Numerical investigation of effect of central gap’s width and length of magnetic material on heat transfer and pressure loss of water flow using computational fluid dynamics

J Thongjamroon\textsuperscript{1,2}, R Techapiesancharoenkij\textsuperscript{2,3} and W Chaiworapuek\textsuperscript{1,2*}

\textsuperscript{1} Department of Mechanical Engineering, Faculty of Engineering, Kasetsart University, 50 Ngamwongwan Road, Chatuchak, Bangkok, 10900 Thailand
\textsuperscript{2} Thailand Center of Excellence in Physics (ThEP), Commission of Higher Education, Bangkok, 10400, Thailand
\textsuperscript{3} Department of Materials Engineering, Faculty of Engineering, Kasetsart University, 50 Ngamwongwan Road, Chatuchak, Bangkok, 10900 Thailand

* Corresponding author’s e-mail address: fengwcc@ku.ac.th

Abstract. This research studied heat transfer and pressure loss due to water flow through the compressed magnetic powder using Computational Fluid Dynamics. The Reynolds number was determined, ranging from 3,000 to 7,000, corresponding to the working flow-rate range in the magnetic refrigeration system. To model the compressed magnetic powder as porous media, the porosity and permeability, calculated from experimental results, were 0.1684 and $3.3076 \times 10^{-10}$ m$^2$, respectively. In this research, porous media which have constant heat flux, were in a cylindrical shape. They had a diameter of 0.012 m and 0.05, 0.10 and 0.15 m in length. The width of the central gap was 0.001, 0.002, 0.003, 0.004 and 0.005 m. The numerical results showed that the Nusselt number and the friction factor increased when the width decreased and the length increased. The maximum friction factor and the Nusselt number were 27.85 and 16.83, respectively at 0.001 m in width and 0.15 m in length under the Reynolds number of 3,000. However, the highest thermal performance was 1.91 at 0.004 m in width and 0.15 m in length under the Reynolds number of 7,000. The results obtained in this research could be utilized for the geometric design of magnetic material for the magnetic refrigeration system in the future.

1. Introduction
Magnetic refrigeration is one of the promising technique due to its high energy efficiency and eco-friendly [1]. It utilizes the magneto-caloric effect of the magnetic material to drive the cycle instead of the general refrigerant. When the material is subjected by a magnetic field, its temperature increases. Conversely, the temperature of the material decreases when the magnetic field is removed. Through this cycle, the working fluid is employed to convect heat transfer in the system and the magnetic refrigeration is established. The magnetic materials are rare earth such as manganite, metal gadolinium, gadolinium
borohydrides and Ni-Mn-based Heusler alloys [2]. They first appear as powder and are compressed to be a specific shape, called “Magnetic bed” [3]. The main power of the refrigeration system relies on pressure loss across the bed [4]. The optimum bed shape is needed to maximize system efficiency [5].

Thus, this research numerically investigated the heat transfer and pressure loss due to water flow through the bed, having a gap along a diameter line. The obtained results can be directly applied to the real magnetic refrigeration system.

2. Experimental Setup
The experiment was set and carried out to obtain properties of porous media, depending on the relation between the pressure loss and flow velocity. The water was pumped from the tank to pass through the porous media as shown in figure 1. The static pressure was measured at the upstream and downstream of the porous media at a distance of 0.5 m to ensure the fully developed condition.

The relation between the obtained pressure difference and velocity, yielded by the flow meter led to the calculation of the permeability of porous media, \( K [m^2] \) as follows:

\[
\nabla p = \frac{\mu}{K} + \frac{\rho c_f}{\sqrt{K}} |v| v
\]

(1)

where \( p \) is pressure [kg/m·s²], \( \mu \) is dynamic viscosity [kg/m·s], \( v \) is velocity [m/s], \( \rho \) is density [kg/m³] and \( c_f \) is inertia coefficient. This equation showed the Darcy’s law, employed to describe the fluid flow through the bed, considered as porous media. It is noted that because the flow domain was under a low velocity regime, the Forchheimer term was added to the Darcy equation to explain inertia resistance [6].

3. Numerical analysis
In computational fluid dynamics (CFD), the numerical results are solved from continuity, momentum and energy equations as follows:

Continuity equation:

\[
\nabla \cdot \rho \vec{v} + \frac{\partial \rho}{\partial t} = 0
\]

(2)

Momentum equation:

\[
\rho \frac{D \vec{v}}{Dt} = \rho g - \nabla p + \mu \nabla^2 \vec{v}
\]

(3)
Energy equation:

$$\rho C_p \left( \frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right) = k \nabla^2 T + S$$  \hspace{1cm} (4)

where \( t \) is time [s], \( C_p \) is heat capacity [J/kg·K], \( T \) is temperature [K], \( k \) is thermal conductivity [W/m·K] and \( S \) is energy source term [W/m^3]. In this simulation, the energy source term [7-9] and Nusselt number were calculated as follow

energy source term:

$$S = -\rho T \frac{\partial M}{\partial T} \frac{dT}{dt}$$  \hspace{1cm} (5)

Nusselt number:

$$Nu = \frac{hD_h}{k}$$  \hspace{1cm} (6)

where \( M \) is magnetization [A·m²/kg], \( H \) is magnetic flux density [Tesla], \( h \) is averaged heat transfer coefficient [W/K·m²] and \( D_h \) is hydraulic diameter [m].

4. Numerical setup

This research simulated water flow through a bed, having a central gap as depicted in figure 2(a). The velocity inlet was defined to be corresponding with the Reynolds number, \( Re \) of 3,000 - 10,000 and pressure outlet was specified as 0 Pa. At the inlet, the water temperature was set as 300 K. The porous media was set in the middle of the domain. Its properties were the porosity of 0.1684 and the permeability of 3.3076 \times 10^{-10} \text{ m}^2. These values were obtained from the experiment. Furthermore, the central gap’s width, \( w \) were 0.001, 0.002, 0.003, 0.004 and 0.005 m while the length of the bed, \( l \), were 0.05, 0.10 and 0.15 m, as shown in figure 2(b). It was set to absorb the heat of 7,785.71 W/m^3. The Realizable k-epsilon model was utilized in this study and the calculation was stopped when the numerical error was below 10^{-5}.

5. Results

After the experiment has been carried out to obtain the value of pressure loss across the bed, the comparison of pressure loss from the experiment and this numerical calculation as depicted in figure 3 showed good agreement with \( R^2 \) of 0.977. This confirmed that the numerical setup in this study was reliable and the obtained model would be used through this research work.
Figure 3. Relationship of pressure loss and velocity obtained from the experiment and numerical simulation.

Figure 4(a) shows the ratio of friction factors under the condition with and without porous media. The friction factor is a dimensionless parameter, used to describe the pressure loss. The results indicated that the $f/f_0$ slightly depended on the length when the $w$ was between 0.003 and 0.005. However, it highly increased when the $w$ was 0.001 and 0.002. Also, the friction factor was increasing with higher flow velocity and the relatively maximum $f/f_0$ was obtained at $w = 0.001$ m and $l = 0.015$ m. Figure 4(b) shows the Nusselt number ratio under the condition with and without a bed. It was found that the $Nu/Nu_0$ gained when the gap was narrower and the bed was longer. The relatively maximum $Nu/Nu_0$ appeared at the same $w$ and $l$ as the case of $f/f_0$.

Figure 4. (a) friction factor ratio. (b) Nusselt ratio. (c) thermal performance. (d) distribution of water flow through the bed when $w = 0.004$ m, $l = 0.15$ and $Re = 7,000$. 
In this study, the thermal performance, TP was calculated from \((\frac{Nu}{Nu_0})/(f/f_0)^{1/3}\). The highest TP was found as 1.91 when the \(w\) and \(l\) were 0.004 and 0.15, respectively at the \(Re\) of 7,000 as illustrated in figure 4(c). Therefore, these obtained bed parameters were recommended for the design of the system of magnetic refrigeration. The example of the water flow velocity through the bed at this condition was also presented as shown in figure 4(d). Finally, the predictive formula for Nusselt number was established as in equation (7). The error was within only 12%.

\[
Nu = \frac{9.3490^{0.9564} Re^{0.005835}}{w^{0.3414} \exp\left(\frac{0.558w}{l}\right)}
\] (7)

6. Conclusion
The friction factor, Nusselt number, and thermal performance of water flow through the magnetic bed, designed to have a gap along the diameter line were investigated. The results showed that the friction factor and Nusselt number increased when the gap was narrower and the bed was longer. Comparing with the case without porous media, the relative maximum friction factor was approximately 320 when \(w\) and \(l\) = 0.001 m and 0.15 m, respectively under the \(Re\) of 10,000. At this size, the relatively maximum \(\frac{Nu}{Nu_0}\) was also obtained. However, when the thermal performance was considered, the optimum size of the bed was found as \(w\) and \(l\) = 0.004 m and 0.15 m, respectively under the \(Re\) of 7,000. Hence, this bed size was recommended for the design of the magnetic refrigeration system. Besides, this research also provided the predictive \(Nu\) formula, having an error within 12%.

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References
[1] Bjørk R, Bahl C R H, Smith A and Pryds N 2010 Int. J. Refrig. 33 437
[2] Qian M, Zhang X, Jia Z, Wan X and Geng L 2018 Mater. Des. 148 115
[3] Guo X, Li K, Shen J, Li Z, Gao X and Dai W 2019 Appl. Therm. Eng. 152 468
[4] Lu X, Xie P, Ingham D B, Ma L and Pourkashanian M 2018 Chem. Eng. Sci. 189 123
[5] Tian L, Kurt E, Kaspar K N and Christian T V 2017 Appl. Therm. Eng. 111 1232
[6] Mahdi R A, Mohammed H A, Munisamy K M, Saeid N H 2019 Renew. Sust. Energ. Rev. 41 715
[7] Wouter de V and Theo H 2017 Appl. Therm. Eng. 111 377
[8] Nielsen K K, Bahl C R H, Smith A, Bjørk R, Pryds N and Hattel J 2009 Int. J. Refrig. 32 1478
[9] Dankov S Y, Tishin A M, Pecharsky V K and Gschneidner K A 1988 Phys. Rev. B 57 3478