordingly with the system requirements; overtreatment will also lead to excessive pressure drop and thus waste of energy [7-9, 10, 11].

1.6 Minimization of system pressure

High-pressure air is more expensive to produce and deliver than low-pressure air. A rule of thumb for systems in the 0.7 MPa range is: for every 14 kPa increase in discharge pressure, energy consumption will increase by approximately 1% [14]. Another problem is that energy waste from air leaks and inappropriate use of compressed air also depends on the system pressure level and is increased when the system pressure is higher than necessary. Therefore the system pressure should be set as low as possible [7-9, 14].

1.7 Waste heat recovery

Industrial-sized air compressors generate a substantial amount of heat that can be recovered and put to useful work. As much as 80% to 93% of the electrical energy going to a compressor becomes available heat. In many cases 50% to 90% of this heat can be recovered and used for producing hot water or hot air [7, 14].

2. METHODOLOGY

The basis for all decisions concerning energy efficiency of compressed air systems is the understanding of the way of their functioning and existence of appropriate data. A systematic approach, to monitor industrial energy consumption and to pin-point sources of wastage, is known as energy audit. An energy audit study helps an organization to understand and analyse its energy utilization and identify areas where energy consumption can be reduced, decide on how to budget energy use, plan and practice feasible energy conservation methods that will enhance their energy efficiency, reduce energy wastage and essentially reduce energy costs [6, 9]. The objectives of the compressed air energy audit are:

1. to identify compressed air energy usage at the enterprise;
2. to identify compressed air energy wastages;
3. to implement energy saving measures, which are applicable and valuable for this enterprise;
4. to provide a pathway to benchmark energy usage of compressed air energy in other facilities and industries [9].

Energy audit requires a systematic approach – from formation of a suitable team, to achieving and maintaining energy savings. A typical process is shown in Fig.2 [8, 9]. There are two types of audits carried out in the compressed air systems: basic (walk-through) audit and comprehensive (in-depth) audit. Conducting a basic audit is the first step in analysing a compressed air system. This type of audit is not intended to provide the level of detail found in a comprehensive audit, but significant reductions energy and lower maintenance costs often result from basic assessment alone. Once initial opportunities have been identified, it can be decided whether additional analysis services are required to further define system dynamics and corresponding system improvement opportunities. The advantage of the two-step auditing process is the ability to ensure in-depth system audits are only conducted where genuine energy saving opportunities exists and any such analysis can be specifically targeted at these opportunities [13, 15]. A range of system performance metrics should be used to determine the potential efficiency gains available for any given system, with additional application to on-going monitoring of the condition and efficiency of compressed air system. These metrics included the following:

1. leakage rates;
2. system pressure — set point and variation;
3. specific demand (demand per unit of plant output);
4. specific power consumption of compressors;
5. environmental variables — air quality, water quality (condensate drains) [13].

The number of metrics used will be site and system specific, with each of these incorporated into the walk-through and in-depth audit [13].

3. MONITORING

The basis for all decisions concerning energy efficiency of compressed air systems is the understanding of the way of their functioning and existence of appropriate data. A systematic approach, to monitor industrial energy consumption and to pin-point sources of wastage, is known as energy audit. An energy audit study helps an organization to understand and analyse its energy utilization and identify areas where energy consumption can be reduced, decide on how to budget energy use, plan and practice feasible energy conservation methods that will enhance their energy efficiency, reduce energy wastage and essentially reduce energy costs [6, 9]. Manufacturing systems with single-staged production process usually consist of poly-functional machine tools (processing equipment, flexible manufacturing modules) that can replace each other by their technological capabilities [16, 17]. In this case, technological possibilities of the machines belonging to

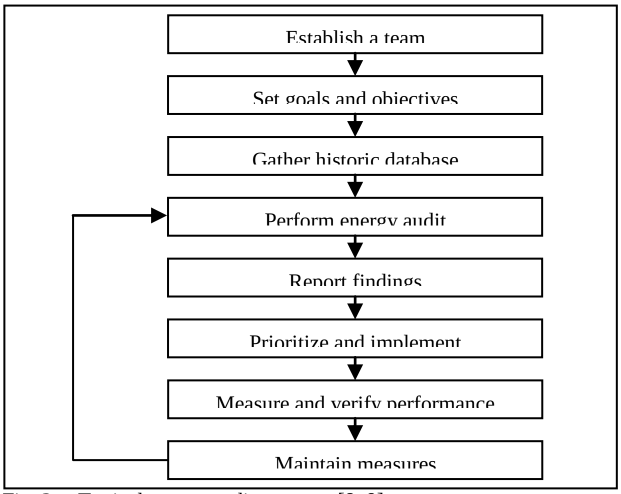

Fig. 2. Typical energy audit program [8, 9]

the system are wide-ranging and by use of these machines it is possible to perform large amount of main operations. Majority of manufacturing systems are with multi-staged production process. Mono-functional machine tools are complementing each other, for total processing of the detail several operations have to be performed and the detail processed passes several processing positions in its technological route. Thus, technological possibilities play important role in designing operational and route technologies but also in management of whole production process. E-manufacturing is the application of open, flexible, reconfigurable computing techniques and communications for the enhancement of efficiency of the whole supply chain. As e-manufacturing is supported by information technology (such as the Internet) and has the capability in multi-site management, it will foster and improve the competitive capability of manufacturing in the global competition [18]. The e-manufacturing system is a set of related models. The number of models depends on the complexity of the system [19]. In the case of each model the architecture (process management, realization principles) and application (information about employing the model, how and in what conditions the model should be employed); and expert for helping decision-making (essential information is gathered from the environment and expert offers optimal solution; decisions made are saved together with the description of the circumstances that were the basis of decision-making, this enables learning of the system and making new decisions based on the previous experience) is described.

4. WSN PRODUCTION ENVIRONMENT MONITORING SYSTEM

When using Wireless Sensor Network (WSN) based monitoring solutions these pose some restrictions to the monitoring approach. The WSN nodes are typically battery powered and with limited computational capacity, which means that the algorithms employed in the nodes should have low requirements for the computational power. The monitoring sensors can be used in the final and optimized WSN having suitable electrical interface (SPI) and low power requirements. An additional data acquisition/interface board was installed between the sensor and the main data acquisition computer as the computer was not equipped with the SPI interface [20, 21]. The data acquisition board was a WSN node prototype, based on the Atmel AVR XMEGA microcontroller. Gateway is a device that creates Ethernet type wireless network between nodes and computer. It uses a standard IEEE 802.15.4. All the sensors attached with the nodes were powered using the node's internal sensor power output terminal named SEN PWR. The correct supply voltage of the sensors was secured by voltage regulator connected between the power terminal of the node and the input terminal of the sensor. The supply voltage of the sensors varied between 5 V and 10 V.

All sensors used within the system had a voltage output which the nodes are able to measure. The output signals of the sensors were calculated into their expected shapes using formulas provided by the producers of the sensors. As the data acquisition board is essentially a fully fledged WSN node, it is also capable of reading sensor data, buffering it and later forwarding it to the computer in serial (RS232) format. Considering the constraints of the interface board memory, processing power and serial communication acquisition speed, the sampling frequency 640 samples/s was chosen. It may be desirable to use a higher sampling frequency, but in order to acquire data for all the axes some trade-offs had to be made. In the final and optimized WSN the serial (RS232) data link will be replaced with a wireless communication module that is already present on the prototype board. Depending on the analysis results and firmware, it is possible to transmit live measurement information continuously or only just the identified state of the machinery being monitored.

5. CONCLUSION

Energy audit measurements were analysed and outlined in this research. Real time monitoring system for monitoring energy consumption in pneumatic systems was performed to be wireless, enabling easy to install and quickly adjustment for utilization. Sample tool kit system for production environment monitoring was created. Sensor system was based on WSN technology produced by National Instruments. The base system contained of several WSN nodes, one gateway, a user interface with processor (touch-screened computer with analysing environment programmed in LabVIEW environment) and sensors. Sensors for measuring temperature, flow rate and system pressure can be used for pneumatic machines. An exemplary monitoring system was created in order to test stability and reliability of WSN nodes in process engineering environment and to evaluate nodes compatibility with different type of sensors.

In sample monitoring device, total duration of measurement and cycle length was entered to start monitoring. As a result user interface software displays all the measured values on the screen both numerically and graphically. All the results were saved to log files. This allowed the measurement data to be analysed later in more details if needed. The software of this measurement system contained also an analysing tool which allows the user to get a quick overview of a measurement results. Monitoring of pneumatic system's condition by online wireless senor network allows forecasting technical, managerial and maintenance problems in larger supply chain.

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7. REFERENCES

[1] Ing.-Büro J.P. Hasenbrink. (2003). *The Pneumatic Trainer Volume 1, Basic Pneumatics*, Erbach : Bosch Rexroth AG, Germany, RE 00296

[2] U.S. Department of Energy. (2004). *Determine the cost of compressed air for your plant, Compressed Air Tip Sheet #1*, DOE/GO-102004-1926

[3] http://ec.europa.eu/energy/efficiency/index_en.htm, (2012). European Comission, Energy Efficiency, *Accessed on 21.09.2012*

[4] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX: 52011DC0109:EN:NOT (2011). European Comission, Energy Efficiency Plan 2011, *Accessed on 21.09.2012*

[5] Radgen, P.; Blaustein, E. (2001). *Compressed Air Systems in the Europian Union*, Rondo Druck, ISBN 3-932298-16-0, Germany

[6] Šešlija, D.; Ignjatović, I.; Dudić, S.; Lagod, B. (2011). Potential energy savings in compressed air systems in Serbia, *African Journal of Business Management*, Vol. 5(14), 2011, pp. 5637-5645, ISSN 1993-8233

[7] Galitsky, C.; Worell, E. (2008). *Energy Efficiency Improvement and Cost Saving Opportunities for the Vehicle Assembly Industry, An ENERGY STAR Guide for Energy and Plant Managers*, Lawrence Berkeley National Laboratory, USA, LBNL-50939-Revision

[8] Abdelaziz, E. A.; Saidur, R.; Mekhilef, S. (2010). A review on energy saving strategies in industrial sector, *Renewable and Sustainable Energy Reviews*, Vol. 15, 2011, pp. 150–168

[9] Saidur, R.; Rahim, N. A.; Hasanuzzaman, M. (2009). A review on compressed-air energy use and energy savings, *Renewable and Sustainable Energy Reviews*, Vol. 14, 2010, pp. 1135-1153

[10] *Compressed air efficiency rating scheme handbook*, (2011). Energy Efficiency and Conservation Authority (EECA), New Zealand, EEC1930

[11] Shanghai, H. Q.; McKane, A. (2008). Improving Energy Efficiency of Compressed Air System Based on System Audit, Lawrence Berkeley National Laboratory, USA, *Available from*: http://escholarship.org/uc/item/13w7f2fc *Accessed on: 21.09.2012*

[12] Yang, M. (2009). Air compressor efficiency in a Vietnamese enterprise, *Energy Policy*, Vol. 37, 2009, pp. 2327-2337

[13] Neale, J. R.; Kamp, P. J. J. (2009). Compressed air system best practice programmes: What needs to change to secure long-term energy savings for New Zealand?, *Energy Policy*, Vol. 37, 2009, pp. 3400-3408

[14] U.S. Department of Energy. (2003) *Improving Compressed Air System Performance, a sourcebook for industry*, Lawrence Berkeley National Laboratory, USA, DOE/GO-102003-1822

[15] Scales, W.; Mcculoch, D. M. (2010), Compressed air system analysis, *Compressed Air Best Practices*, August 2010, pp. 34-38

[16] Otto, T.; Riives, J.; Loun, K. (2008). Productivity improvement through monitoring of human resources competence level. B. Katalinic (Toim.). *DAAAM International Scientific Book 2008* (565 - 576). Vienna: DAAAM International Vienna

[17] Lõun, K.; Riives, J.; Otto, T. (2011). Evaluation of the operation expedience of technological resources in a manufacturing networ. Estonian Journal of Engineering, 17(1), 51 - 65

[18] Wang, L. D. An information-integrated framework to support e-Manufacturing. *Int. J. Adv. Manufact. Technol*., 2007, 32, 625–630

[19] Lõun, K., Otto, T., Riives, J. (2009). E-manufacturing concept solution for tooling sector. Estonian Journal of Engineering, 15(2), 108 - 120

[20] Aruväli, T.; Serg, R.; Preden, J.; Otto, T. (2011). In-process determining of the working mode in CNC turning. *Estonian Journal of Engineering*, 17(1), 4 - 16

[21] Aruväli, T.; Reinson, T.; Serg, R. (2011). Real-time Machinery Monitoring Applications in Shop Floor. In: World Congress on Engineering and Computer Science 2011 *Proceedings: International Conference on Intelligent Automation and Robotics 2011, USA, San Francisco, 19-21.10.2011. IAENG* , 2011, 337 - 342