THERMAL ANALYSIS OF EFFICIENT ACTIVE MAGNETIC REGENERATORS FOR GAS LIQUEFIERS

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RESUME
Cet article présente une méthode de simulation numérique pour l'analyse thermique d'un liquéfacteur magnétique à gaz.. Le principe de fonctionnement d'un tel dispositif est basé sur l'effet magnétocalorique, étant généré par le processus de magnétisation ou démagnétisation dans un régénérateur magnétique actif (AMR). Ce dernier constitue l'élément essentiel du liquéfacteur. Deux configurations de AMR ont été étudiées : (i) régénérateur à plaques parallèles et (ii) régénérateur à tubes (conduites de section circulaire). Le gaz à liquéfier est le méthane (CH_4). Le logiciel Fluent a été utilisé pour résoudre les équations régissant les échanges de chaleur entre le gaz et le solide dans l'AMR. Ont été suggérées des corrélations, entre les propriétés physiques du gaz, ainsi que les paramètres de design et les propriétés thermomagnétiques de l'AMR. Le régénérateur à plaques parallèles s'avère le plus performant.

ABSTRACT
This paper presents a numerical simulation method for thermal analysis of magnetic gas liquefier. The principle of operation of such a device is based on magnetocaloric effect, being produced by magnetization or demagnetization processes within an active magnetic regenerator (AMR). This latter constitutes the heart of such a magnetic system. Two configurations of AMR have been studied : (i) regenerator made of parallel-plates and (ii) regenerator made of tubes (circular passage). The gas to be liquefied is the methane (CH_4). Fluent has been used to solve the equations governing heat exchanges between gas and solid within AMR. Correlations have been suggested, between gas-thermophysical properties, as well as the design parameters and thermomagnetic properties of the AMR. It has been found that the AMR made of parallel-plates to be more efficient.

1. INTRODUCTION
The needs for developing more promising and environmentally friendly gas liquefaction devices, such as production of liquid hydrogen or liquefied of natural gas, have prompted a renewed interest in the study of magnetic refrigeration (MR) technology ([1]-[6]). Engineering and economic evaluations indicate that, in principle, MR with its promises of higher efficiencies and lower capital investment costs would create an immediate market niche and new opportunities. The concept of MR is based on the principle of the magnetocaloric effect (MCE) exhibited by some materials, when they are subjected to changes in external magnetic field (i.e. magnetisation or demagnetisation processes of materials). The magnitude of MCE is about 2 K or 3 J/kg.K per Tesla of field change

for typical ferromagnets. Hence large temperature–span magnetic systems (such as gas liquefaction devices) are based on regenerative thermodynamic cycles. ([7], [8]). Among the cycles that have been extensively studied and built in practical magnetic systems is the active magnetic regeneration (AMR cycle). In this work, the study will be focused on the simulation of the unsteady cooling process of gas to be liquefied through the AMR (i.e. the unsteady demagnetisation process); in order, to asses the AMR geometrical configurations. For this purpose, a computational fluid dynamics (CFD) method is proposed for predicting thermal and fluid fields of gas to be liquefied within the regenerator bed. The unsteady Navier-Stokes and energy equations are considered to account for the heat transfer between magnetic material and the gas flowing throughout the regenerators. Methane (CH_4) is considered as the gas to be liquefied. The resulting mathematical model has been solved by Fluent. The simulation results include mainly discussions on the correlations between gas-thermophysical properties, as well as the design parameters and thermomagnetic properties of AMR.

2. DESCRIPTION OF THE AMR CYCLE

Unlike conventional mechanical-cycles, AMR cycle involves complex thermodynamic interactions between fluid and magnetic regenerator. Figure 1 shows a schematic of such an AMR device, which is constituted primarily of a magnetic regenerator (solid refrigerant media) and circulating fluid (gas to be liquefied and/or regenerative fluid). The AMR cycle consists of magnetisation / demagnetisation process of solid refrigerant (through an adiabatic or isothermal steps; in this study, only isothermal steps are considered) and two isofield steps (warm and cold blows). A complete steady operation cycle can be briefly described as follows :

(i) *Isothermal magnetisation process*: the bed is magnetised when the magnetic field increases from zero to given strength. During this process, the valves **1** et **2** being opened (while the valves **3** et **4** being closed), the regenerative fluid is forced to circulate throughout the bed and absorbing the amount of heat, Q_H, which is released to the surroundings, through the hot reservoir heat exchanger (HRHEX) at temperature T_H.
(ii) *Warm blow at applied field B*: again the valves **1** et **2** being opened (while the valves **3** et **4** being closed), the HRHEX being not activated, the regenerative fluid continues absorbing heat from the magnetized bed and thus decreasing its temperature to the low reservoir temperature T_L (liquefied temperature of gas -to be liquefied-).
(iii) *Isothermal demagnetisation process*: by reducing magnetic field from given strength to zero, the regenerator bed is demagnetised. During this process, the valves **3** and **4** being opened (while the valves **1** et **2** being closed), the gas to be liquefied is forced to circulate throughout the bed and releasing the amount of heat, Q_L, which is the amount of heat required to liquefy the gas.
(iv) *Cold blow at zero field*: now the valves **1** et **2** are reopened (while the valves **3** et **4** being closed), the regenerative fluid is then forced to circulate throughout the regenerator bed in order to increase its temperature from T_L. to the initial room temperature T_H.

3. MATHEMATICAL MODEL

The unsteady flow of the gas to be liquefied throughout the magnetic regenerator bed, during the isothermal demagnetisation process, are described by the continuity and Navier-Stokes equations. To account for the heat transfer rate between the gas and magnetic regenerator, the energy equation for the gas is considered. To take into account the temperature dependency of gas-thermophysical properties (namely density, viscosity, specific heat, and thermal conductivity), thermodynamic tables [9] have been introduced to obtain the appropriate relationships of different gas-thermophysical properties.

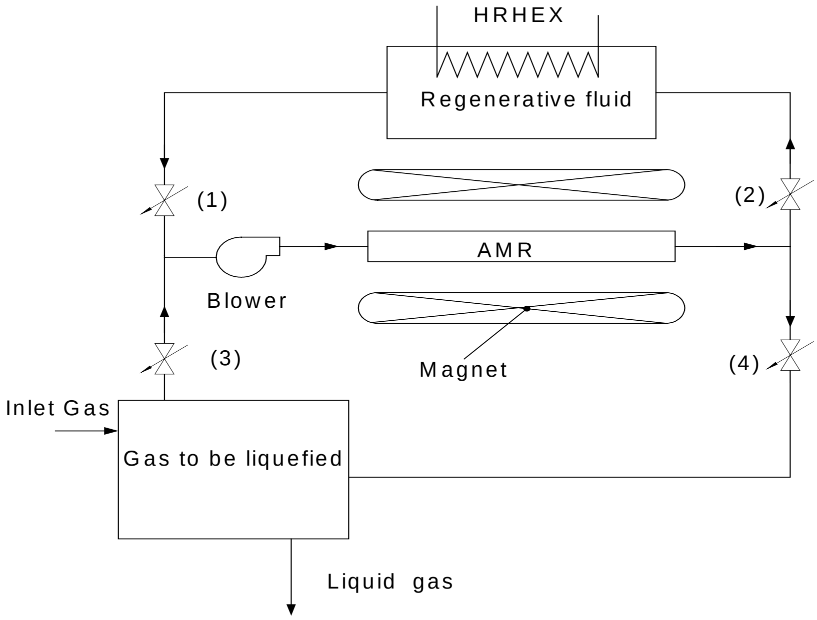

Figure 1. Schematic of principal of operation of AMR liquefier

4. NUMERICAL METHOD

The complete set of gas equations consists of two momentum equations for transport of velocity, the continuity equation, and energy equation. The solution of these equations is accomplished by employing Fluent. Fluent uses a control-volume-based technique to convert the governing equations to algebraic equations that can be solved numerically. The explicit scheme is used for time discretization.

4.1 Computational domain

The geometrical configurations of the AMR being investigated here are shown in Figure 2 : parallel flat plate and circular tube passages. This study deals with the gas flow throughout single passage, either parallel-plate or circular passage. The following dimensions have been considered : the length of regenerators is 0.5 m, for a circular passage the diameter is of 0.005 m, and for parallel-plate the cross area is of 1m x 0.005 m. The computational domain, being composed of fluid region, consists of either cylinder or rectangular, represented by the geometrical dimensions of single passage for given regenerator, as shown in Figure 3.

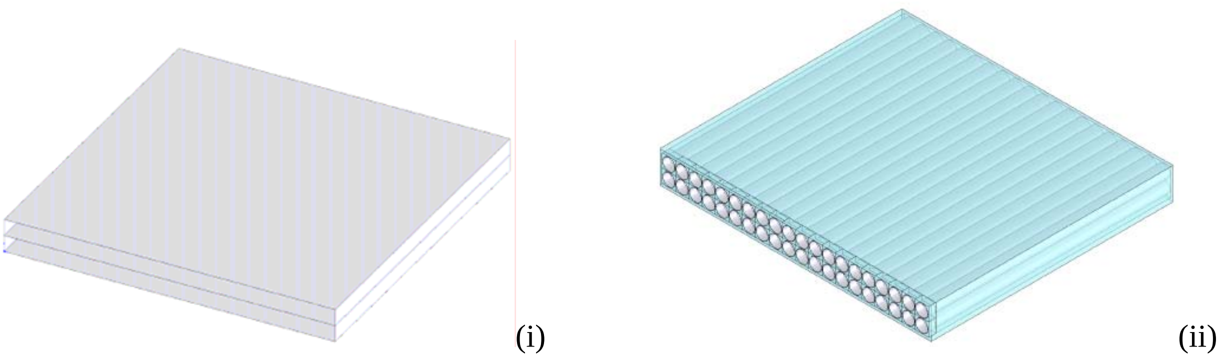

Figure 2. Geometrical configuration of AMR: (i) parallel-plates configuration and (ii): circular tube configuration

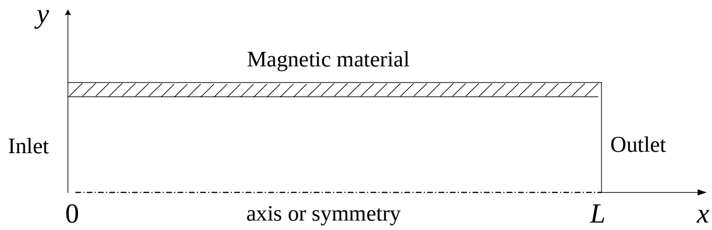

Figure 3. Computational domain

4.2 Boundary and initial conditions

Initially, (i.e. t = 0), both gas to be liquefied and regenerator temperatures are assumed to be equal to given value T_i. During the isothermal demagnetization process, (i.e. $0<t<\tau$; τ denotes time period of demagnetisation process), a uniform velocity field, $u(x=0,y)=U_0$, and temperature field, $T(x=0,y)=T_{in}$, are prescribed at the inlet boundary (i.e. x = 0) for the gas. At the wall boundary, no slip conditions are prescribed for the velocity field, while heat transfer between gas and solid (magnetic material) is specified by heat flux, due to the isothermal demagnetization process. Under this process, the resulting MCE is introduced by the magnetic entropy change, ΔS; and thus the heat flux can be described by the relationship

$$q'' = -T_{av}\Delta S\frac{m}{\tau A} \tag{1}$$

where, $T_{av} = \int_{t=o}^{\tau} T_S(t)dt/\tau$, T_S is the solid temperature, A and m are respectively a heat exchange surface area and a mass of magnetic material that constitutes the AMR bed.

5. RESULTS AND DISCUSSION

In this work, methane (CH_4) is considered as the gas to be liquefied at atmospheric pressure. The study is focused on the simulation of the unsteady cooling process of CH_4 through the regenerator (i.e. the unsteady demagnetisation process), for efficient magnetic regenerators, i.e. those producing constant magnetic entropy change ΔS (i.e. MCE) over the whole temperature range. Thus, as reported previously [7], regenerators are constituted of layered materials (such as gadolinium-dysprosium Gd-Dy alloys). The simulations have been carried out under the following typical conditions, namely, Reynolds numbers : $25 \le \mathrm{Re} \le 100$; magnetic entropy change values ΔS = 1, 2, and 3J/kg.K; initial methane temperature T_i = 300 K, and time period values τ =2, 5, and 10s. The cooling process of CH_4 from its initial temperature T_i has been repeated several cycles, (i.e. a number N_c of cycles), until the liquefaction temperature is reached. Based on the simulation results, we have suggested correlations between the number of cycles N_c, inlet and outlet gas temperatures, T_{in} and T_{out}, gas-thermophysical properties, and the EMC, ΔS. The following correlation have been obtained

$$\frac{T_{in}}{T_{in}-T_{out}} = \frac{1}{N_c}\left(\frac{C_1 k}{c_p}\right)^{-0.36} \mathrm{Pr}^{-0.18}\left(\frac{c_p}{\Delta S}\right)^{1.02} - C_2 \tag{2}$$

where, Pr denotes Prandtl number, and the coefficients C_1 and C_2 are given by Figures 4a and 4b, for parallel-plates and circular passages respectively. These correlations may play prominent role in preliminarily selections of optimum design parameters and suitable geometrical configurations for given thermal and magnetic conditions. It can be seen that the circular configuration is slightly more promising, i.e. the number of cycles N_c to attain the liquefaction temperature of CH_4 can be lowered. On the other hand, the resulting entropy generations $\dot{S}_g$, due to the temperature difference between gas and solid, throughout the regenerators, as function of Re, are shown in Figure 5. As it can be seen, significant differences between the circular and parallel-plates configurations can be noted. The parallel-plates configuration exhibits significantly lower entropy generation values, by about 30% - 42%. Furthermore, from practical point view, the circular configuration is more expensive to manufacture than the parallel-plates one.

6. CONCLUSION

A numerical simulation method is proposed to investigate the effects of AMR geometrical configurations on the optimum operation conditions. Two configurations have been considered, namely, parallel-plates and circular passages. The simulation of the cooling process of CH_4, for given thermal and magnetic conditions, from the initial gas temperature has been repeated several cycles, until the liquefaction temperature is reached. From the simulation results, it has been found that regenerators made of parallel-plates appear to be more promising configuration; since significant lower values of entropy generations have been observed.

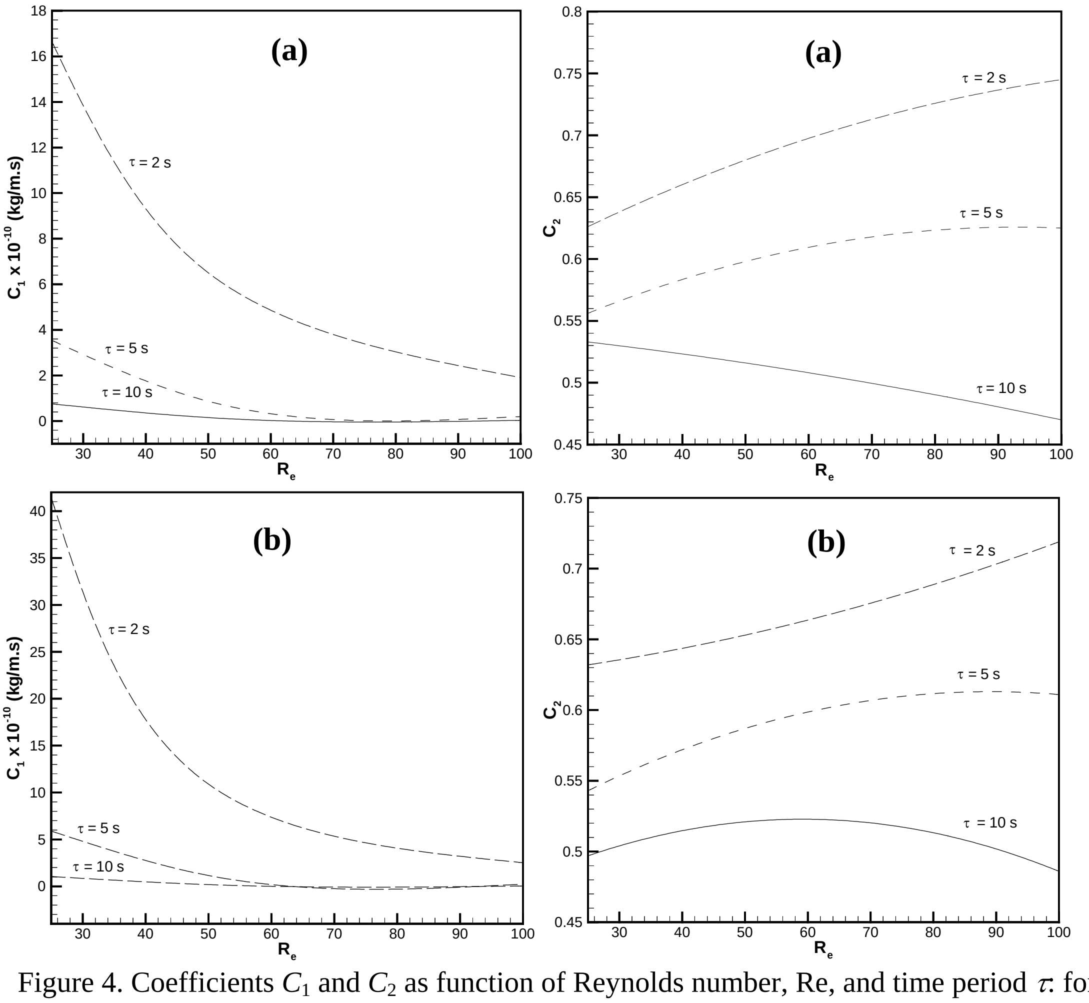

Figure 4. Coefficients C_1 and C_2 as function of Reynolds number, Re, and time period τ: for (a) parallel-plates configuration; (b) circular configuration

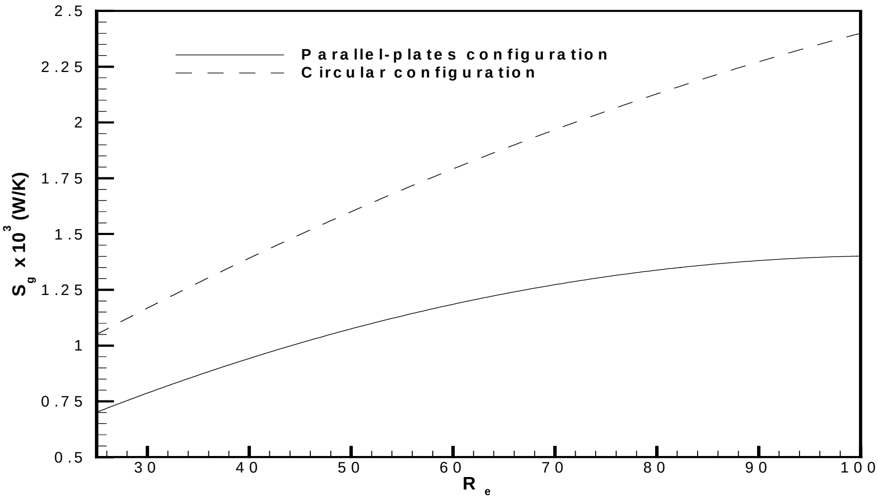

Figure 5. Entropy generation throughout magnetic regenerators

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