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Research Paper

A cost-effective compressed air generation for manufacturing using modified microturbines

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HIGHLIGHTS

- A new cost-effective way of compressed air generation for manufacturing in SME is proposed.
- The approach is based on a modified microturbine configuration.
- Thermodynamic and life cycle analyses are presented and economic benefit is demonstrated.

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ABSTRACT

Compressed air is an irreplaceable energy source for some manufacturing processes, and is also common in applications even when there are alternatives. As a result, compressed air is a key utility in manufacturing industry, but unfortunately the cost of compressed air production is one of the most expensive processes in a manufacturing facility. In order to reduce the compressed air generation cost an unconventional way using a microturbine configuration is proposed. The concept is based on an extraction of a certain amount of compressed air from/after the compressor with the residual air flowing to the turbine to produce sufficient back power to drive the compressor. A thermodynamic and life cycle analysis are presented for several system variations, including a simple cycle without a recuperator and a complex configuration with an intercooler, recuperator and reheating. The study is based on the typical requirements (i.e. quantity, pressure) for a small to medium sized industrial compressed air system. The analysis is focused on the North American market due to the low price of natural gas. The lowest life cycle cost alternative is represented by a microturbine concept with a recuperator, air extraction after partial compression, intercooler and aftercooler. A comparison of an electric motor and conventional microturbine prime movers demonstrates the economic benefit of the proposed compressed air generation method, for the design parameters and utility prices considered.

1. Introduction

Duflou et al. [7] have synthesized the research in energy and resources efficiency in manufacturing. One of the aspects of energy efficiency in manufacturing is Compressed Air (CA) generation and use. It has been recognized previously that compressed air generation and treatment generally account for approximately 10% of the total energy consumption in an industrial facility [20]. Furthermore, compressed air energy is, and will be, an important industrial utility given that for some production processes the use of compressed air is irreplaceable. Eret et al. [9] have shown that the low overall energy efficiency of industrial compressed air systems is caused by inappropriate and wasteful utilization at the end use point. The compressors are usually driven by electric motors, hence the cost of the electricity is the largest contributor to life cycle costs of a typical compressed air system [10].

An alternative to electric motors and gas turbines as compressor prime movers is to use an engine working on a modified gas turbine principle directly. The concept shares much in common with bleed air used in jet engines for aircraft. It is based on an extraction of a certain amount of compressed air from/after the compressor while the rest of the medium runs through the system to the turbine producing just enough back power to drive the compressor. Benchmarking revealed that a typical size of a compressor in small to medium manufacturing compressed air systems would have a rated capacity of about 28–56 N m^3/min (1000–1200 scfm) and a discharge pressure level of 9–10 bar(a) approximately. At this scale, the modified gas turbine approach to CA generation would require microturbines.

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Nomenclature

β	pressure ratio
$\Delta p/p$	percentage pressure drop
$\dot{m}$	mass flow rate
$\dot{Q}$	heat rate
ϵ	recuperator effectiveness
η	isentropic efficiency
κ	specific heat ratio
Ξ	cost function
C	present value of the costs
$c_1,\ c_2$	cost coefficients for compressor
C_p	constant-pressure specific heat
$cc_1,\ cc_2$	cost coefficients for combustion chamber
f	recuperator material cost factor
ic_1	cost coefficient for intercooler/aftercooler
LCC	Life Cycle Cost
p	pressure
r_1	cost coefficient for recuperator
T	temperature in Kelvin
$t_1,\ t_2$	cost coefficients for turbine

Subscripts

a	air
c	compressor
cc	combustion chamber
cor	corrected
E	energy
g	gas
I	total investment
max	maximum
occ	occurrence
OMR	non-fuel operating, maintenance and repair
pre	present
r	recuperator
ref	reference
RES	residual value
t	turbine
W	water
in	inlet
out	outlet

Microturbines are small gas turbine units with a power range of less than 500 kWe [12]. Compared to the other small scale power generation technologies (i.e. reciprocating engines), small gas turbines offer a number of advantages: compact size, flexibility of operating on liquid or gaseous fuels, small number of moving parts, extremely low emissions (about one order of magnitude lower than those of reciprocating engines) and low maintenance costs. On the other hand, microturbines have lower efficiency in their basic configuration in comparison to other small scale power generation technologies. Several modifications such as recuperator or intercooler lead to significant increases in thermal efficiency or specific power [21], but also increase system complexity. Moreover, McDonald and Rodgers [18] have shown that there is a potential in the use of ceramic components for the eventual development of recuperated microturbine efficiency to 40% or higher. The increasing complexity means that a complete thermoeconomic analysis is necessary to properly evaluate whether the proposed system is cost effective [12,15]. The main barrier to microturbines market penetration is higher investment costs (above 1000 USD/kWe). However, the initial costs of microturbines are estimated to decrease significantly over the next decade resulting in new potential applications.

This study investigates the attractiveness of the generation of compressed air using a modified gas turbine open cycle configurations from both thermodynamic and economic points of view. The analysis is focused on the North American market due to the low price of the fuel (natural gas). The European market is also briefly commented. For the sake of simplicity it is assumed that the device operates at mandatory design conditions (i.e. fully loaded). Possible ways to control mass flow rate and pressure level are: (i) blow-off valve installed directly on CA bleed, which might prevent compressor instabilities at the expense of some CA waste, (ii) inlet modulation/bypass and (iii) variable speed engine. A proper control methodology and various off-design scenarios can be researched in future work.

2. Thermodynamics of open cycles

2.1. Simple and advanced cycles

Fig. 1 shows schematically the most complex configuration of the system under investigation, since all other cycles can be interpreted as a simplification of this layout. After the air is induced into the compressor (at point 1) a two stage compression is used, with an optional cooling between each stages (2–3) to improve the efficiency of the overall process. It is possible to preheat the compressed air stream exiting the compressor (4) in the recuperator (4–5) using waste heat from the turbine exhaust. This airstream is then mixed with fuel and ignited in the combustion chamber (5–6). The hot combustion gas is expanded through a two stage turbine (6–9) with an optional secondary combustion chamber between the two stages. The exhaust is eventually rejected (10) after passing through the recuperator. The configuration with additional reheating (two stage expansion) is included into the analysis for the sake of interest, because at the moment no microturbine exists with a reheat solution, which is particularly difficult to be implemented at the size of small gas turbines.

The thermodynamic analysis of five variants of the gas turbine cycle is initially performed. These are listed below:

- SC: simple cycle (no recuperator).
- R: regenerated cycle (recuperator).
- R + R: reheating + recuperator.
- I + R: intercooling + recuperator.
- I + R + R: intercooling + recuperator + reheating.

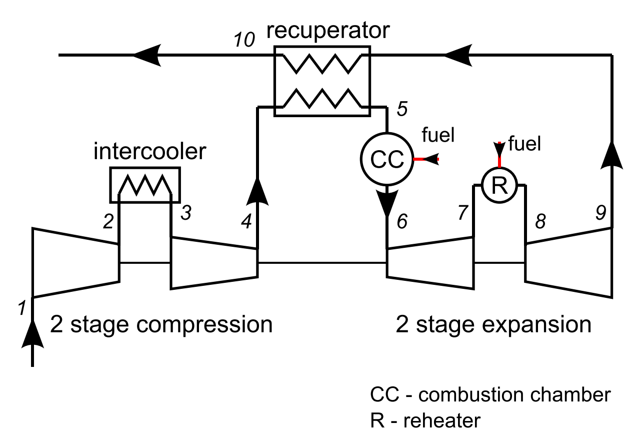

Fig. 1. Schematic of the most complex system configuration in this study.