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Numerical prediction of thermal performance of an electrocaloric device based on ceramic material

***Abstract**. The main objective of this work is to efficiency prediction and parameter optimisation of an electrocaloric refrigeration system based on ceramic materials ($BaTiO_3$) and nanofluids (Al_2O_3, CuO). For this purpose, an electrocaloric device is used and studied. The principle consists in the heating and cooling of the ceramic material under the application and removal of electrical field respectively. The nanoparticles suspended in water increase the heat thermal between solid electrocaloric material and carried fluid, so we have much faster heat exchanges that cause an increase in coefficient of performance (COP) and temperature span; the temperature difference between the cold heat exchanger (CHEX) and the hot heat exchanger (HHEX). Indeed, the performances of these systems are strongly dependent on the interactions between the thermal, the fluidic and the electricity in order to be able to evaluate and optimize these systems in terms of cooling power, and the observation is that there are very few current studies in this area. Finally, a parametric study effected by using the COMSOL Multiphysics identified the characteristic quantities that have a significant influence on thermal behavior in electrocaloric refrigeration systems based nanofluids and ceramic material.*

Streszczenie.** Tematem artykułu jest analiza i optymalizacja systemu chłodzenia bazującego na materiale ceramicznym $BaTiO_3$ i nanocieczy Al_2O_3, CuO. W tym celu analizowano element elektrokaloryczny I współczynnik wymiany ciepła CCP. Przedstawiono wyniki badań elementu jak I całego systemu chłodzenia. **Numeryczna analiza i optymalizacja chłodzącego urządzenia elektrokalorycznego bazującego na materiałach ceramicznych

Keywords: Electrical field, Nanofluids, Electrocaloric device, Comsol Multiphysics, Nanoparticles.
Słowa kluczowe: urządzenia chłodzące, efekt elektrokaloryczny, ceramika $BaTiO_3$.

Introduction

Electrocaloric refrigeration is an environmentally clean technology that looks promising. Indeed, this technology exploits the electrocaloric effect (ECE) [1-3], which is translated by an instantaneous and reversible variation of the temperature and the entropy of the electrocaloric materials under the effect of a variation of electric field [4, 5-18]. This effect is maximal around the paraelectric ferroelectric transition temperature (Curie temperature). The types of materials using can be single crystals and ceramics (in solid form, in thick layer or in thin layer), as well as polymers, the electrocaloric materials, theoretically have a reversible operation leading to an energy efficiency close to the ideal Carnot cycle[6]. In recent years, a new type of fluid is emerging namely nanofluid. The nanofluid is a heat transfer fluid such as water, glycol-water, the oil which is added metal nanoparticles (Al, Cu, Ag, Au, etc.), non-metallic oxide (SiO_2, Al_2O_3, TiO_2), and other (allotropic forms of carbon) in relatively small amounts (0.1 to 6% of the total volume) [7- 9]. These nanofluids would thus allow to be able to evacuate more quickly the heat emitted by a refrigerating machine or any type of industrial installation requiring a significant evacuation of heat. The idea of improving the thermo-physical properties of fluids [10 -12]. Pak and Cho was the first in 1998 to put forward the idea that nanofluids transfer heat better as the base fluid [13, 14, 15], thanks to the fact that the metal nanoparticles have a thermal conductivity much greater than that of the fluid. Nanofluids can be distinguished by different criteria, namely: size and shape of the nanoparticles, the type (metal or metal oxide) and its concentration, the surfactant used as well as its concentration in the water, the preparation method [7, 8, 16].

As part of this work, we analyzed the different scientific articles on the characteristics of nanofluids for below ambient temperatures, and to compare their conclusions in order to know which studies could allow us to advance the use of nanofluids in electrocaloric refrigeration systems. Once this knowledge has been acquired, simulation will be performed under COMSOL Multiphysics in order to evaluate and compare the performance of nanofluids with respect to the base fluid in electrocaloric refrigeration systems. To select our nanoparticles, we need three key parameters: thermal conductivity, heat capacity and density. A three types of nanofluids are used in order to study the performance of an electrocaloric refrigeration system through the temperature span, cooling capacity and coefficient of performance.

Electrocaloric refrigeration system description

The numerical model developed in this study can be presented in Fig. 1 which showing in detail the main components of an active electrocaloric refrigeration (AER) device. A multi-physics model that takes into account three distinct phenomena (electricity, fluid mechanics and heat transfer), The regenerator made in parallel plates of the electrocaloric material, which is used to transfer heat to the moving nanofluid, to achieve greater temperature differences between the cold heat exchanger (CHEX) and the hot heat exchanger (HHEX). This model will identify an optimal design strategy for an Active Electrocaloric Regenerator to design efficient electrocaloric refrigeration systems. We want to predict the performance and the energy interest of nanofluids for electrocaloric refrigeration systems.

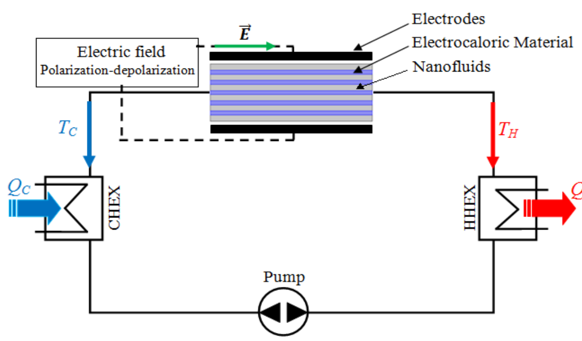


Fig.1. Schematic diagram of the AER cycle setup

BaTiO3 and electrocaloric effect

The effect of an applied electric field on the electrocaloric material based on BaTiO3 as measured by the adiabatic temperature change ΔT and entropy change ΔS [6-19-20] are illustrated in figure. 2 can find in detail in reference [6].

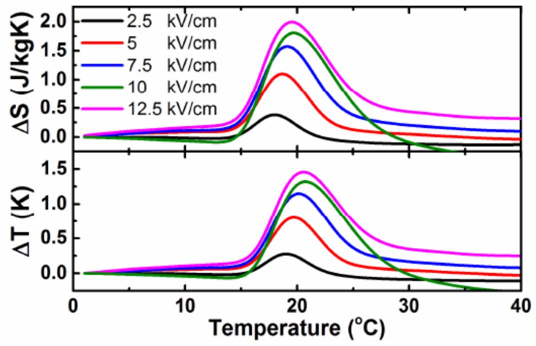


Fig.2. Electrocaloric effect in BaTiO3 ceramics near room temperature [6]

Numerical model

The physical model considered is shown schematically in figure 3. A parallel plate AER geometry has been chosen in which a nanofluid flowing under a laminar flow regime. Regenerator is the core of an electrocaloric refrigerator. Moreover, the operation of a regenerator is complex because characterized by operation in transient regime and steady state and by a thermal-fluidic-electric coupling. Some simplifying assumptions have been considered; the flow velocity u =0.05 m /s, Newtonian fluid, incompressible fluid, two-dimensional. The viscous dissipation is negligible, the thermophysical properties of the nanofluids are constant and presented in Table 1.

Table 1. The parameters of AER

parameters	Notation	Val
EC Materials	ECM	$BaTiO_3$
Curie Temperature	T_C [K]	297
Nanofluids	-	Al_2O_3; CuO
Electric field	E [kV/cm]	2.5; 5; 10
Frequency	f [Hz]	1
Flow velocity	U [m/s]	0.05
Time Pol/Depol	$t_{Pol/Depol}$ [s]	2
Length of AER	L [m]	50
Width of AER	l [m]	10
Height of ECM	e_s [m]	1
Gap between ECM	e_f[m]	0.3
Number of layers	N	14

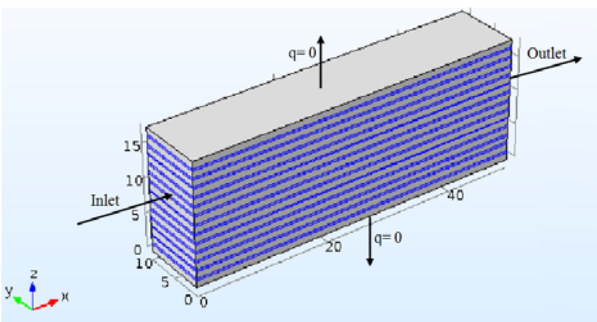


Fig.3.The boundary conditions and parallel plates AER

In our work we use the single phase model which considers the nanofluid as a continuous medium. Assuming that the nanoparticles are well dispersed in the base fluid, we can calculate the properties of AER (nanofluid and electrocaloric material) by the following formulas:

Maxwell's relations [1-3-17-21]:

$$\left(\frac{\partial S}{\partial E}\right)_T = \left(\frac{\partial P}{\partial T}\right)_E \quad (1)$$

where: S – entropy, E– electric field, P – polarization, T – temperature.

The velocity and temperature distribution in the fluid is determined by Navier-Stokes, continuity and energy equations [4, 5]:

$$\rho_f\left(\frac{dU}{dt}+(U.\nabla)U\right)-\mu_f\nabla^2+\nabla p=0 \quad (2)$$

$$\nabla.U=0 \quad (3)$$

$$\rho_{p,s}\frac{\partial T_S}{\partial t}-k_S\nabla^2 T_S=0 \quad (4)$$

$$\rho_f c_{p,f}\left(\frac{\partial T_f}{\partial t}+(U.\nabla)T_f\right)-k_f\nabla^2 T_f=0 \quad (5)$$

where: ρ – the density, U – the velocity, t – time, μ – dynamic viscosity, p – pressure, k – thermal conductivity and cp – heat capacity.

The Nanofluid density can be expressed by the relation [5]:

$$\rho_{nf}=(1-\phi)\rho_f+\phi\rho_S \quad (6)$$

where: ϕ – the volume concentration

Specific heat capacity [7-9]:

$$(\rho c_p)_{nf}=(1-\phi)(\rho c_p)_f+\phi(\rho c_p)_S \quad (7)$$

The viscosity and thermal conductivity of the nanofluid is determined by relation of Brinkman and Maxwell-Garnetts relations [8, 9] respectively:

$$\mu_{nf}=\frac{\mu_f}{(1-\phi)^{2.5}} \quad (8)$$

$$\frac{k_{nf}}{k_{nf}}=\frac{k_S+2k_f-2\phi(k_f-k_S)}{k_S+2k_f+2\phi(k_f-k_S)k_f} \quad (9)$$

The coefficient of performance COP of AEC system; can be expressed as [2]:

$$COP=\frac{Q_C}{Q_H-Q_C}=\frac{Q_C}{W} \quad (10)$$

where: COP – the coefficient of performance, Q_C – the heat from the cold reservoir, Q_H – the heat from the hot reservoir, W – electrical work.

Table 2. Thermophysical properties of base fluid and nanoparticles

Thermophysical properties	Al_2O_3	CuO	Water
Thermal conductivity k [$WK^{-1}m^{-1}$]	36	69	0.6
Specific heat capacity c_p [$Jkg^{-1}K^{-1}$]	765	535	4183
Density ρ [kg m-3]	3970	6350	999.2

Results and discussions

The numerical model is a 2D implemented in the COMSOL Multiphysics. The model is based on geometry with parallel plates of electrocaloric material. This configuration indicates the best performance in terms of the efficiency of heat transfers and pressure drops. The thermal behavior of the material is modeled by a coupling between the heat equation in the solid to which a source term has been added to integrate the electrocaloric effect, and the heat equation in the nanofluid at the solid-fluid interface which is considered as an additional boundary condition. Nanofluid flow has been modeled with the Navier Stokes equations for a conventional incompressible fluid. The thermodynamic characteristics of the chosen fluid correspond to those of water. As electrocaloric materials we used the reference material in the field, BaTiO3.

Figure 4 shows the evolution of the regenerator temperature, during a cycle, which comprises four characteristic phases. This temperature evolution is consistent with the correlation between the heat transfer nanofluid translation and the electric field displacement of the model, presented in Figure 1. In order to be able to construct the cooling cycle at an appropriate ambient temperature, the temperature of the ferroelectric transition (or more precisely the Curie temperature) should be slightly below room temperature. In addition, EC materials must exhibit high dielectric permittivity to withstand high electric fields and produce high ΔT.

During the first step, in the polarization process the temperature of the regenerator increases because of the electrical field. After, during the second step, the nanofluid flows from the cold exchanger to the hot exchanger (cold blow). In this step, over a duration of tcold.blow, the fluid flows through the regenerator, taking part of the heat and the temperature of the regenerator is reduced. In the third step, the depolarization step, with a duration of tdepolarization, the temperature of the solid is further reduced due to removal of the electric field. In the last stage of the cycle, of thot.blow duration, the step of flow of the nanofluid from the hot exchanger to the cold exchanger (hot blow) the solid is regenerated by the nanofluid and its temperature increases.

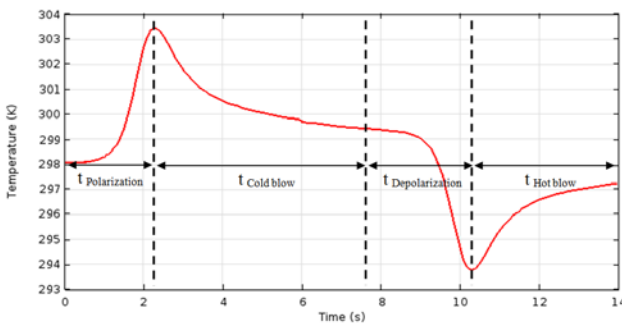
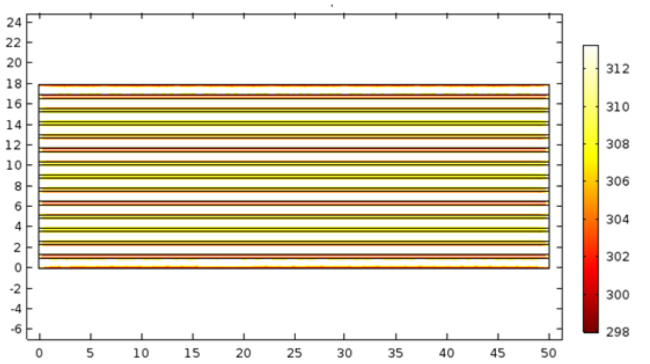


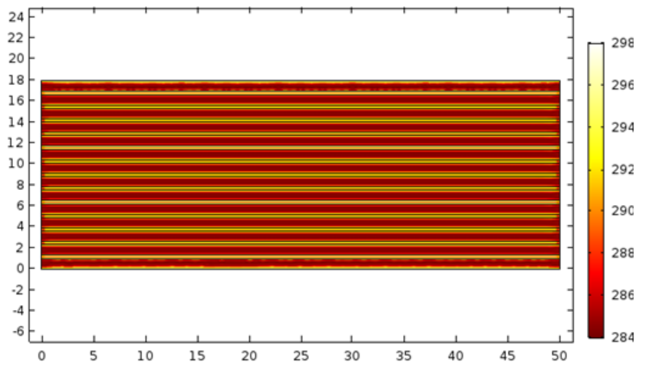
Fig.4.The evolution of the regenerator temperature during a cycle

The characteristic operating times of a cycle are of paramount operating parameters of the system and they must be imposed carefully. If too short a time is chosen it is possible that the thermal transfer is carried out partially and if the time is too long the thermal gradient along the regenerator may decrease.

The effect of the type of the nanoparticles on the evolution of the temperature is presented in figure 5. This figure shows that the effect of the type of the nanoparticles on the heat transfer is very large in agreement with the curve corresponding to the water pure, moreover, these nanoparticles cause an improvement of the coefficient of performance COP. The most important information to remember is that the nanofluid having base Al_2O_3 is for the moment favorite as a substitute for water or water glycol in thermal exchange.



(a): T_H=312 K



(b): T_C=284 K

Fig.5. Temperature distribution during: The hot blow (a); and the cold blow (b) for Al_2O_3

Table 2. Comparison of results: Water; CuO and Al_2O_3 (implemented in the COMSOL Multiphysics)

	Al_2O_3	CuO	Water
T_H [K]	312	308	306
T_C [K]	284	288	290
ΔT[K]	28	20	16

In figure 6 we can observe the evolution of the temperatures representative of the system, during the first 25 seconds; under transient conditions the temperature profile evolves rapidly and the regenerator gradually enters steady state. In addition, the heat transfer in the presence of Al_2O_3 nanoparticles is improved compared to the results obtained with CuO nanoparticles. The temperature evolution of the AER and the maximum temperature difference value between the two exchangers depends on several factors such as the geometric characteristics of the system, the operating parameters and the thermophysical properties of the nanofluid and the solid electrocaloric material.

Figure 7 shows the variation of the cooling power as a function of time for different nanofluids. Comparing the different cases, it is found that the cooling capacity for the nanofluid Al_2O_3 are higher than those of the CuO nanofluid. This shows that Al_2O_3 is a good heat conductor compared to CuO and water.

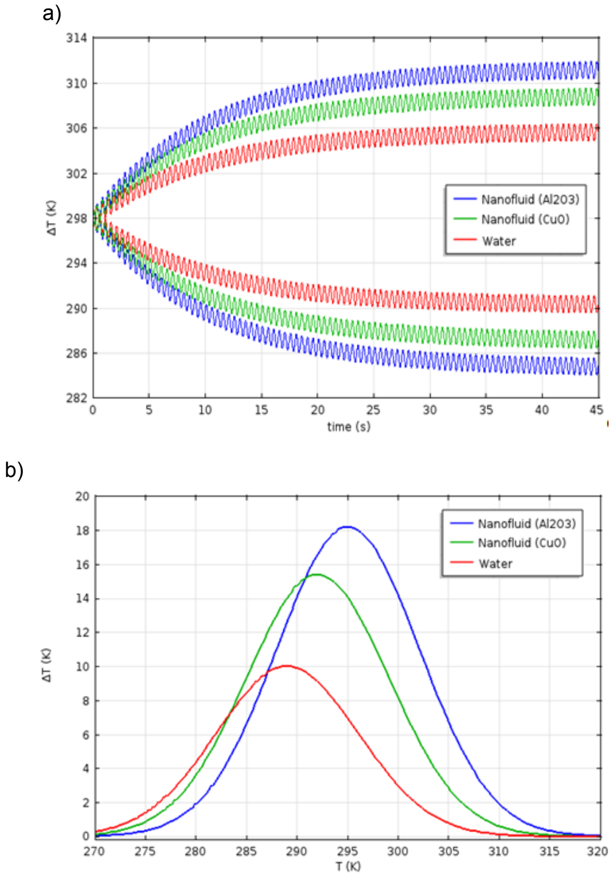


Fig.6. Evolution of temperatures span as

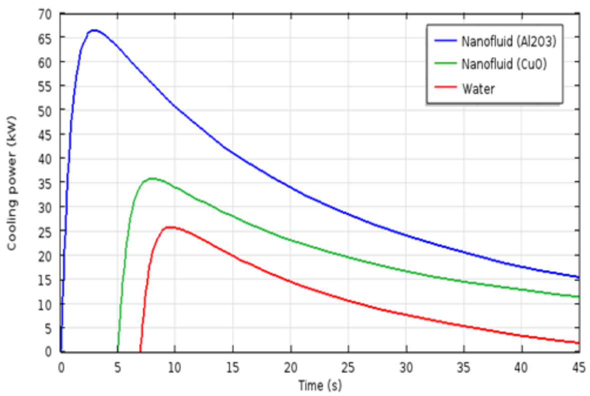


Fig.7.The variation of cooling capacity as a function of time

Figure 8 shows the cooling capacity and the coefficient of performance COP for Al2O3 as a function of the temperature difference between the heat exchangers in a system having a flow rate of nanofluid; 0.05 m / s (see Table 1). The cooling capacity shows maximum values in the temperature difference about 1-4K, and the coefficient of performance shows maximum values in the temperature difference around 2-5K after the performance decreases with the increase of the temperature difference between the exchangers.

Figure 9 shows the coefficient of performance COP as a function of the time in a system having a flow rate of nanofluid; 0.05 m / s calculated from equation (10). The coefficient of performance shows maximum values at around t = 20-25 s is observed at the Curie temperature which corresponds to the phase transition temperature, after the performance decreases with the increase of the time.

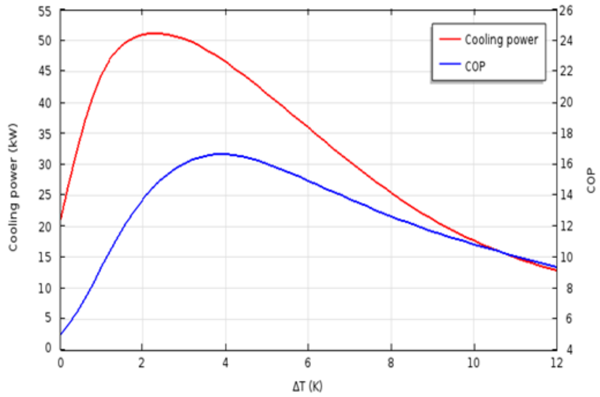


Fig.8.The variation of cooling capacity and coefficient of performance (COP) for Al_2O_3 as a function of temperature difference

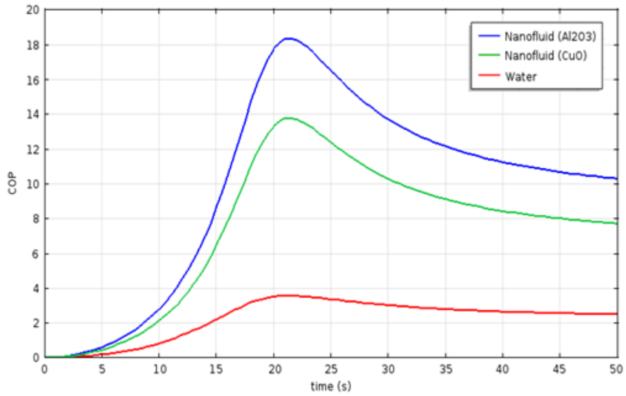


Fig.9.The variation of coefficient of performance COP as a function of the time

We present in figure 10 the curve of the heat capacity of the electrocaloric material recorded in the temperature range around 270 to 310 K; calculated from equation (7) for different electrical field levels; the electric field is imposed so as to avoid the breakdown of the electrocaloric material (see Table 1 and Fig. 2). An anomaly is observed at the temperature 297 K which corresponds to the phase transition temperature.

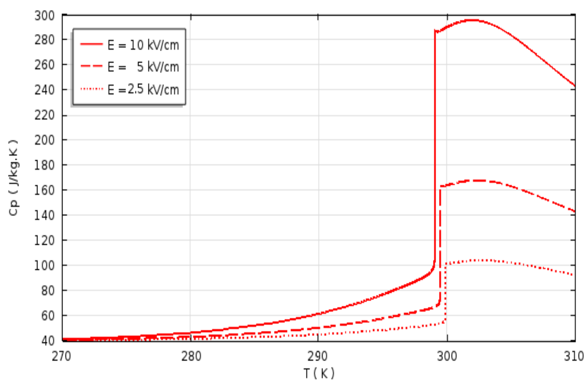


Fig.10.The variation of heat capacity as a function of temperature

Conclusions and future prospects

In this work we have opened a door to the use of nanofluids in electrocaloric device. This study has allowed us to understand one essential thing: nanofluids are a way to improve energy expenditure and heat transfer. On the other hand, the main problem is to keep the nanofluid stable over time so that the viscosity does not slow down this performance.

The numerical study with COMSOL Multiphysics revealed that nanofluids are indeed superior to the traditional heat transfer fluid and that they increase heat transfer very quickly. Regarding the comparison of different nanoparticles in terms of thermo-physical and thermodynamic properties, we can say that the best results were obtained with the nanoparticles of aluminum oxide (Al_2O_3). Indeed, the alumina oxide has the best improvement rate of the COP with a lower coefficient of pressure drop.

The numerical model developed in this study paves the way for further studies of electrocaloric systems using nanofluids in which the following effects could be considered:

- Effect of the geometrical shape of the AER (Active Electrocaloric Regenerator)
- Effect of shape and concentration of nanoparticles
- Effect of the nature of the base fluid
- Study of the thermal performance of nanofluids based on carbon nanotubes in an electrocaloric refrigeration system (carbon nanotubes transfer two to three times better heat than Al_2O_3)

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