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Experimental study of a static system based on a magneto-thermal coupling in ferrofluids

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ABSTRACT

Liquid cooling of electronic devices requires generally a mechanical pump which reduces the performance of the system and its reliability. It has already been shown that ferrofluids with low Curie temperature are able to create a liquid flow without any mechanical part. In fact a pressure gradient can be obtained when subjecting this ferrofluids to both a temperature gradient and a magnetic field. In this paper a novel experimental setup is proposed. It is thermally and magnetically instrumented to achieve a precise analysis of the local behavior of the ferrofluids. A MnZn based ferrofluid was investigated on steady and transient states. The results confirm that a hydrostatic pressure can be successfully created. The behavior of the ferrofluid is analyzed considering a homogeneous applied magnetic field or not. A pressure drop is also highlighted and discussed in terms of temperature gradient evolution and magneto-convection in the ferrofluid.

Étude expérimentale d'une pompe statique fondée sur le couplage magnéto-thermique au sein des ferrofluides

Mots clés : Ferrofluides à faible temperature de Curie ; Pompe statique ; Refroidissement des composants électroniques ; Couplage magnétothermique

1. Introduction

Despite the high performance of modern power electronic converters, heat dissipation in semiconductor devices is not negligible due to conduction and commutation losses (Mohan et al., 2003). In order to improve the converter characteristics (voltage ripple reduction, audible noise, volume, weight, etc.), the switching frequency must be increased (Jankovskis et al., 2010) intensifying the losses in power electronic components. Nowadays, power electronics is to be found in lots of applications, especially in transports, a domain where the weight is an important issue and where the size of electronic components must be reduced. Size reduction and power increase lead both to higher power densities. 500 W cm^{-2} is a

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Nomenclature

Roman letters

P_m	Pyro-magnetic coefficient
H	Magnetic field [A m^{-1}]
J	Magnetic polarization [T]
M	Magnetization [A m^{-1}]
B	Magnetic flux density [T]
T	Temperature [°C]
I	Current [A]

Greek letters

Δp	Static pressure [Pa]
ΔT	Temperature span between the hot and the cold sources [K]
Φ	Heat Flux [W]
μ_0	Vacuum permeability [4π 10^{-7} H m^{-1}]

Subscripts

0	Initial value
∞	Static state value
n	Normalized value

practical requirement for modern power electronics while the maximum junction temperature is in the range 125 °C–200 °C. Thermal management is therefore a key challenge for next steps in power electronics. Several efficient water cooling techniques like base-plate integrated coolers (Rondier et al., 2008), micro jet cooling devices (Leland et al., 2002), spray or nozzle coolers (Pautsch and Shedd, 2005; Cole and Scarine, 2002) are very efficient but they require the use of a mechanical pump which reduces the overall performances of the converter and its reliability. Other cooling systems are therefore proposed in scientific literature and in industrial applications like heat pipes, capillary pumped loop (Tawk et al., 2011). The main goal is to remove the mechanical pump from the system and to create a passive (i.e. autonomous) pumping system.

In this paper, another solution is discussed. It is able to take the place of the mechanical pump and get nevertheless an effective cooling system. It is based on the use of ferrofluids which are colloidal suspensions of magnetic particles in solvents like kerosene, Olefin-Paraffin or water (Auzans et al., 1999). For example, rotating or slippery magnetic fields can attract and move ferrofluids (Mao et al., 2011). This system does not need any mechanical pump but need the creation of a variable magnetic field. However, this magnetic field is obtained by a multiple phase current system, which can be difficult to achieve. In addition, it is energy consuming and thus not autonomous. Some ferrofluids are thermo-sensitive, so their magnetic properties change with temperature (Rosensweig, 1985). For example, Manganese–Zinc ferrites based ferrofluids have a Curie temperature close to 150 °C and their saturation magnetization decreases strongly from 50 °C to the Curie point. This effect can be used to increase natural convection with an additional magneto-convective phenomenon (Souhar et al., 1999; Zablotsky et al., 2013) and also to realize passive pumps (Love et al., 2004) (Matsuki et a1., 1977) (Li et al., 2008) (Riccetti, 2009). The Curie temperature of MnZn based ferrofluids being close to the power electronics working temperatures, passive pumps based on this physical phenomenon can be used to cool semiconductor devices (Fumoto et al., 2007).

The goal of this paper is to give complementary results to previous works carried out on the passive pumping using low Curie temperature ferrofluids. In fact, pressure drop creation using magnetothermal coupling has already been experimentally proved but few published experimental setups exist. Moreover, authors who have compared theoretical and experimental results (Bermùdez-Torres, 2008) have demonstrated that non-negligible differences exist between results obtained by both approaches but the instrumentation was not enough to conclude on the main reasons of these differences. The present paper proposes therefore to study in more details the creation of a pressure drop in a straight tube filled with a MnZn ferrofluid and submitted to a magnetic field. The developed experimental setup is instrumented with thermocouples as it is proposed by Souhar et al. (1999) in the case of an annular geometry.

2. Magnetothermal pumping principle

Magnetic fluids have a paramagnetic behavior (Massart et al., 1995), and are therefore temperature sensitive (Love et al., 2004). The pyromagnetic coefficient P_m, defined by Eq. (1), is especially higher if the temperature is close to the Curie temperature.

$$P_m|_H = \frac{\partial}{\partial T} M(H) \tag{1}$$

The magnetothermal effect is therefore the highest around this temperature. As said before, the most common used ferrofluids are the MnZn based ones. The thermomagnetic effect is based on the interaction between a temperature gradient and a static magnetic field. The increase of

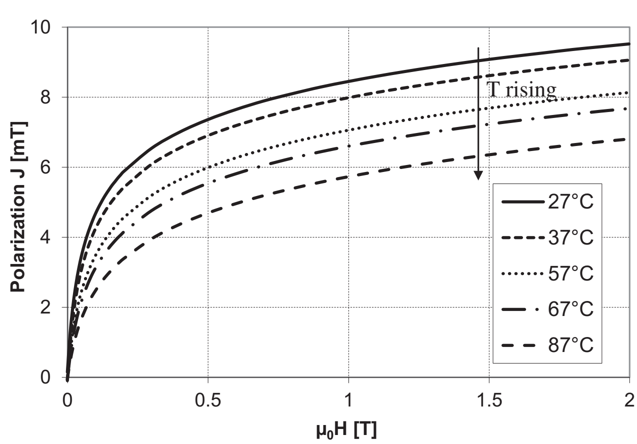

Fig. 1 – Magnetization of a ferrofluid regarding the applied magnetic field and the temperature.