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Review

Industrial compressed air system analysis: Exergy and thermoeconomic analysis

Kamran Taheri[a,*], Rainer Gadow[a,b]

[a] Graduate School of Excellence advanced Manufacturing Engineering (GSaME), 70569 Stuttgart, Germany
[b] Institut für Fertigungstechnologie keramischer Bauteile (IFKB), Allmandring 7b, 70569 Stuttgart, Germany

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ABSTRACT

In manufacturing, compressed air systems generate, store and distribute energy in the form of compressed air for use throughout facilities. However, compressed air is considered as one of the most expensive energy carriers which is accompanied with very high inefficiencies and losses.

According to the thermodynamic concept of technical work, the delivered mechanical work to the consumers and pneumatic drives by the compressed air is influenced by the change of the pressure and flow rate of compressed air. Therefore, it is promising to minimize the losses regarding these parameters. It has been argued that exergy concept is more suitable for evaluation of the efficiency of the compressed air system compared to the energy analysis. Exergy analysis can highlight and classify internal (irreversibilities) as well as external (waste heat) losses. In this study, in the context of sustainable manufacturing, compressed air system is evaluated based on energy consumption, exergy efficiency and thermoeconomics. Therefore, exergy weighted sum (*EWS*) is introduced as an analysis factor which encompasses all the above analysis criteria for the energy efficiency optimization decision support. It is emphasized that *EWS* can be used for evaluation and comparison of the alternative improvement scenarios or technologies.

The results of exergy weighted sum indicate that recovery of the waste heat as well as reduction of air leaks are the best energy efficiency optimization scenarios regarding the power consumption, exergy efficiency and thermoeconomics for the investigated compressed air system.

Contents

Introduction

Resource efficiency in all fields, especially when it comes to energy saving is a big issue of all times. In manufacturing, compressed air is commonly used to perform a wide variety of tasks such as cleaning, operating pneumatic equipments, testing of

Abbreviation: EWS, Exergy weighted sum.

* Corresponding author. Fax: +49 711 685 68299.
E-mail addresses: kamran.taheri@gsame.uni-stuttgart.de, kamran.t@mail.de (K. Taheri).

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Nomenclature

c	Cost per unit of exergy (€/kJ)
C	Cost of exergy stream (€)
C_p	Specific heat capacity at constant pressure (kJ/kg k)
$\dot{E}$	Exergy rate (kW)
h	Specific enthalpy (kJ/kg)
H	Enthalpy (kJ)
$\dot{m}_a$	Air flow rate (g/s)
M	Molar mass (g/mol)
n	Polytropic index
$\dot{Q}$	Heat flow (kW)
p	Pressure (bar)
R	Gas constant (J/mol K)
s	Specific entropy (kJ/kg K)
T	Temperature (°C or K)
$\dot{V}$	Volume flow rate (m^3/min)
$\dot{W}$	Electrical power (kW)
Z	Capital cost (€)

Subscript

0	Ambient condition
a	Air
act	Actual
ave	Average
cv	Control volume
d	Destruction
ele	Electricity
en	Energy
in	Input stream
k	Component
l	Loss
min	Minimum
out	Outlet stream
P	Product
poly	Polytropic
Rec	Recovered
w	Power

Greek letter

f	Exergoeconomic factor
η	Energy efficiency
Ψ	Rational efficiency

the manufactured products and etc. However, due to the pressure and air flow rate drop, compressed air systems are associated with high amount of energy quantity and quality losses which cost a lot for the companies [1].

Using the thermodynamic concept of technical work, the generated pressurized air delivers the mechanical work ($\Delta p \cdot V$) to consumers and pneumatic drivers by change in pressure and volume [2], see Fig. 1. However, due to the irreversibilities (e.g. flow friction, pressure drops through the system components and also the air leaks) pressure and air flow rate are decreased. These cause the reduction of the system performance and delivered mechanical work to the end-use equipments. From the resource accounting perspective, the losses bring an additional energy cost by an increase of electrical power consumption as the compressor must work with higher power intake or longer cycle time to make up for the losses [3,4].

Referring to Fig. 2 a typical compressed air system is split into three main segments, namely generation (often including air preparation), distribution and application [5]. It is illustrated that

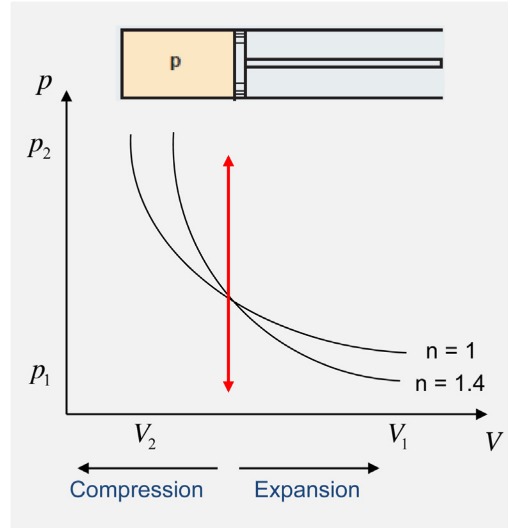

Fig. 1. Isothermal and polytropic curves in p–V diagram [4].

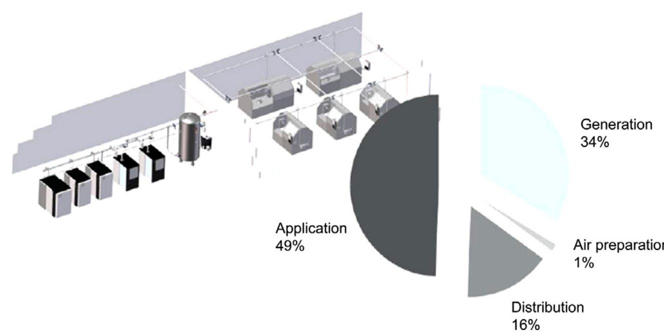

Fig. 2. Layout of typical compressed air system and the estimated savings in each area [5].

the main saving can be achieved in application and distribution followed by the compressed air generation part.

Studies showed that the efficiency of compressed air system is about 5–10% [6]. This persistent assumption is based on the energy flow diagram in Fig. 3(a). It shows that the useful pneumatic output which is delivered to the pneumatic drives is about 6.9% [7].

In the context of pneumatic power evaluation, energy and enthalpy methods lead to a misunderstanding of the mechanical work output as they are the only function of temperature and do not account for pressure change. For example, with an assumption of the isothermal system, the total electrical power consumption by the compressor must be removed as the heat to keep the temperature and enthalpy of the air constant. Therefore, the energy efficiency of the compressor will be 0%. On the other hand, if the waste heat from the compressor is taking into account as the useful output for recovery, the efficiency will be 100%. Both efficiencies are correct, but significantly depend on the analyzed system boundaries. It can be concluded that the thermodynamic concept of energy is not suitable to describe the correct efficiency of a compressed air system. To overcome this limitation, exergy analysis has been proposed which takes into account the influence of both the pressure and air flow rate on the mechanical work output and the true description of the system efficiency [8]. As it is shown in Fig. 3(b), in contrast to energy efficiency, exergy efficiency of the compressed air system is almost 42% [2,9].

Exergy analysis has been successfully applied as a powerful analysis tool for the efficient design of the engineering systems