Direct Generation of Compressed Air from Waste Heat by Cascaded Thermocompressors with Self-Excited Overdriven Free Displacers

Analytical and Numerical Analysis

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Compressed air is a widely used but expensive and inefficient industrial energy source. At the same time, large amounts of waste heat remain unused. In order to exploit and utilize this waste heat potential at low production and operating costs, a novel concept based on reciprocating thermocompressors has been developed. It focusses on maximum constructional simplicity by arranging a cascade of identical stages, and on the application of self-excited, overdriven free displacers, the frequencies of which may adapt independently of the pressure to ensure optimum operation of all stages, while largely maintaining or even exceeding thermal similarity to the first stage. In order to prove the feasibility of such a system, it has been investigated by means of an analytical and a numerical analysis.

The basic layout of a reciprocating thermocompressor shows similarities to a β- or γ-type Stirling engine, in which a pair of check valves replaces the power piston. Thus, the air to be compressed simultaneously acts as the working fluid of an open cycle. Figure 1 shows the schematic arrangement of two consecutive stages k and k+1 within a cascade. Their reciprocating displacers periodically relocate the air between the hot and cold cylinder volumes via a duct consisting of a cooler, a regenerator and a heater. During the downward motion, the pressure is raised due to isochoric heating, until it reaches the outlet pressure. From then on, it remains constant, since the outlet valves open and discharge the air into the upward buffer volume. At the end of stroke, the displacers hit elastic limit stops, so that their motion is reversed, preserving their kinetic energy in the ideal case. The outlet valves close, and the pressure drops due to cooling, until the inlet valves open and air from the downward buffer enters the cycle volume. At the lower end of stroke, the displacers once again bounce back elastically, and the cycle is closed. As the displacer rod periodically plunges into the cold cylinder, the overall cycle volume varies, and p,V-work is generated. When properly designed, this work compensates any friction losses, thus eliminating the need for external actuation.

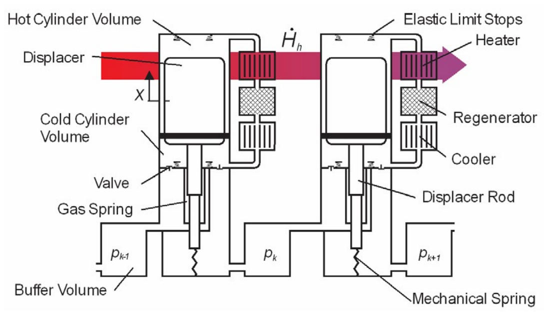

Figure 1: Schematic drawing of two stages of a cascade of identical overdriven free-displacer thermocompressors.

All relevant operating parameters, such as the conveyed mass of air, the heat absorbed and the exergy gain of the compressed air flow, depend on the stage pressure ratio in such a way that a self-controlled steady-state operation can be expected. The results obtained with an analytical model indicate that such stable operating points exist above a critical stage pressure ratio.

To further investigate the operating characteristics, a three-stage cascade was modelled in Simulink® with its extension SimscapeTM. Figure 2 exemplarily shows the exergy gain of the compressed air flow as a function of the total pressure ratio for the single stages k and for the entire cascade. The simulation results confirm the expected stable operation of all stages for a wide range of total pressure ratios as well as the existence of lower stability limits, where the lowest operating stage stops.

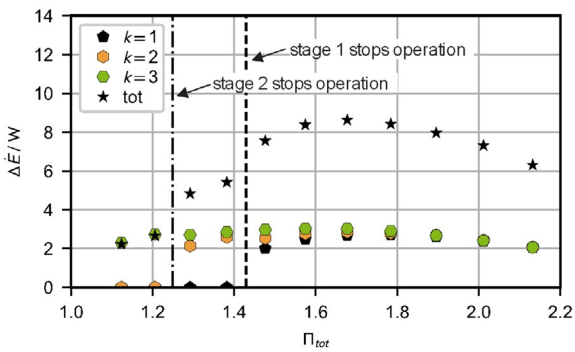

Figure 2: Exergy gain ΔĖ of the compressed air flow (total and for each stage k of the three-stage cascade) vs. total pressure ratio Πtot.

The results demonstrate that the presented concept is a promising approach to generate compressed air from waste heat in a both economically and ecologically advantageous way, and therefore strongly suggest further experimental investigations as the next step.

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