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Assessment of the energy consumption of the glass production process by compressed air flow measurements

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ABSTRACT

In this work the authors propose a methodology to manage the operation of a compressed air plant to guarantee its best energy efficiency, so controlling the energy consumption of the industry where such a plant is present. In particular, the aim is to set a strategy for controlling the optimal operation of the compressors in the plant, in the perspective of Industry 4.0, to ensure the minimization of energy consumption found by their use and their automated management. The methodology bases its principle on the digitization of the operational maps of the machines, able to provide in real-time their operating conditions found by the measurements of the characteristic parameters, and thus intervene, through feedback chains, on control systems to restore optimal conditions, when possible, or intervene with routine maintenance to prevent irreversible damage. It is intended to test the procedure on a compressed air plant of a glass industry located in southern Italy.

1. Introduction

The glass industry is one of the industrial sectors identified as hard to abate due to the high emissions connected to its production process. Various actions were undertaken by countries, following the Paris Agreement of 2015, where was set the limit of 1.5 °C of increment of the mean earth surface temperature from the pre-industrial era to avoid climate change effects. For example, the EU ETS (Emissions Trading System), launched in UE in 2005 and its fourth trading phase (2021–2030), is one of the measures adopted by UE in the "Fit – for 55" package to reduce the greenhouse gas emissions in the European Union. There are four segments of the glass industry: flat glass, container glass, specialty glass, and fiberglass, [1]. The object of the present work is a case study of the container glass industry. Container glass can be classified as hollow glass, for the food and beverage industry and white glass for pharmaceutical and perfumery, [2]. Container glass belongs to soda-lime glass,es, made of soda (Na_2O), lime (CaO) and silica (SiO_2), with small amount of magnesia (MgO) and alumina (Al_2O_3) and other minor elements, [3]. Glass manufacturing starts preparing the raw materials in the batch made of soda-lime; other elements, like stabilizers, colorants, formers, and fluxes, all of them depending on the desired properties of the final product; and cullet, crushed glass that can be external, if comes from glass recycling, or internal, if it comes from the plant. The batch is sent to the furnace where is heated at a temperature above $1500^{\circ}C$ with different residence times depending on the required glass quality. The melting process produces gases as CO_2 and SO_2 that are removed in the fining process, which typically happens in two steps at different temperatures, [4]. After leaving the melting furnaces and the finishing phase, the forming process starts where the desired shape is imposed to the molten glass in automatic machines where small drops of molten glass are transferred through containers where the desired shape is imposed at a temperature that drops from 1200 °C to 500 °C, [5]. After forming, the container glass is subjected to annealing and coating. Annealing is a slow cool-down to relieve internal stresses. Coating happens by applying two layers: titanium oxide, to prevent scratching and materials like polyethylene to obtain good lubricity, [4]. Of particular interest in the process is the plant producing compressed air, highly energy-intensive, and is estimated to need at least 10 % of the energy for the entire plant. Compressed air plays an important role in the forming process, and it's considered as the "fourth utility", after natural gas, electricity, and water in industry. In order to reduce energy consumption, therefore, it is necessary to ensure that the compressors intended for this purpose can operate as much as possible under optimum operating conditions through continuous monitoring of their basic parameters. A stochastic approach has been developed to face the problem, [6, 7], of monitoring the energy consumption of the compressors in a certain period and relating this to the mass of air processed in that period: the relation has to be linear, when the plant works at the constant flow rate, and any distortion from that behavior is a symptom of compressors malfunction. One problem is that action can only be taken at the end of the observation period so that we cannot avoid dissipating energy, or even affect production in the event of more serious inefficiencies. In this work, the authors suggest an alternative approach, deterministic, to contain the energy dissipations resulting from the non-optimal operation of the air compression system. The compressed air system is divided into the supply side, composed of electrical motors, compressors, and dyers, and the consumption side, where the distribution system and the consumer equipment are located. Both sides have a significant influence on the energy efficiency of compressed air systems, [8]. Energy efficiency is a pivotal factor in reducing energy costs of industries and ISO 50001 is the standard to elaborate an energy management system to ensure the highest energy efficiencies. In compressed air systems, the most adopted solutions to increase energy efficiency envisage:

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- replace compressors, air supply, and refrigerator systems with more efficient ones;
- install seals or replace damaged components in the air distribution system;
- fit valves and pressure regulators;
- install tanks;
- correctly size pipes, fittings, filters, and hoses, [1].

All these measures can lead to improved electricity savings, estimating 502 Toe/year, [2].

Our aim, here, is to set up a deterministic strategy to control and minimize the energy dissipations of the forming section of a glass containers industry named Vetrerie Meridionali S.p.A., belonging to the Owens Illinois group and located in Castellana Grotte (BA), South Italy, where we intend to test the proposed procedure, developed under Industry 4.0 guidelines.

2. Strategy procedure

The energy required to produce glass is also a function of the power processed by the compressors. The latter depends on the compression ratio and the air flow rate disposed of by the machines, according to the relative characteristic curves, Fig. 1,

$$W_a = f(\dot{m}, \beta, T). \quad (1)$$

where $\dot{m}$ is the mass flow rate, β is the compression ratio, and T the temperature.

To optimize the energy consumption of the compressed air system, the idea is to digitalize the operating maps of the compressors to continuously monitor the point of operation of the same through flow and pressure measurements at the supply and intake sections (and a reference temperature), Following this deterministic approach [9], these measured data will allow us to identify, in real-time, the point of operation of the machines to verify their operating efficiency and take appropriate actions when this efficiency is lower than a certain predetermined threshold, regarding the optimal operating conditions.

Operational interventions can be of two types:

- actuating of regulating organs, through control of the characteristic parameters in feedback, to restore the optimal operating conditions;
- maintenance, through an intervention on the system, when the efficiency of the system is heavily compromised (exceeding the threshold imposed to guarantee optimal operation), or in case of appropriate alarms.

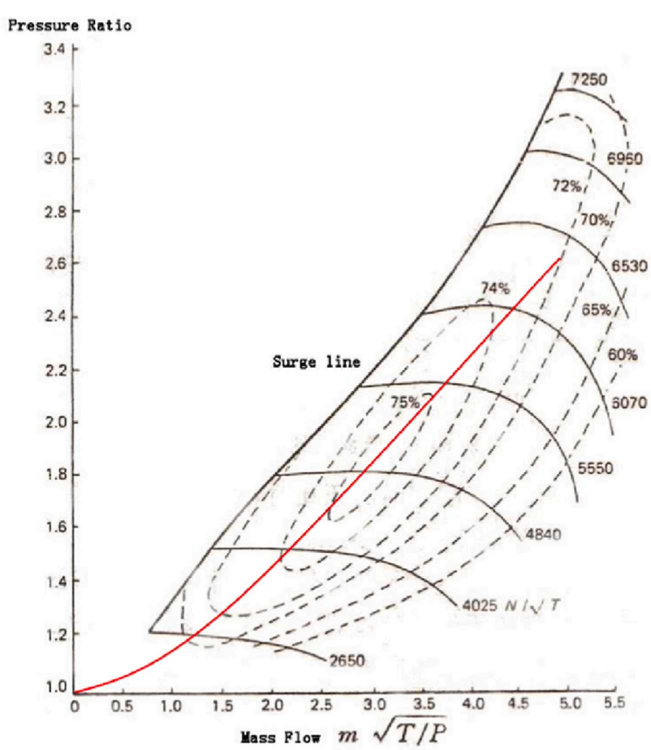

Fig. 1. Example of a compressor map, where the red line is the load curve.

The measured data acquired over time will also allow, periodically, to formulate a statistical analysis of the energy consumption and verify the correct linearity between the energy provided to the compressors at the time of investigation (given by the energy meters) and the mass of air supplied to the forming equipment in that time.

The mathematical relation (usually obtained by linear regression of the acquired data) can be written as,

$$E = k \cdot Cap + b \quad (2)$$

where:

- E Energy consumption [kWh];
- Cap Compressed air produced [Nmˆ3];
- k and b are dimensional constants.

Loss of linearity, whether it is a jump or continuous over time, would indicate abnormal operation of the machines at the time they occur, but recognizable only at the end of the investigation period, while the deterministic approach detects and signals it immediately when the anomaly occurs.

3. Case of study

As said above, the case study is a glass container industry located in South Italy. The plant produces glass containers for food and beverages, like bottles for wine, sparkling wine, vinegar, mineral water, fruit juice, tomato sauce, and soft drinks. In Fig. 2 a view of the pipelines of the plant under consideration is shown. The forming process is executed in an Individual Sections Forming Machine (ISM), with twenty independent sections. The molten glass is divided into gobs that are automatically injected into the molds, [10]. The mold of the ISM machine has a “blank”, where the parison is formed, and a “blowing” area where the final shape is given, [11].

3.1. Compressed air measurement

To monitor the energy efficiency of compressors, flow, pressure, and temperature meters are installed on compressed air lines.

In, Fig. 3, the low-pressure compressed air production line (3.5 bar) and the positions of the instruments are highlighted.

Fig. 2. Case of study: hollow glass industry, glass plant in south Italy.

As flow meters, the thermal dispersion mass flowmeters are chosen because, even if intrusive, they minimize the flow alteration so warranting, at the same time, a very good accuracy of the measure, Fig. 4. Their working principle is based on King's law (energy balance equation) which estimates the mean flow velocity from heat exchanged with a temperature-set object, [12]. There are two major categories of thermal mass flowmeters: thermal dispersion flowmeters and capillary tube flowmeters. Both provide the flow rate measure from the measure of the thermal energy dissipated by a hot wire immersed in the flowing fluid, by convection heat transfer, also dependent on the fluid properties. These flowmeters operate on the principle of heat transfer, where the flow of fluid within a pipe is subjected to a heating power through a resistor with an electric current passing through it. This heating power is absorbed by the fluid, allowing the flow rate to be measured, [13]. Thermal dispersion mass flowmeters are suggested for higher flow rates, while capillary tube mass flowmeters are suggested for lower flow rates, [14].

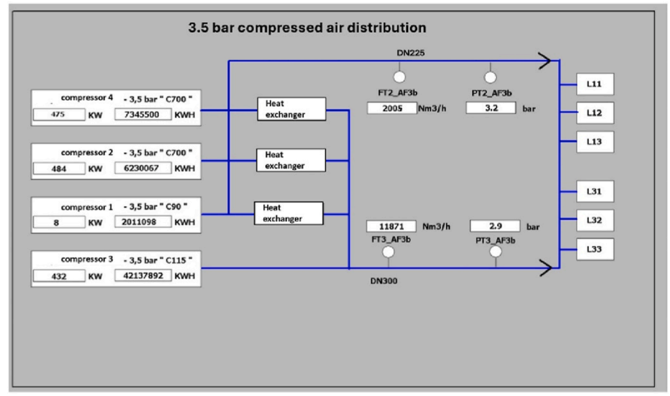

Fig. 3. Scheme of the compressed air system.

Fig. 4. Installation of the thermal flow meter on a compressed air line of the plant.

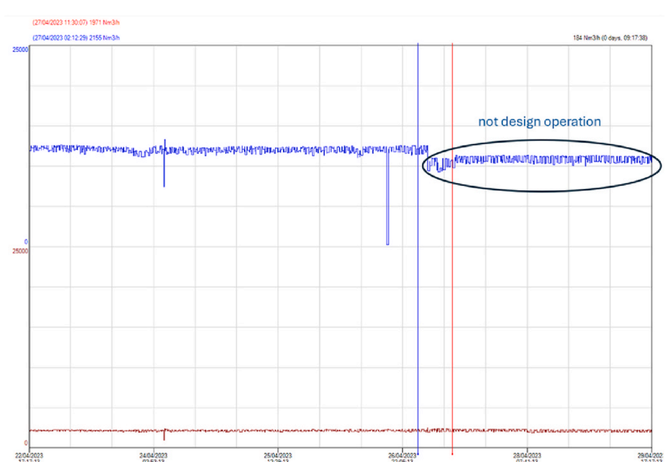

Fig. 5. Acquired flow rate signal.

4. Results

The tests just begun provided measurements of flow rates, pressures, and temperature over time, reported here, flow rate only, for the first week of testing in the graph of Fig. 5.

The flow measurements, in particular, were carried out on a line of low-pressure compressed air fed by a single compressor (red line and hot air), and on the cold air line collecting the flow supplied by all 4 compressors.

The graph shows a decrease in flow rate on 26 April, which indicates a malfunction in one of the other 3 cold air compressors (the fourth hot air compressor shows no anomalies in the period). The digitized maps of the machines, from the measure of flow and pressure, would immediately signal the information of the compressor out of range of optimal operation, thus being able to act on the regulating organs of the same, through a chain in feedback, to restore normal operating conditions immediately or by signalling an alarm in the event of a major anomaly to stop the plant and intervene with the maintenance.

5. Conclusions

This work introduces a deterministic approach to the control and regulation of the compressors of a compressed air system in the light of the Industry 4.0 guidelines, to minimize energy dissipation resulting from off-plan compressor operation. One can easily see the difference with the statistical approach proposed in the literature for similar plants, which cannot guarantee the management of energy dissipation in accordance with what is expected by the industrial automation, although easier in the analysis, a posteriori, but that cannot prevent and/or intervene in a short time on the anomaly that occurred. The results of the first continuous measurements carried out, demonstrate the possibility of emergency intervention when a failure occurred, having the availability of the digitized maps that would instantly provide the operating conditions of the machines thus allowing a timely intervention in the event of failure. the procedure thus allows to minimize the energy dissipations, in addition to ensuring the automation of the management of the plant.

This research lays the foundation for implementing digital twin technology in predictive maintenance systems. Future work will focus on refining the data analytics algorithms to enhance fault detection accuracy and optimize maintenance scheduling.

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References

[1] Galitsky, Christina, Worrell, Ernst, Galitsky, Christina, Masanet, Eric, & Graus, Wina. Energy Efficiency Improvement and Cost Saving Opportunities for the Glass Industry. ENERGY STAR Guide Energy Plant Manag. United States. https://doi.org/10.2172/927883.

[2] A. Cantini, L. Leoni, S. Ferraro, F. De Carlo, C. Martini, F. Martini, M. Salvio, Technological energy efficiency improvements in glass-production industries and their future perspectives in Italy, Processes 10 (12) (2022) 2653, https://doi.org/10.3390/pr10122653.

[3] D.D.F. Del Rio, B.K. Sovacool, A.M. Foley, S. Griffiths, M. Bazilian, J. Kim, D. Rooney, Decarbonizing the glass industry: a critical and systematic review of developments, sociotechnical systems and policy options, Renew. Sustain. Energy Rev. 155 (2022) 111885.

[4] M. Zier, P. Stenzel, L. Kotzur, D. Stolten, A review of decarbonization options for the glass industry, Energy Convers. Manag. X 10 (2021) 100083.

[5] A.K. Varshneya, Fundamentals of Inorganic Glasses, Elsevier, 2013.

[6] M. Benedetti, F. Bonfà, V. Introna, A. Santolamazza, S. Ubertini, Real time energy performance control for industrial compressed air systems: methodology and applications, Energies 12 (20) (2019) 3935.

[7] P. Sovilj, D. Pejić, M. Urekar, S. Mandić, Digital stochastic measurement and industry 4.0, in: 26th IMEKO TC4 International Symposium 24th International Workshop on ADC and DAC Modelling and Testing IMEKO TC-4 2023 Pordenone, Italy, September 20-21, 2023.

[8] J.J.C. Eras, A.S. Gutiérrez, V.S. Santos, M.J.C. Ulloa, Energy management of compressed air systems. Assessing the production and use of compressed air in industry, Energy 213 (2020) 118662.

[9] L. Fabbiano, et al., A strategy to control industrial plants in the spirit of Industry 4.0 tested with a fluidic system, Acta IMEKO 11 (2) (2022) 1–7.

[10] Hiltmann Kai, Neubauer Tobias, Case study: gob loading in a glass moulding machine, Procedia CIRP 39 (2016) 203–208.

[11] S. Okwuobi, F. Ishola, O. Ajayi, E. Salawu, A. Aworinde, O. Olatunji, S.A. Akinlabi, A reliability-centered maintenance study for an individual section-forming machine, Machines 6 (4) (2018) 50.

[12] King, L. V. XII. On the convection of heat from small cylinders in a stream of fluid: determination of the convection constants of small platinum wires with applications to hot-wire anemometry. Philos. Trans. R. Soc. Lond. - Ser. A Contain. Pap. a Math. or Phys. Character, 214(509–522), 373-432.

[13] M. Farzaneh-Gord, S. Parvizi, A. Arabkoohsar, L. Machado, R.N.N. Koury, Potential use of capillary tube thermal mass flow meters to measure residential natural gas consumption, J. Nat. Gas Sci. Eng. 22 (2015) 540–550.

[14] J.G. Olin, Industrial thermal mass flowmeters—Part 1: principles of operation, Meas. Contr. 193 (1999) 83–90.

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