DTU Library

A new numerical scheme for the simulation of active magnetic regenerators

Torregrosa-Jaime, B.; Engelbrecht, Kurt; Payá, J. ; Corberán, J. M.

Link back to DTU Orbit

A NEW NUMERICAL SCHEME FOR THE SIMULATION OF ACTIVE MAGNETIC REGENERATORS

B. TORREGROSA-JAIME[(a)], K. ENGELBRECHT[(b)], J. PAYÁ[(a)], J. M. CORBERÁN[(a)]

[(a)] Instituto de Ingeniería Energética, Universitat Politècnica de València
Valencia, Spain, bartorja@iie.upv.es, jorpaher@iie.upv.es, corberan@ter.upv.es
[(b)] Department of Energy Conversion and Storage, Technical University of Denmark
Roskilde, Denmark, kuen@dtu.dk

ABSTRACT — A 1D model of a parallel-plate active magnetic regenerator (AMR) has been developed based on a new numerical scheme. With respect to the implicit scheme, the new scheme achieves accurate results, minimizes computational time and prevents numerical errors. The model has been used to check the boundary condition of heat transfer in the regenerator bed.

1. INTRODUCTION

1D models of parallel-plate active magnetic regenerators (AMR) offer a good compromise between accuracy and computation time [1]. The numerical technique employed to solve the AMR equations is decisive to minimize computation time and numerical errors and instability. However, to the authors' knowledge, the suitability of the different numerical techniques in AMR applications has not been analyzed yet in depth. The finite differences method is the most common approach [1-3], although few authors of 1D AMR models specify which numerical scheme they employ.

In literature of 1D AMR models different correlations of the Nusselt number have been reported. The hypothesis of fully developed laminar flow is generally assumed. Some authors [1,4] employ the constant temperature boundary condition while others [2] assume a constant heat flux. In this work, both hypotheses have been analyzed.

2. METHODS

The modelled device consists of a stack of parallel plates made of a magnetocaloric material (MCM) subjected to a fluid flow and limited by a cold and a hot reservoir. The fluid flows through the stack of plates from one reservoir to the other synchronized with the magnetization of the MCM, performing the AMR cycle. The model receives as inputs the internal magnetic field and the fluid mass flow rate at the temperature of the corresponding reservoir, and calculates the temperature of the fluid and solid parts of the regenerator in the flow direction. The energy balances on the fluid and on the solid in [1] are solved with the finite difference method using a formulation based on the incoming and outcoming energy flows.

The different terms of the equations have been analyzed in detail. The thermal conduction in the fluid in the flow direction has been studied but it is negligible compared to advection in a typical parallel-plate AMR. If conduction is neglected in the fluid equation, an explicit scheme can be used to solve the advection term. A new numerical scheme based on a combination of implicit and explicit techniques has been consequently developed. The scheme can be solved efficiently with the tridiagonal matrix algorithm.

3. RESULTS

The modelled AMR has a mini-channel of 0.5x39x80 mm (HxWxL) and the Gd plates have a thickness of 0.25 mm. The simulations are run until cyclical steady state is reached. The AMR worked with a utilization of 0.63, a maximum internal field of 0.56 T and a period of 5.4 s with a dwell time of 1.4 s. A temperature span of 11 K was fixed between the hot and cold reservoirs. Table I compares the results obtained by the model with the implicit scheme in [1] (IMP) and with the new numerical scheme (UPV NS).

TABLE I.   COMPARISON OF SIMULATION RESULTS WITH THE TWO SCHEMES.

Scheme	max($|T_f - T_{f,ref}|$) (K)	δ (%)	t (s)	Q_f (W)	COP
IMP Nx=100 CFL= 0.04	0.040	-2.24e-08	7977	1.607	15.06
IMP Nx=100 CFL= 0.08	0.086	-2.87e-08	3791	1.600	14.91
UPV NS Nx=400 CFL= 0.94	ref	5.57e-09	3810	1.605	14.35
UPV NS Nx=200 CFL= 0.94	0.100	-1.55e-10	1913	1.599	14.30
UPV NS Nx=100 CFL= 0.94	0.294	9.21e-10	955	1.587	14.22

In Table I, *Nx* is the number of spatial nodes, *CFL* is the ratio of the distance the fluid travels in one time step to the length of a spatial node, T_f is the fluid temperature, $T_{f,ref}$ is the fluid temperature of the reference simulation in order to compare different simulations, δ is the energy conservation error expressed as the total energy variation along the calculation minus the energy difference between final and initial states, *t* is the simulation time, Q_f is the cooling power and *COP* is 'coefficient of performance'.

While the implicit scheme needs a very fine time grid to obtain accurate results [1], the new scheme allows the use of a time step as large as *CFL*=1. Larger CFLs decrease the computational time and the numerical diffusion.

In the model with the implicit scheme changes in the Gd properties during a time step are neglected given that the time step employed is very small [1]. When the time step increases, the values of the Gd properties must be averaged in each time step in order to obtain consistent results of the AMR performance. Averaging the regenerator properties seems to provide more accurate results. Despite the average Gd properties are calculated iteratively, increasing by nearly three times the computational cost, the simulation time with the new scheme still remains lower than with the implicit scheme.

The boundary conditions of heat transfer in the regenerator were analyzed by means of the model. Both the wall temperature (Fig. 1) and the heat flux (Fig.2) vary significantly during the simulations. However, in parallel plates the Nusselt number remains very similar [5] no matter the boundary condition (constant wall temperature or constant heat flux). The impact in the predicted performance is consequently small. For instance, the COP varies only by 0.5% between the two options.
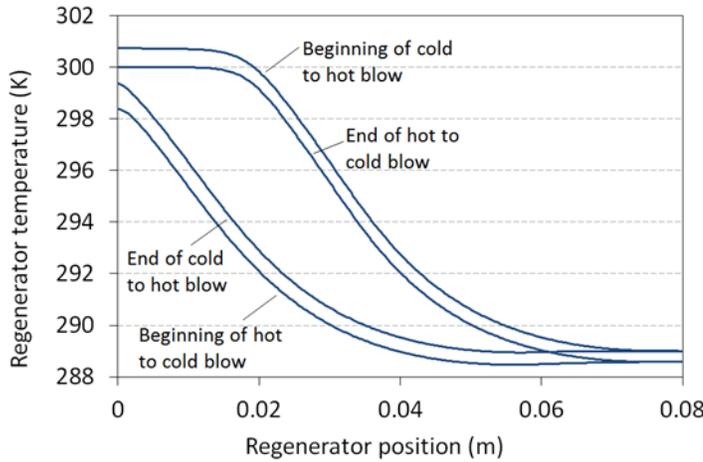

Fig. 1. Wall temperature at several moments of the AMR cycle with a constant temperature boundary condition.
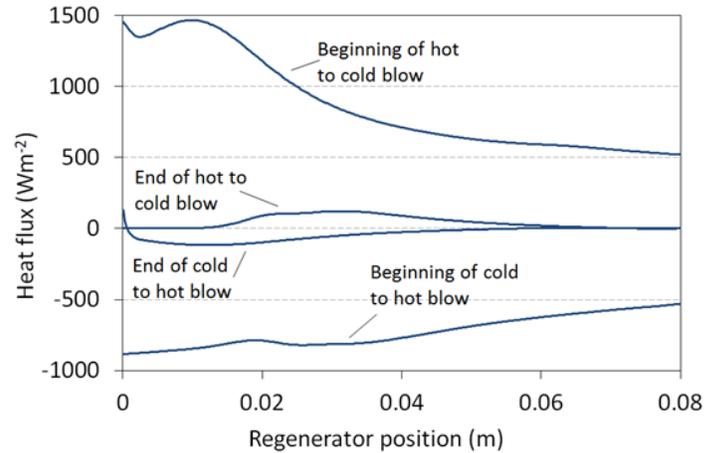
Fig. 2. Heat flux from the wall to the fluid at several moments of the AMR cycle with a constant heat flux boundary condition.

4. CONCLUSION

A new numerical scheme based on a combination of explicit and implicit techniques simulates the AMR behavior with less computational effort and numerical diffusion than the implicit scheme. The increase of the time step enabled by the new scheme required using average Gd properties in each time step, which may yield more accurate results.

The boundary condition of heat transfer in the parallel-plate AMR is complex since both the wall temperature and the heat flux vary during the cycle. However, there is only a small difference in the results when employing classical Nusselt number correlations. Nevertheless, the influence of the boundary condition in the calculation of the Nusselt number should be further studied.

REFERENCES

[1] K. Engelbrecht, "A numerical Model of an Active Magnetic Regenerator Refrigerator with Experimental Validation", PhD Thesis, University of Wisconsin-Madison, 2008.
[2] M. Risser, C. Vasile, T. Engel B. Keith and C. Muller, "Numerical simulation of magnetocaloric system behaviour for an industrial application", Int. J. Refrig, vol. 33, pp. 973–981, 2010.
[3] P. A. Oliveira, P. V. Trevizoli, J. R. Barbosa Jr. and A. T. Prata, "A 2D hybrid model of the fluid flow and heat transfer in a reciprocating active magnetic regenerator", Int. J. Refrig, vol. 35, pp. 98–114, 2012.
[4] D. Vuarnoz and T. Kawanami, "Experimental validation of a coupled magneto-thermal model for a flat-parallel-plate active magnetic regenerator", Appl. Therm. Eng., vol. 54, pp. 433–439, 2013.
[5] R.K. Shah and A.L. London, Laminar Flow Forced Convection in Ducts, Academic Press, New York, 1978.