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Morgan Almanza, Afef Kedous-Lebouc, Salvatore Miraglia. An original 1D transversal magnetothermal cycle model for preliminary design of AMR regenerator. 6th IIR/IIF International Conference on Magnetic Refrigeration THERMAG VI, Sep 2014, Victoria, Canada. hal-01066010

HAL Id: hal-01066010

<https://hal.science/hal-01066010>

Submitted on 22 Mar 2017

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AN ORIGINAL 1D TRANSVERSAL MAGNETOTHERMAL CYCLE MODEL FOR PRELIMINARY DESIGN OF AMR REGENERATOR

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ABSTRACT—A 1D transversal model has been developed for purpose of AMR optimization. The model is fast to compute and is focused on transversal exchange. It is applied via numerous simulations to estimate the best working point considering a large number of parameters. The relevance of our model is validated through the most complex cases which are compared with a more complex 2D model. Method of similarity and dimensionless analysis are associated to our approach in order to have guidelines for the system optimization.

1. INTRODUCTION

The magnetocaloric refrigeration is an environmentally friendly alternative to classic gas compression technology. An optimized system could fit the specification requested while providing improved efficiency. An optimization of a multiphysics system as active magnetic regenerative (AMR) cooling system is a complex task linked to the number of parameters and the simulation time. Many AMR cycle models based on different approaches have been developed [1]. 1D longitudinal models [2] are fast but have to face the main issue of description of the heat transfer with a single coefficient. Whereas 2D models require more important computing time and memory, therefore they are not suitable for optimization. In this paper, we present an optimization approach based on the method of similarity and a new 1D transversal model for the analysis of the AMR local behavior. The weak coupling between temperature and fluid mechanics authorizes to decouple the physics areas and solve the periodic fluid flow beforehand. Thus in all our simulations, the periodic fluid solution previously solved is introduced in the thermal model. The magnetic field is also assumed to be homogeneous.

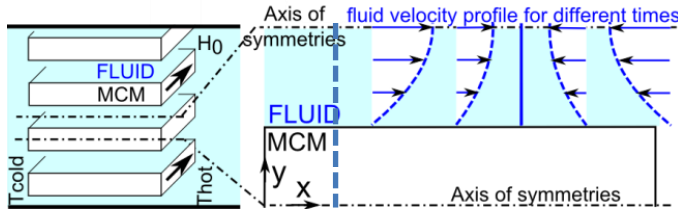


Fig. 1. AMR system, the 1D transversal model focuses on blue dash line. MCM for magnetocaloric material

TABLE I. SCALED VARIABLES

Parameters	Conduction dominance	Friction dominance
Size $y: y_w^*, y_m^*$	α	α
Size $x: x^*$	α	α^2
Time: t^*	α^2	α^2
Velocity: v^*	$1/\alpha$	1

2. METHOD OF SIMILARITY

The optimization of the system leads to study degrees of freedom. The method of similarity looks for a transformation which keeps invariant the system behavior. An optimal situation reveals a set of solutions through a linear transformation linking space, time, etc. A dimensionless analysis of the thermal equation describing the AMR is done Eq. (1) with μ viscosity, c volumetric thermal capacity, λ thermal conductivity, s entropy, subscript m for MCM and w for the fluid, T temperature, v fluid velocity. The same analysis is achieved for the fluid equation and for the boundary condition at the interface between fluid and MCM. “ $\bar{\cdot}$ ” indicates dimensionless variables whereas the superscript “ $*$ ” represents the characteristic quantities. ΔT^* is the temperature span between the hot and cold sources. Src represents the magnetocaloric effect. In the same manner, the magnetic work and cooling power densities are written on Eq. (2), neglecting the conduction heat transfer.

$$\frac{c_w^*}{\Delta T^*} \left(\frac{1}{t^*} \frac{\partial \bar{T}}{\partial \bar{t}} + \frac{v^*}{x^*} \bar{v} \frac{\partial \bar{T}}{\partial \bar{x}} \right) = \frac{\lambda_w^*}{\Delta T^* y_w^{*2}} \frac{\partial^2 \bar{T}}{\partial \bar{y}^2} + \frac{\lambda_w^*}{\Delta T^* x^{*2}} \frac{\partial^2 \bar{T}}{\partial \bar{x}^2} + \frac{2\mu v^{*2}}{y_w^{*2}} \left(\frac{\partial \bar{v}}{\partial \bar{y}} \right)^2 \quad (1)$$

$$\frac{c_m^* \bar{c}_m}{t^* \Delta T^*} \frac{\partial \bar{T}}{\partial \bar{t}} = \frac{\lambda_m^*}{\Delta T^* y_m^{*2}} \frac{\partial^2 \bar{T}}{\partial \bar{y}^2} + \frac{Src^* H^*}{t^*} \frac{\partial \bar{H}}{\partial \bar{t}} + \frac{\lambda_m^*}{\Delta T^* x^{*2}} \frac{\partial^2 \bar{T}}{\partial \bar{x}^2}$$

$$w = \frac{x^*}{x^* y_m^* t^*} \int_{space} \int_0^1 -y_m^* T s_m^* \frac{d\bar{s}_m}{d\bar{t}} + \frac{2t^* \mu v^{*2}}{y_w^*} \left(\frac{\partial \bar{v}}{\partial \bar{y}} \right)^2 d\bar{t} d\bar{y} d\bar{x} \quad q_{cold} = \frac{c_w^* y_w^* t^*}{\Delta T^* x^* y_m^* t^*} \int_0^1 \int_0^1 v^* \bar{v} \bar{T}(0, \bar{t}) d\bar{t} d\bar{y} \quad (2)$$

Two cases are distinguished. The first is when conductive heat exchange prevails over heat produced by viscous friction, i.e. $1 \gg \frac{y_w^2}{x^{*2}} \gg \frac{2\mu v^{*2} \Delta T^*}{\lambda_w^*}$. In this case, Eq. (1) remains similar when the y size is multiplied by a factor α if the others variables are multiplied by the values given in the 1st column of Table 1. Thus, the power density (Q_{Cold}) is increased by $1/\alpha^2$ while the coefficient of performance (COP) is kept constant. But the heat produced by viscous friction rapidly increases in $1/\alpha^2$ compared to other terms and leads to the second case where viscous friction term prevails over longitudinal conduction ($1 \gg \frac{2\mu v^{*2} \Delta T^*}{\lambda_w^*} \gg \frac{y_w^2}{x^{*2}}$). In this case, Eq. (1) remains similar when the y size is multiplied by a factor α if the others variables meet the requirements specified in the 2nd column of Table 1. Thus, Q_{Cold} is increased by a factor $1/\alpha^2$ while COP is kept constant.

This method is very powerful and constitutes a general principle that needs only few assumptions. Also, it urges us to reduce the size of the regenerator in order to improve the exchange surface. We also use this property to fix, in a first study, one degree of freedom, for instance the thickness of the magnetocaloric material is chosen equal to 0.5 mm.

3. 1D TRANSVERSAL MODEL

The 1D model is developed for quick optimization. It mainly focuses on the transversal direction (Fig.1, dash line) of the regenerator and not on the longitudinal one as currently done. The key assumption is to assume an invariance of the behavior along the regenerator. Mathematically we translate this invariance by forcing each term of the thermal equation to be independent of the position. The solution is given by the form $T = a + bx + f(y, t)$ with a and b two constants. To solve both the thermal and fluid equations in steady state, Sturm-Liouville for piecewise continuous domains and Fourier methods are used. An accurate and fast resolution is then achieved in one second, so the influence of many parameters can be explored. For a set of parameters and a given working point, a 2D model is developed with Comsol software and comparisons are presented in Fig. 2.a and c. The model shows in particular that the regenerator can work in more or less regenerative way (Fig. 2.b). Indeed multiple periods are possible for the same cooling power. In this case, the temperature variation of the fluid changes in accordance with Fig. 2.b. The limitation of 1D model comes from the non-consideration of the heat exchange at the ends of the regenerator. 1D model results agree with those of the 2D simulations although the computation times are different: 10 mm and 2 days respectively for the 1D and 2D models.

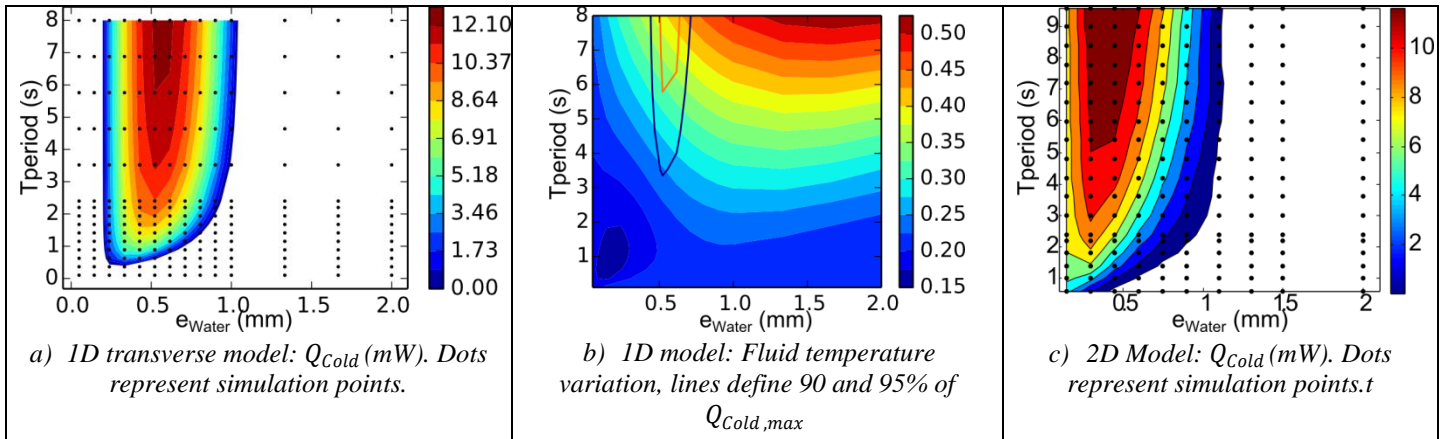


Fig.1. 1D transverse model results and comparisons with 2D model
 $v = 2.5$ cm/s, e_{Water} half of the water thickness, $\Delta T_{adia} = 1$ K, $length = 10$ cm, $T_{hot} - T_{cold} = 3$ K.

An optimization approach based on an original 1D transverse model is presented. From an existing system, the method of similarity allows parameters variation ranges to be first estimated. Secondly, the 1D model application leads to an optimum set of parameters. Finally, 2D simulations can be performed to validate and refine this optimum.

This work is supported by the French National Research Agency through the ANR-10-STOCK-E-008 project MagCool

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