Renewable and Sustainable Energy Reviews 89 (2018) 72–87

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Linking energy efficiency measures in industrial compressed air systems with non-energy benefits – A review

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ARTICLE INFO

Keywords:
Energy efficiency
Compressed air systems
Energy efficiency measures
Non-energy benefits
Industry
Systematic literature review

ABSTRACT

Compressed air is widely used in supporting industrial manufacturing processes due to its cleanness, practicality and ease of use. However, the efficiency of compressed air systems is often very low. Typically, for compressed air-driven tools only 10–15% of the energy input is utilised as useful work. Despite these recognised inefficiencies, and even though energy efficiency measures for compressed air systems normally offer several opportunities for energy savings and energy cost savings, generally, less attention has been given to the energy use and energy costs incurred in compressed air systems. Industrial energy efficiency measures might also yield additional effects, beyond the energy savings, which are denoted as non-energy benefits. This study reviews the existing base of scientific knowledge on energy efficiency in compressed air systems combined with the perspective of non-energy benefits. Even though some measures were mentioned more frequent than others, the results revealed significant variation in which measures could be undertaken to improve energy efficiency in compressed air systems. However, few publications employ a comprehensive approach by examining the entire compressed air system. Furthermore, few publications have addressed the possible additional benefits to be gained from energy efficiency measures in compressed air systems. This study provides a compilation of the various energy efficiency measures reported in the reviewed scientific literature that can be undertaken in order to improve energy efficiency in compressed air systems. It also provides a comprehensive take on the measures, including a systems perspective, by categorising them in respect to where in the compressed air system they can be undertaken. This paper suggests that energy efficiency measures in compressed air systems, and related non-energy benefits, should be studied on a specific measure level to fully understand and acknowledge their effects on the energy use of a compressed air system and possible additional effects, i.e. non-energy benefits.

1. Introduction

Compressed air supports many industrial processes and is a widely used application in manufacturing industries due to its cleanness, practicality and ease of use. Some of the applications in which compressed air is used consist of tools driven by compressed air, and processes such as stirring, blowing, moulding and sorting [1]. The energy source used for the production of compressed air is most often electricity. In the EU-15 countries, the energy used to produce industrial compressed air accounts for 10% of their annual electricity use [1]. However, the efficiency of a compressed air system is often very low. For instance, for tools driven by compressed air, just 10–15% of the energy input into a compressed air system is utilised as useful work [1]. This inefficiency is for instance the result of heat losses during the compression stage or due to leakages in the system. If a life-cycle cost perspective were applied, it would show that the energy use of a compressed air system represents a major share of the total cost, representing almost 80%. Despite the fact that energy efficiency measures for compressed air systems normally offer great opportunities, both for energy savings and energy cost savings, little attention has been paid to the energy use and energy costs incurred in compressed air systems. However, based on data from the United States, Canada, the European Union, Thailand, Vietnam and Brazil, McKane and Hasanbeigi [2] reported a 56% technical savings potential for compressed air; moreover, many of the proposed energy efficiency measures were considered to be low-cost measures. Marshall [3] further stressed that an efficient compressed air system (i.e. an optimised compressed air system) uses 66% less energy than a standard system. Hence, there seems to be an unexploited potential, i.e. energy efficiency in compressed air systems can still be improved.

Energy efficiency measures for compressed air systems are, and have been, proposed by handbooks and guideline documents on compressed air systems, for example, and by suppliers, supply associations and energy audit experts of compressed air systems. However, to the

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https://doi.org/10.1016/j.rser.2018.02.018
Received 16 November 2016; Received in revised form 12 October 2017; Accepted 20 February 2018
1364-0321/

author's best knowledge, a review of academic contributions on energy efficiency and energy efficiency measures for compressed air systems has not yet been conducted. The current lack of a summary of published scientific articles on the topic calls for a literature review to be conducted on energy efficiency in compressed air systems. Furthermore, a review on energy efficiency measures for compressed air systems that focuses on the whole system including all sub-parts will illustrate which measures can, theoretically, be undertaken to improve the energy efficiency of the system.

Hence, since there seems to be a potential for further improvements of energy efficiency in compressed air systems, the first part of the objective of this paper is, via a comprehensive take, to review and summarise the energy efficiency measures for compressed air systems as proposed by the scientific publications on the topic, and further, to structure the measures in respect to where in the compressed air system they can be undertaken.

Even if great potential for energy efficiency improvements to be made in compressed air systems seems to exist, the proposed measures are not always realised. Previous literature explains this non-implementation by the existence of barriers to energy efficiency, e.g. [4,5] and [6], and Trianni et al. [7] have further shown that the implementation of energy-efficient technologies, such as for compressed air, and even specific energy-efficient measures for a certain technology, face different barriers. Cagno and Trianni [50] concluded that specific energy efficiency measures in compressed air systems often face information-related barriers, such as lack of information on costs and benefits regarding the considered measure.

However, the implementation of energy efficiency measures might also yield additional effects, so-called non-energy benefits, that extend beyond energy savings and energy cost savings, e.g. [8]. Various types of non-energy benefits have been observed as a consequence of improving energy efficiency in general, for instance, benefits such as improvements in production, less operation and maintenance, and improvements in the work environment, e.g. [8] and [9]. Previous studies have shown that if quantified and translated into monetary terms, the value of the non-energy benefits are significant; in some cases, it even exceeded the value of the energy savings for implemented energy efficiency improvements, e.g. [8] and [9]. This raises the interest to also investigate additional benefits as a consequence of energy efficiency measures undertaken in compressed air systems.

Even if previous studies have observed various types of non-energy benefits of industrially implemented energy efficiency measures, most have addressed them as an outcome of energy efficiency in general; or, from another perspective, they have observed and reported on the non-energy benefits of specific measures as one entity. In other words, in most studies, particular non-energy benefits have not been related to specific energy efficiency measures, and vice versa. Furthermore, the main focus of the literature has been on the quantification of non-energy benefits, rather than relating the benefits to specific energy efficiency measures. Hence, there seems to be a gap in recognition of the particular non-energy benefits of specific energy efficiency measures or a lack of reporting on the non-energy benefits of specific energy efficiency measures. This investigation is of interest since knowledge on specific non-energy benefits might be a means to overcome specific barriers to energy efficiency measures in compressed air system, which might improve energy efficiency and unlock the potential for further improvements. Therefore, the second part of this study´s objective consists of studying the specific non-energy benefits as an outcome of realised energy efficiency compressed air measures.

To conclude, this paper aims to provide an academic perspective on energy efficiency in compressed air systems by reviewing the scientific literature in the area of energy efficiency in industrial compressed air systems including the perspective of the non-energy benefits.

The remainder of this paper starts with an overview of the system for compressed air including a historical background on compressed air (Section 2), followed by an introduction to non-energy benefits (Section 3). In Section 4, the research methods applied are described and Section 5 provides the results of reviewing the literature on energy efficiency in compressed air systems and non-energy benefits. Thereafter, the results are discussed in Section 6. The paper ends with a concluding discussion and implications for future studies in Section 7.

2. The use of compressed air in industry

Compressed air is used in industrial processes for various applications; as a part of several industrial processes, such as stirring, blowing, moulding and sorting, or as an energy medium, for instance, in compressed air-driven tool actuators [1]. Saidur et al. [10] have presented examples of various compressed air applications in different industrial sectors that showed that industrial sectors have individual needs for their use of compressed air. This implies that the design of compressed air systems varies between sectors, but that the system should also match the processes and the production within the individual firm. Hence, each industrial compressed air system could be considered as unique and specifically adjusted to processes in the individual firm.

2.1. Historical overview of the development of the industrial use of compressed air

In technological terms, the use of compressed air started in the late nineteenth century, but the history of compressed air started thousands of years ago with the use of the human lungs when early civilisations blew on cinders to create fire [52]. Gårdlund et al. [52] describe that as the science of metallurgy developed, more powerful tools were needed to cool the metals and this led to the first types of mechanical compressors, for instance the blowpipe, which was followed by hand- and foot-operated bellows (around 1500 BC) and then water-wheel-driven blowing cylinders (around 50 AD). These tools were all used for about 2000 years to ventilate mines and to generate blast to furnaces until blowing engines were invented in the eighteenth century [52]. During the nineteenth century several attempts to transfer compressed air were made and a major step in that sense and in the history of compressed air is the excavation of the Mont Cenis Tunnel between France and Italy between 1857 and 1871 [52]. Pneumatic drills were powered by a compressed air plant, which increased productivity compared to the use of manual drilling methods and furthermore, the drilling of the 12.2-kilometre tunnel showed that compressed air could be distributed over longer distances than before [52].

The interest in compressed air continued to increase; a large compressed air system was installed and adopted in Paris in 1888. Gårdlund et al. [52] describe that the system, which consisted of a 7-kilometre main distribution piping and a 50-kilometre distribution piping of smaller size, was powered by various types of motors, both smaller ones and those of large types. At that time, 12 compressors generated a system pressure of 6 bar, but the system was later on extended with more compressors and the proponents of compressed air claimed it to have surpassed energy carriers like steam and electricity [52].

The industrialisation during the nineteenth century was characterised by the replacement of heavy manual processes that required human power by mechanical processes where the mechanical energy was transferred by compressed air [51]. Motor-driven hand-operated tools were powered by electricity, steam and compressed air, of which compressed air later was shown to be the prevailing one, mainly because compressed air-driven tools had a simple construction, few moving parts, were reliable, robust, easy to repair and very efficient considering their weight [52], and these are still used as arguments for the use of compressed air-driven tools nowadays even if the efficiency of compressed air systems normally is low. However, already in the 1950s, Möre [51] addressed that efficiency could be improved in compressed air systems if compressed air-driven tools were turned on only when used and then turned off when not used.

In the beginning of the twentieth century, there was a great