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Numerical and experimental analyses of different magnetic thermodynamic cycles with an active magnetic regenerator

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HIGHLIGHTS

- New thermodynamic cycles with an active magnetic regenerator (AMR) are presented.
- Three different thermodynamic cycles with an AMR were analyzed.
- Numerical and experimental analyses were carried out.
- The best overall performance was achieved with the Hybrid Brayton–Ericsson cycle.
- With this cycle the temperature span of test device was increased by almost 10%.

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ABSTRACT

We have analyzed the influence of different magnetic thermodynamic cycles on the performance of a magnetic cooling device with an active magnetic regenerator (AMR) based on the Brayton, Ericsson and Hybrid Brayton–Ericsson cycles. Initially, a numerical simulation was performed using a 1D, time-dependent, numerical model. Then a comparison was made with respect to the cooling power and the *COP* for different temperature spans. We showed that applying the Ericsson or the Hybrid Brayton–Ericsson cycle with an AMR, instead of the standard Brayton cycle, can increase the efficiency of the selected cooling device. Yet, in the case of the Ericsson cycle, the cooling power was decreased compared to the Hybrid and especially compared to the Brayton cycle. Next, an experimental analysis was carried out using a linear-type magnetic cooling device. Again, the Brayton, Ericsson and Hybrid Brayton–Ericsson cycles with an AMR were compared with respect to the cooling power and the *COP* for different temperature spans. The results of the numerical simulation were confirmed. The Hybrid Brayton–Ericsson cycle with an AMR showed the best performance if a no-load temperature span was considered as a criterion.

1. Introduction

The ever-growing demands for energy in all sectors and an awareness that increased energy consumption can have a negative impact on the environment have led to the search for new technologies that are more energy efficient and environmentally friendlier. In the field of refrigeration, the current vapor-compressor technology is reaching its limits in terms of energy efficiency. Furthermore, because of harmful refrigerants, potential working-fluid leakages can have a negative impact on the environment [1].

As an answer to these problems, new technologies are emerging, one of them being magnetic refrigeration [2]. This technology is based on an exploitation of the magnetocaloric effect (MCE). When a material exhibiting the MCE is exposed to an increase in magnetic field the material heats up. The opposite happens when the magnetic field is decreased, and so the magnetocaloric material (MCM) cools down. So far, the most promising way to make use of this effect in a cooling device is based on what is referred to as an active magnetic regenerator (AMR) [3]. An AMR is a porous structure of MCM through which a fluid is pumped in a counter-flow direction. Most of the already-described devices that use an AMR operate under the Brayton magnetic refrigeration cycle [3]. Furthermore, the majority of numerical analyses of AMRs were also based on the Brayton cycle [4]. In order to distinguish between the conventional Brayton, the regenerative Brayton and the Brayton cycle with an AMR the

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Nomenclature

a	AMR height [m]
B	magnetic flux density [T]
c_f	specific heat of fluid [J/kg K]
COP	coefficient of performance [/]
c_s	specific heat of solid [J/kg K]
d	hydraulic diameter [m]
L	AMR length [m]
$\dot{m}_f$	mass-flow rate [kg/s]
m_s	AMR mass [kg]
$\dot{Q}_c$	cooling power [W]
r	distance between AMR plates [m]
s	specific entropy [J/kg K]
p	AMR width [m]
T	temperature [°C]
U	utilization factor [/]
v_f	fluid-flow velocity [m/s]
ν	frequency [Hz]
τ_c	time of constant magnetic field [s]
τ_f	time of fluid-flow period [s]
τ_{mag}	(de)magnetization time [s]

reader is referred to Kitanovski et al. [5]. The Brayton cycle with an AMR operates with the following four processes: a) the AMR is magnetized and heats up due to the MCE; b) next, a fluid flows through the AMR and the MCM transmits the heat to the working fluid; c) in the third step the AMR is demagnetized and its temperature decreases; d) finally, the fluid flows in the counter-flow direction (relative to step two), the fluid is cooled down and the MCM in the AMR is heated up.

This is not the only way to perform a magnetic thermodynamic cycle with an AMR. There are many other new and alternative thermodynamic cycles. This leads to a potential improvement in the performance of the magnetic cooling device. Moreover, it is possible to reduce the required magnet mass and the overall costs of the magnetic refrigerator [6].

In the past different magnetic thermodynamic cycles were being considered [7]; yet, these did not include magnetic thermodynamic cycles with an AMR. Later, mainly after 2000, most of the published work relates to specific single-stage magnetic thermodynamic cycles [8] and basic thermodynamics [9], but no systematic research of different magnetic thermodynamic cycles with an AMR was performed.

In this article numerical and experimental analyses of the different magnetic thermodynamic cycles with an AMR were performed. The Brayton, Ericsson and Hybrid Brayton–Ericsson cycles with an AMR were compared, and based on this comparison some conclusions and potential guidelines for future developments in the field of magnetic cooling devices are presented.

2. Magnetic thermodynamic cycles with an AMR

The magnetocaloric effect of currently known magnetocaloric materials at room temperature is limited to a few Kelvins (for a magnetic field achievable with permanent magnets). In order to enlarge the temperature span (the difference between the heat source and heat sink temperature) of the potential magnetocaloric device a heat-regeneration process is required. Among the different types of heat regenerators, in recent years the AMR has shown the greatest potential for applications in a magnetic refrigerator working at room temperature. The AMR is a heat regenerator that uses a magnetocaloric material as a regenerative material. It has a double function in the magnetic refrigerator: it works as a refrigerant, since it contains a magnetocaloric material; and it works as a heat regenerator and makes it possible to establish a temperature gradient along its length. As a result, the temperature span of the AMR can be much greater than the adiabatic temperature change of the MCE. The formation of this temperature profile means that each particle of the MCE in the AMR is subjected to a different temperature, therefore performing its own small thermodynamic cycle. If the AMR is taken as a whole, its thermodynamic cycle is a combination of the cycles of the individual particles.

Fig. 1 shows four different thermodynamic cycles with an AMR: the Brayton, the Ericsson, the Carnot and the Hybrid Brayton–Ericsson cycle in a steady-state condition (after the establishment of the temperature span) are presented in *T*–*s* diagrams. The plots were obtained from the results of a 1D dynamic numerical model of the AMR presented in Tušek et al. [10]. Since each individual particle is performing its own cycle, it is impossible to show the whole AMR process. For this reason the thermodynamic cycles of only three individual particles are shown: the coolest, the hottest and a selected particle in between.

The Brayton cycle with an AMR is presented in Fig. 1(a). It is a combination of adiabatic magnetization (1-2), an isofield heat-transfer process, i.e., heat rejection from the cycle (2-3), adiabatic demagnetization (3-4) and an isofield heat-transfer process, i.e., heat absorption from the cooled environment (4-1). It must be pointed out that because of inevitable heat-transfer process between the MCM in the AMR and the working fluid during the time of (de)magnetization, the temperature change is not ideally adiabatic. The Ericsson cycle with an AMR (Fig. 1(b)) undergoes an isothermal magnetization (1-2) followed by an isofield heat rejection (2-3), isothermal demagnetization (3-4) and isofield heat absorption (4-1). Again, in this case the (de)magnetization process is not ideal. The ideal isothermal process only occurs when the heat-flux generation in the MCM due to the MCE is equal to the heat-flux transfer from the MCM to the working fluid. Since the properties of the MCM in the AMR are a function of the temperature and the magnetic field, the heat flux generated due to the MCE is not constant along the AMR. In order for an isothermal process to take place, the fluid flow should change with time and location along the AMR. In real applications this is difficult to achieve and that is why we can only talk about a quasi-isothermal temperature change. In Fig. 1(d) the Hybrid Brayton–Ericsson cycle with an AMR is shown. Here the (de) magnetization process runs as a combination of an adiabatic and an isothermal process (1-2, 3-4). Also, in this case it is hard to achieve the ideal isothermal and adiabatic (de) magnetization.

The Carnot cycle with an AMR is shown in Fig. 1(c). The (de) magnetization process (1-2-3, 3-4-1) is similar to the case of the Hybrid cycle with an AMR; however, there are no heat-rejection and heat-absorption processes at a constant magnetic field. Therefore, there is no need for a region of constant magnetic field and as a result the magnet assembly could be much simpler (and less expensive) than in the case of the other cycles [6]. It must be pointed out that in this case only individual particles of the AMR are performing the Carnot cycle, while the whole AMR cycle is in general very similar to the Hybrid cycle with the AMR.

In order to perform a thermodynamic cycle with an AMR the magnetic cooling device must work under the appropriate regime. The working regime of a magnetic cooling device is defined by the characteristics of the fluid-flow profile and the magnetic field profile. The regimes for the Brayton, Ericsson, Carnot and Hybrid cycles with an AMR are shown in Fig. 2.