Letter

Self pumping magnetic cooling

V Chaudhary¹,²,³, Z Wang³, A Ray³, I Sridhar⁴ and R V Ramanujan³

¹ Interdisciplinary Graduate School (IGS), Nanyang Technological University, Singapore 639798, Singapore
² Energy Research Institute @ NTU (ERI@N), Nanyang Technological University, Singapore 637553, Singapore
³ School of Materials Science & Engineering, Nanyang Technological University, Singapore 639798, Singapore
⁴ School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore

E-mail: ramanujan@ntu.edu.sg

Received 5 October 2016, revised 8 November 2016
Accepted for publication 24 November 2016
Published 19 December 2016

Invited by Board Member Sara Majetich

Abstract
Efficient thermal management and heat recovery devices are of high technological significance for innovative energy conservation solutions. We describe a study of a self-pumping magnetic cooling device, which does not require external energy input, employing Mn–Zn ferrite nanoparticles suspended in water. The device performance depends strongly on magnetic field strength, nanoparticle content in the fluid and heat load temperature. Cooling (ΔT) by ~20 °C and ~28 °C was achieved by the application of 0.3 T magnetic field when the initial temperature of the heat load was 64 °C and 87 °C, respectively. These experiments results were in good agreement with simulations performed with COMSOL Multiphysics. Our system is a self-regulating device; as the heat load increases, the magnetization of the ferrofluid decreases; leading to an increase in the fluid velocity and consequently, faster heat transfer from the heat source to the heat sink.

Keywords: magnetic nanoparticles, ferrofluid, thermomagnetic convection, thermal management device

(Some figures may appear in colour only in the online journal)

1. Introduction
Numerous thermal management technologies, exist, including, e.g. micro jet cooling and spray cooling [1–6]. However, most of these techniques have drawbacks, such as vibration, noise, high maintenance and large power consumption due to mechanical pumps and other moving parts. To overcome these drawbacks, researchers are now avoiding mechanical pumps and have instead proposed membrane based actuators, e.g. magnetic, piezoelectric, thermo-pneumatic and shape memory alloy actuators [7–9]. However, such techniques generally provide pulsatile flow, resulting in undesirable temperature fluctuations.

Cooling devices based on field induced flow are very attractive for thermal management. The interaction between an external magnetic field and a ferrofluid results in a pumping force. These interactions can be divided into three classes: (i) electrohydrodynamics (EHD), corresponding to the electric force effect i.e. the Coulomb force on a low electrical conductivity fluid, (ii) magnetohydrodynamics (MHD), corresponding to the Lorentz force, i.e. the force between a magnetic field and a fluid conductor of electricity and (iii)
ferrohydrodynamics (FHD), corresponding to the forces of magnetic polarization [10]. Systems based on EHD and MHD have no moving parts and therefore possess a simple structure, however, identifying a working fluid with suitable electrical conductivity is still a challenge. In addition, MHD systems require a high magnetic force to generate significant flow because of high fluid viscosity.

The body force in FHD is the result of a change, in the presence of an applied magnetic field, of the magnetization of the magnetic material with temperature. The mechanics of FHD depends on the physical properties of a colloidal suspension of ferri- or ferromagnetic nanoparticles in a suitable liquid carrier, called a ferrofluid. A ferrofluid experiences a change in magnetization when the fluid temperature changes [11, 12]. The magnetization is higher in the low temperature region compared to the high temperature region. Under the influence of an applied magnetic field, a driving force is produced for fluid flow. This ferrofluid can therefore be used as a heat transfer medium. Figure 1 shows a schematic of the system. A cold magnetic fluid (green circle) which has finite magnetization ($M > 0$) is attracted by the magnetic field. As the fluid enters the thermal field of the heat load, the temperature increases (red circle) beyond the Curie temperature of the magnetic nanoparticles in the ferrofluid. Therefore, in the thermal field, the ferrofluid becomes paramagnetic ($M = 0$) and is no longer attracted to the magnetic field. This allows ferrofluid continue to move towards the heat sink. The ferrofluid again become ferromagnetic by transferring the heat to the heat sink. The service temperature of the device can be changed by simply changing the Curie temperature of the nanoparticles in the ferrofluid.

Previous studies have referred to this effect as thermomagnetic convection [13–15]. Zhou et al proposed an engine whose the performance of the engine can be controlled by an external magnetic field or ferrofluid temperature [16]. Several investigations has been carried out on thermomagnetic convection of magnetic fluids, including for energy transport [13, 17–27]. Lian et al established a mathematical model to predict fluid flow and heat transport of the ferrofluid and to design an energy transport device [11]. Xuan et al designed a cooling device in which waste heat from an electronic device was used as the driving force for fluid flow [14].

There is still considerable scope for improvement of these devices [28, 29]. Hence, a device was constructed and experiments conducted to determine the effect of heat load, magnetic particle content and magnetic field on self-pumping magnetic cooling. We fixed the initial temperature of the heat load and examined the temperature drop of the heat load due to the application of magnetic field. For the first time, the switching (application and removal of magnetic field between measurements) effect of magnetic field on cooling was studied. Modeling with COMSOL Multiphysics was also performed. These devices have a wide variety of applications, since no external energy is required for pumping, and there is no noise or vibration. Examples include space craft, server cooling, electronic devices, cold chain systems and for power generation [12, 30].

2. Experimental details

2.1. Synthesis of nanoparticles and ferrofluid

Mn$_{x}$Zn$_{1-x}$Fe$_2$O$_4$ nanoparticles ($x = 0.3, 0.4$ and $0.5$) were synthesized via the hydrothermal method. In a typical synthesis manganese (II) chloride tetrahydrate (MnCl$_2$ · 4H$_2$O, 99%), zinc chloride, anhydrous (ZnCl$_2$, 98%) and iron (III) chloride hexahydrate, ACS (FeCl$_3$ · 6H$_2$O) were used as starting precursors. Sodium hydroxide (NaOH) was used to adjust the pH value. Each starting precursor was dissolved in appropriate molar quantities of purified water. 5M-NaOH was added to the iron chloride solution until the pH value was 8. The precipitate was centrifuged and washed four times with DI water. The salt solutions were then added together and vigorously stirred while adding sodium hydroxide drop wise until the pH of the reaction mixture reached a value of 11. The resulting slurry was decanted into a pressure vessel.
and placed into an oven at 190 °C for 4 h. The nanoparticles obtained by this method were washed several times with DI water followed by vacuum drying overnight.

Powder x-ray diffraction (XRD) was performed using a Bruker 8D ADVANCE diffractometer. The XRD data was collected from 20° to 70° with a step size of 0.02° and scan rate of 2° min⁻¹. The instrument was operated at 35 kV and 25 mA using CuKα radiation (λ = 0.154 nm). The Rietveld refinement of x-ray pattern reveals a single phase spinel structure (not shown). To determine the size and crystal structure, transmission electron microscopy (TEM) was carried out using a JEOL 2010 TEM at an operating voltage of 200 kV. Samples were prepared by ultrasonically dispersing a small quantity of powder in hexane, followed by placing a drop of the suspension on a holey carbon-coated copper grid and drying in air. Figure 2 shows a typical bright-field TEM image of the equiaxed Mn₀.₄Zn₀.₆Fe₂O₄ nanoparticles. The inset of figure 2 shows a histogram of the particle size distribution, revealing an average particle size of ~11 nm. The average size observed from TEM was consistent with the value obtained from x-ray analysis.

Mn₀.₄Zn₀.₆Fe₂O₄ nanoparticles were used to prepare the ferrofluid. The nanoparticles were coated by a surfactant to prevent their agglomeration in water. The dried nanoparticles were added to a mixture of oleic acid and HNO₃ in the ratio of 1:10, followed by 1 h mechanical stirring at 70 °C. After cooling to room temperature, the nanoparticles were extracted from the excess HNO₃ and oleic acid by a permanent magnet. Finally, the coated particles were dispersed in DI water. The stability of these nanoparticles in the fluid is crucial for self-pumping magnetic cooling. The ratio of thermal energy to magnetic energy results in an expression for particle size $d < (6kT/\pi\mu H)$, suggesting that small particles can be suspended in a fluid, even in the presence of high magnetic fields [10, 31]. Fe–Ni based nanoparticles have great potential for ferrofluid applications, not only because of their good magnetization but also soft magnetic properties [32–37]. However, the long-term stability of metallic nanoparticles in the fluid is a challenge.

2.2. Self-pumping magnetic cooling device

To build a self-pumping magnetic cooling device, a 5.2 mm inner diameter, 60 cm circumference polymer tube was used for circular flow. A heat load (electric heater made from Kanthal wires) and a heat sink (ice bath) were placed opposite each other. A Nd–Fe–B permanent magnet which can provide a maximum field of 0.3 T was placed close to the heat load. A temperature data logger with SD card was used to record the temperature as a function of time. The initial temperature of the heat load was tuned by changing the current and the voltage across the wire using a Keithley power supply (Model: 2231 A-30-3). To avoid buoyancy effect, a spirit level was used to fix the device in a horizontal position.

The experiments were carried out for heat load temperature of 64 °C, 74 °C and 87 °C, while heat sink temperature was fixed at a temperature of 0 °C by the use of ice.

3. Numerical simulation

2D modelling was performed using COMSOL Multiphysics simulation software version 4.4, using the finite element method and extremely fine mesh. The governing equations used in the simulation are given in the following sections.

3.1. Fluid flow equation

The value of magnetic susceptibility in the model was calculated from the magnetic susceptibility of the magnetic particles and volume concentration of these particles in the fluid. Water is diamagnetic, the value of volume magnetic susceptibility is $-9.0 \times 10^{-6}$. The Navier–Stokes equation describes the incompressible, viscous, laminar flow inside the tube [38–40]:

$$\frac{\partial}{\partial t} (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \left[ \eta(\nabla \mathbf{u} + \nabla \mathbf{u}^T) \right] + \mathbf{F}_f \quad (1)$$

where $\rho$, $\mathbf{u}$, $p$, $\eta$ and $\mathbf{F}_f$ represent the local density of the flow, flow velocity, pressure, fluid viscosity and external volume force vector within each mesh cell, respectively.

3.2. Magnetic field equation

To describe the magnetic field, the following equations were used:

$$\Delta \cdot \mathbf{B} = 0 \quad (2)$$

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) = \mu_0 (1 + \chi) \mathbf{H} = \mu_s \mathbf{H} \quad (3)$$

where $\chi$ is the local susceptibility of the ferrofluid diluted by the carrier fluid. The vector $\mathbf{B}$, $\mathbf{M}$, $\mathbf{H}$, $\mu_0$ and $\mu_s$ represent...
the magnetic flux density, magnetic field strength, magnetization, permeability of vacuum and relative permeability, respectively.

3.3. Force calculation

The volume force term $F_f (N \cdot m^{-3})$ in the Navier–Stokes equation is the sum of the magnetic force vector $F_m$ and gravitational force vector $F_g$

$$ F_f = F_m + F_g $$  (4)  

The direction of gravity is perpendicular to the flow plane in our experiments, therefore, its effect is neglected.

$$ F_f = F_m = \chi \mu_0 (B \cdot \nabla B) $$  (5)  

In the model, the magnetic fluid is assumed to be a single phase incompressible Newtonian fluid. The no slip boundary condition was applied to the channel walls.

The properties of the ferrofluid in the model are taken to be: density $\rho = 1044 \text{ kg} \cdot \text{m}^{-3}$, specific heat $C_p = 1616 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ and thermal conductivity $k = 0.16 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. For the thermal boundary condition, a constant surface temperature of 273.15 K was assumed at the heat sink section and at the tube wall in the section where the heat load was placed.

The driving force is the result of magnetic and thermal gradients; the temperature distribution of the fluid can be controlled by changing the applied magnetic field. The effect of magnetic field and load temperature on cooling was studied.

4. Results and discussion

4.1. Magnetic properties of nanoparticles

The magnetic properties of the samples were measured using a physical property measuring system (PPM EverCool, Quantum Design USA) equipped with a vibrating sample magnetometer probe. Figure 3 shows the temperature dependence of magnetization $M(T)$ for Mn$_x$Zn$_{1-x}$Fe$_2$O$_4$ ($x = 0.3, 0.4$ and 0.5) nanoparticles at magnetic fields of (a) 100 Oe and (b) 500 Oe. In all the samples, magnetization decreases with increasing temperature, this effect is useful for self-pumping magnetic cooling. The ferromagnetic-paramagnetic transition temperature shifts to higher values when the Mn content increases ($x$ increasing from 0.3 to 0.5). For all samples, magnetization is higher when the applied field is 500 Oe compared to the value when the applied field is 100 Oe.

4.2. Effect of magnetic field on cooling

Experiments were carried out to determine the effect of magnetic field on cooling. Figure 4 shows the temperature distribution of the fluid in the circular loop with and without magnetic field. From the temperature distribution, it can be concluded that the fluid starts to flow only when the magnetic field is applied i.e. the driving force is the result of both magnetic and thermal fields.

Figure 5 shows the effect of magnetic field on the heating coil temperature for a 4.4 W heat load. The initial temperature of the heating coil in the absence of magnetic field was fixed at 74 °C. Magnetic fields of 0 T, 0.2 T, 0.25 T and 0.3 T were applied for both the experiments and the simulations. The magnetic field was tuned by changing the distance of the permanent magnet from the tube. It is evident that the temperature of the heating coil drops with increasing magnetic field, which indicates that thermomagnetic convection, induced by the magnetic field, increases with increasing magnetic field strength.

The combination of temperature gradient and applied magnetic field results in thermomagnetic convection. Since magnetization of the magnetic fluid decreases with increasing temperature, the magnetic fluid in the heat load section possesses lower magnetization compared to other sections. It was reported in our previous work that the magnetization of MnZn ferrite nanoparticles increases with increasing magnetic field [31]. The volume force $(F_M)$ depends on the magnitude of the applied magnetic field; larger magnetic field results in a greater cooling effect. In both experiments and simulations, with non-zero magnetic field, the temperature profiles exhibit a transient behavior (marked by an ellipse in figure 5). This behavior can be understood by the fact that the cold magnetic fluid from the heat sink reaches the hot section only after a
transient time. Once the magnetic fluid from the cold section reaches the magnet (and therefore near the heat load), the temperature gradient increases, which results in greater thermomagnetic convection. Xuan et al also reported that the surface temperature of the chip shows a peak before reaching steady state [14]. Jin et al reported an enhancement in heat transfer with increasing applied magnetic field [41]. The temperature differences after 25 min, for both experiments and simulations, are plotted in figure 6.

4.3. Effect of load temperature

To determine the effect of initial temperature of heat load on cooling, the initial temperatures of 64 °C, 74 °C and 87 °C were used. A magnetic field of 0.3 T was applied near the heat load. Figure 7 shows the temperature profiles for the heat load with and without magnetic field of 0.3 T. An obvious reduction in temperature can be seen when the magnetic field is applied. Our experimental results are in good agreement with the simulations, the parameters used in the simulation are the same as those used in the experiments.

4.4. Effect of fluid concentration

To examine the effect of volume fraction of the magnetic nanoparticles, we prepared magnetic fluids with 3%, 5%, 7% and 10% of magnetic nanoparticles in water. The initial temperature of the heat load was 74 °C. Figure 9 shows the effect of particle content on the relationship between the cooling of the heat load and time. As the particle content increases, the assumption that the particles do not aggregate is less valid, weakening the agreement between experiment and simulation.
At high field, particles start to settle in the magnetic field direction after some time, which can decrease the fluid velocity, resulting in reduced cooling. Figure 10 shows the temperature difference of the heat load with different volume fraction of magnetic nanoparticles for experiments (black square) and simulation (red circle).

4.5. Switching (‘0’ and ‘1’) of magnetic field

Figure 11 shows the temperature profiles of the heat load when the magnetic field was applied and removed in between the measurements for fixed initial temperature in the absence of magnetic field. After achieving steady state, a magnetic field of 0.3 T was applied; a sharp drop in temperature was obvious in all cases.

When the field was removed, the temperature of heat load again increased up to the initial temperature and steady state...
Higher the heat load, the faster the heat transfer. These magnetic cooling devices are self-regulating, i.e. the results were in good agreement with experimental findings. ~64 °C was achieved by application of 0.3 T on the temperature profile for initial temperature of ~20 °C, when the initial temperature was ~24 °C, ~74 °C and ~64 °C, respectively. The simulation was obtained. The cooling (ΔT) increased from ~20 °C to ~28 °C, when the initial temperature of heat load was changed from 64 °C to 87 °C. Interestingly, the temperature drop in every cycle was almost constant for fixed initial temperature. This change in temperature was achieved in less than 3 min.

5. Conclusions

A self pumping magnetic fluid based cooling device was studied. Chemically synthesized Mn–Zn ferrite nanoparticles were coated by oleic acid and dispersed in the water to prepare a ferrofluid. The ferrofluid was used in a device to examine the cooling of a heat load. The device consists of magnet, heat load, heat sink, polymer tube, connecters and ferrofluid. It was found that the performance of the cooling device depends strongly on the heat load temperature, magnetic particle content in the fluid and the magnetic field strength. A temperature drop of ~16 °C and ~27 °C was achieved by application of 0.3 T magnetic field when the nanoparticle content in fluid was 5% and 10%, respectively. The in situ application and removal of magnetic field of 0.3 T resulted in cooling of ~20 °C, ~24 °C and 28 °C, when the initial temperature was ~64 °C, ~74 °C and ~87 °C, respectively. The simulation results were in good agreement with experimental findings. These magnetic cooling devices are self-regulating, i.e. the higher the heat load, the faster the heat transfer.

Acknowledgments

This Research is conducted by NTU-HUJ-BGU Nanomaterials for Energy and Water Management Programme under the Campus for Research Excellence and Technological Enterprise (CREATE), that is supported by the National Research Foundation, Prime Minister’s Office, Singapore.

Reference

[1] Yong H, Boon Long L and Xiaowu Z 2015 Package-level microjet-based hotspot cooling solution for microelectronic devices IEEE Electron Device Lett. 36 502–4
[2] Fabbri M, Jiang S and Dhir V K 2005 A comparative study of cooling of high power density electronics using sprays and microjets J. Heat Transfer 127 38–48
[3] Webb B W and Ma C F 1995 Single-phase liquid jet impingement heat transfer Adv. Heat Transfer 26 105–217
[4] Lytle D and Webb B W 1994 Air jet impingement heat transfer at low nozzle-plate spacings Int. J. Heat Mass Transfer 37 1687–97
[5] Stevens J and Webb B W 1991 Local heat transfer coefficients under an axisymmetric, single-phase liquid jet J. Heat Transfer 113 71–8
[6] Zhang Y, Pang L P, Xie Y Q, Jin S C, Liu M and Ji Y B 2015 Experimental investigation of spray cooling heat transfer on straight fin surface under acceleration conditions Exp. Heat Transfer 28 564–79
[7] Wang B, Chu X, Li E and Li L 2006 Simulations and analysis of a piezoelectric micropump Ultrasonics 44 e643–6
[8] Stemme E and Stemme G 1993 A valveless diffuser/nozzle-based fluid pump Sensors Actuators A 39 159–67
[9] Shinozawa Y, Abe T and Kondo T 1997 A proportional microvalve using a bi-stable magnetic actuator 10th Annual Int. Workshop on Micro Electro Mechanical Systems. MEMS '97, Proc. (IEEE) pp 233–7
[10] Rosenweig R E 1985 Ferrohydrodynamics (Cambridge: Cambridge University Press)
[11] Love L J, Jansen J F, McKnight T E, Roh Y and Phelps T J 2004 A magnetocaloric pump for microfluidic applications IEEE Trans. Nanobiosci. 3 101–10
[12] Ramanujan R V and Chaudhary V 2016 Self-pumping magnetic cooling Singapore Patent Application 102016060447V
[13] Lian W, Xuan Y and Li Q 2009 Design method of automatic energy transport devices based on the thermomagnetic effect of magnetic fluids Int. J. Heat Mass Transfer 52 5451–8
[14] Xuan Y and Lian W 2011 Electronic cooling using an automatic energy transport device based on thermomagnetic effect Appl. Therm. Eng. 31 1487–94
[15] Yamaguchi H, Kobori I and Kobayashi N 1999 Numerical study of flow state for a magnetic fluid heat transport device J. Magn. Magn. Mater. 201 260–3
[16] Zhou L, Xuan Y, Li Q and Lian W 2009 A new miniaturized engine based on thermomagnetic effect of magnetic fluids Front. Energy Power Eng. 3 160–6
[17] Suslov S A 2008 Thermomagnetic convection in a vertical layer of ferromagnetic fluid Phys. Fluids 20 084101
[18] Niu X-D, Yamaguchi H and Yoshikawa K 2009 Lattice Boltzmann model for simulating temperature-sensitive ferrofluids Phys. Rev. E 79 046713
[19] Li Q, Lian W, Sun H and Xuan Y 2008 Investigation on operational characteristics of a miniature automatic cooling device Int. J. Heat Mass Transfer 51 5033–9
[20] Mukhopadhyay A, Ganguly R, Sen S and Puri I K 2005 A scaling analysis to characterize thermomagnetic convection Int. J. Heat Mass Transfer 48 3485–92
[21] Banerjee S, Mukhopadhyay A, Sen S and Ganguly R 2009 Thermomagnetic convection in square and shallow enclosures for electronics cooling Numer. Heat Transfer A 55 931–51
[22] Ganguly R, Sen S and Puri I K 2004 Thermomagnetic convection in a square enclosure using a line dipole Phys. Fluids 16 2228–36
[23] Petit M, Avenas Y, Kedous-Lebouc A, Cherief W and Rullière E 2014 Experimental study of a static system based on a magneto-thermal coupling in ferrofluids Int. J. Refrig. 37 201–8
[24] Bahiraei M and Hangi M 2015 Flow and heat transfer characteristics of magnetic nanofluids: a review Magn. Magn. Mater. 374 125–38
[25] Kaneda M, Kano H and Suga K 2015 Development of magneto-thermal lattice Boltzmann heat and fluid flow simulation Heat Mass Transfer 51 1263–75
[26] Ghofrani A, Dibaei M H, Hakim Sima A and Shafii M B 2013 Experimental investigation on laminar forced convection heat transfer of ferrofluids under an alternating magnetic field Exp. Therm Fluid Sci. 49 193–200
[27] Jahani K, Mohammadi M, Shafii M B and Shiee Z 2013 Promising technology for electronic cooling: nanofluidic micro pulsating heat pipes J. Electron. Packag. 135 021005
[28] Jaka Tušek U T, Kitanovski A, Plaznik U, Ožbolt M and Poredos A 2015 Magnetoferromagnetic Energy Conversion (Berlin: Springer)
[29] Rosensweig R E 2006 Refrigeration aspects of magnetic particle suspensions Int. J. Refrig. 29 1250–8
[30] Chen X 2016 The magnetoferromagnetic effect in Fe₃P based alloys PhD Thesis School of Materials Science and Engineering, Nanyang Technological University Singapore
[31] Chaudhary V and Ramanujan R V 2014 Iron oxide-based magnetic nanoparticles for high temperature span magnetocaloric applications MRS Proc. 1708 mrss14-1708-vv10-08
[32] Chaudhary V and Ramanujan R V 2015 Magnetic and structural properties of high relative cooling power (Fe₇₀Ni₃₀)₂Mn₉ magnetocaloric nanoparticles J. Phys. D: Appl. Phys. 48 305003
[33] Chaudhary V, Maheswar Repaka D V, Chaturvedi A, Sridhar I and Ramanujan R V 2014 Magnetocaloric properties and critical behavior of high relative cooling power Fe₇₀Ni₃₀-Fe alloy nanoparticles J. Appl. Phys. 116 163918–26
[34] Chaudhary V, Chaturvedi A, Sridhar I and Ramanujan R V 2014 Fe–Ni–Mn nanoparticles for magnetic cooling near room temperature IEEE Magn. Lett. 5 6800104
[35] Ucar H, Craven M, Laughlin D E and McHenry M E 2014 Effect of Mo addition on structure and magnetocaloric effect in γ-FeNi nanocrystals J. Electron. Mater. 43 137–41
[36] McNerny K L, Kim Y, Laughlin D E and McHenry M E 2010 Chemical synthesis of monodisperse γ-Fe–Ni magnetic nanoparticles with tunable Curie temperatures for self-regulated hyperthermia J. Appl. Phys. 107 09A312
[37] Chaudhary V and Ramanujan R V 2016 Magnetocaloric properties of Fe–Ni–Cr nanoparticles for active cooling Sci. Rep. 6 35156
[38] Wang Z M, Wu R G, Wang Z P and Ramanujan R V 2016 Magnetic trapping of bacteria at low magnetic fields Sci. Rep. 6 20945
[39] Chaudhary V 2016 Study of iron based magnetocaloric nanomaterials PhD Thesis Interdisciplinary Graduate School, Nanyang Technological University Singapore
[40] Wang Z, Varma V B, Xia H M, Wang Z P and Ramanujan R V 2015 Spreading of a ferrofluid core in three-stream micromixer channels Phys. Fluids 27 052004
[41] Jin L, Zhang X and Niu X 2012 Lattice Boltzmann simulation for temperature-sensitive magnetic fluids in a porous square cavity J. Magn. Magn. Mater. 324 44–51
[42] Lian W, Xuan Y and Li Q 2009 Characterization of miniature automatic energy transport devices based on the thermomagnetic effect Energy Convers. Manage. 50 35–42