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Energy conservation in industrial pneumatics: A state model for predicting energetic savings using a novel pneumatic strain energy accumulator

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HIGHLIGHTS

- Developed model-based efficiency performance metrics for industrial pneumatic systems.
- Quantified system efficiency increases due to the Pneumatic Strain Energy Accumulator.
- Experimentally validated model efficiency increases ranging from 32% to over 78%

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ABSTRACT

A number of national organizations have recently expressed interest in research to develop materials and devices that achieve greater energy storage capacity, power density and increased energy efficiency on the heels of a report finding that the pneumatic sector of the fluid power industry averages only 15% efficiency. One way of improving efficiency is the use of compressed air storage and recycling devices. The pneumatic Strain Energy Accumulator is a recently developed device that recycles exhaust gas from one pneumatic component, stores it in a highly efficient process, and reuses the stored exhaust gas at a constant pressure to power another pneumatic component. This work analyzes system efficiency increases directly attributable to the implementation of a pneumatic strain energy accumulator by applying an analytical methodology for system level efficiency improvement calculations, experimental validation, and compressed air savings projections. Experimentally determined efficiency increases ranged between 32% and 78%, demonstrating that the pneumatic strain energy accumulator can be a viable part of the solution to the fluid power efficiency challenge.

1. Introduction

A report published in 2012 by Oak Ridge National Labs (ORNL), in conjunction with the National Fluid Power Association (NFPA), revealed that the operations in the fluid power industry are only 22% efficient [1]. The pneumatic sector of the fluid power industry was found to be even worse averaging just 15% efficiency. One technology that has been developed to improve the efficiency of the fluid power industry is the strain energy accumulator (SEA) [2–5].

The pneumatic version of the SEA, or the pSEA, is an energy storage device, consisting of an expandable rubber bladder inside of a rigid shroud that utilizes the hyperelastic behavior of rubber to store energy in the form of strain energy of the stretched rubber material and pressure energy of the stored compressed gas within the material as shown in Fig. 1. The pSEA reclaims exhaust gas from pneumatic cylinders at an initial constant expansion pressure (P_{exp}), temporarily stores the exhaust gas and its accompanying

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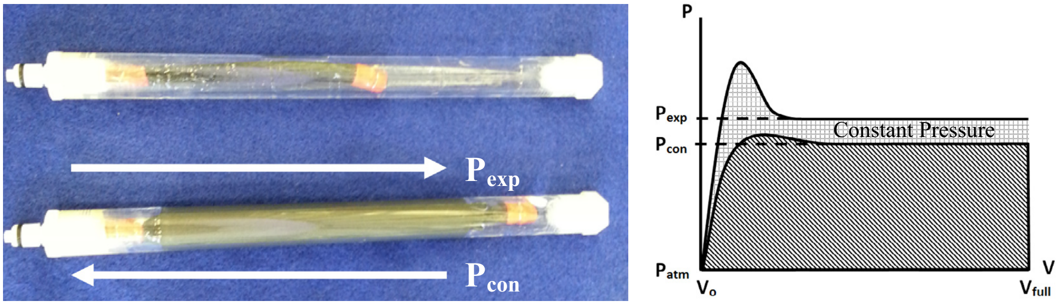

Fig. 1. (left) Empty pSEA on top and filled pSEA on bottom; and (right) PV curve of pSEA with expansion pressure P_{exp}, contraction pressure P_{con}, and constant pressure region.

energy and then recycles it at a lower constant contraction pressure (P_{con}) at a later point in time in a highly efficient process [6].

Compressed air energy storage (CAES) is an active area of research. Ibrahim et al. [7] evaluated several types of energy storage methods, including CAES and small-scale CAES (SSCAES), in areas such as high cycle rates and energy storage capacity to meet the growing energy storage needs in managing renewable energy but did not perform an in-depth study on any one energy storage method. Raju and Khaitan [8] developed a dynamic simulation model for large scale CAES inside of caverns using mass and energy balance methods of a large scale system with a rigid boundary. Luo et al. [9] investigated how system efficiency is affected by component performance and parameters to help achieve higher efficiencies in adiabatic CAES systems and Zhao et al. [10] studied the impact of different discharge modes on CAES efficiency. Each of the modeling efforts focused on large scale compressed air storage and dynamic models which often breakdown with changes in assumptions or are difficult to implement in small scale highly transient systems.

A common source of energy loss in compressed air storage is through heat generation resulting from continuous pressure increases. Several methods to overcome heat loss have been developed and studied including the use of hybrid liquid air CAES systems [11,12] that require long storage times for acceptable efficiencies, and the used of packed bed thermal energy storage [13,14] which do not solve the heat generation problem but increase system complexity in an effort to mitigate heat losses. Kim et al. [15] developed and characterized a constant-pressure hydro CAES system to improve storage efficiency. A number studies look at the economics [16], configurations [17], performance and cost [18], role [19], market [20], and optimal operation [21] of CAES systems to estimate their impact on energy demands. While each of these studies investigated various elements of increasing efficiency on a large scale and/or the economic impact of compressed air energy storage, none combined small scale energy storage that minimizes energy loss through mechanical material properties while developing models that are used to make economic projections at both the local and national levels.

Saadat et al. [22] proposed and modelled an open accumulator CAES system with simulation results. Van de Ven [23] introduced a constant hydraulic pressure non-constant gas pressure energy storage hydraulic accumulator. Bing et al. [24] studied the efficiency increase of a hydraulic elevator applied system using a hydraulic accumulator. Finally, Harris et al. [25] reviewed existing industrial pneumatic efficiency increase approaches and identified the need for model-based performance metrics to quantify and improve the efficiency of pneumatic systems. Even though each of these studies most closely aligns with the use of accumulators and evaluation of efficiency increase methods in pneumatics, none combine a small scale fully pneumatic constant pressure device with simple models and compressed air savings projections. The gaps identified in the literature that the current work addresses, thus introducing the novelty of the work, are that the pSEA is a small-scale fully pneumatic compressed air energy storage device that operates at a constant pressure with first principles model-based performance metrics delivering experimentally validated, compressed air savings projections.

An application using the pSEA that serves as a motivation for the current work is the Ankle Foot Orthosis (AFO) stroke rehabilitation device (Boes et al. [26]). The AFO uses a rotary actuator powered by a compressed gas supply that helps raise and lower a patient's foot during rehabilitation. Similar to industrial applications, the AFO desires to minimize compressed air usage by maximizing efficiency so a patient can carry as small of a portable compressed air supply tank as possible.

During multiple trials, while changing several system parameters simultaneously, efficiency increase estimates ranging from 25% to 75% when using the pSEA on the AFO were reported when compared to the AFO without the pSEA. With no way to directly identify the efficiency increase attributable to the pSEA, a need to quantify the pSEAs impact is needed. This need has led to the development of a lumped parameter state model to estimate system level efficiency improvements. The ultimate goal for the current research is to accurately define efficiency increase limits that can be realized for various systems while using the pSEA and make compressed air savings projections based on currently available data.

One such source of available industry data is the aforementioned 2012 ORNL fluid power efficiency report. According to the ORNL report, there are over 200,000 industrial facilities in the United States that use compressed air. One tenth of all industrial energy consumption goes towards powering industrial air compressors. In some sectors, like chemical manufacturing, industrial air compressors account for over twenty percent of energy consumption. In aggregate, this amounts to 150 billion kilowatt hours ($10 billion) of electricity each year.

According to the US Department of Energy, three fourths of the total life cycle cost (capital expenditure, maintenance, and operations) of an industrial air compressor goes towards electricity. Manufacturing and material handling facilities are the biggest users of compressed air. Because of this, these end users stand to gain the most from decreased compressor demand resulting from increased pneumatic efficiency. Pneumatic technology has remained essentially unchanged for over fifty years. With rising energy costs and intense competition from international firms, companies are now more conscious of controlling costs than ever before.

2. Pneumatic system state efficiency

Prior to conducting efficiency experiments, system level efficiency models were developed in Cummins et al. [27]. The purely