Numerical simulation of a magnetic refrigerator with an improved valve-system design

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Introduction

Magnetic refrigeration is becoming a promising alternative to conventional vaper-compression technology. It is based on the magnetocaloric effect (MCE) that when the magnetocaloric material (MCM) is placed in a magnetic field, it heats up, and when removed from the magnetic field, it cools down.

Active magnetic regenerator (AMR) and multiple regenerator beds have been widely applied in current magnetic refrigerators to increase the temperature span and cooling power. But these may cause two problems. One is the dead volume, which means the volume of connecting pipes with bidirectional flow, and the other is the heat leak from the switching of valves. To solve the problems, we have proposed an improved valve system in our next magnetic refrigerator and used COMSOL to verify such a design.

Fig.1 Magnetic refrigerator system and AMRs with valves

Working principle

The system refrigeration cycle consists of 4 processes: magnetization, hot blow, demagnetization, and cold blow. To realize such a cycle, the fluid flow has to be reciprocating, but this can make some dead volume in the connecting pipes. Hence, we add SV or CV at each connecting pipe to make a unidirectional flow. The SVs are all set at the hot end to prevent the eddy-current heat from leaking to the cold HEX. Besides, due to multi-beds design, the SVs are also used to control the flow distribution in different AMRs.

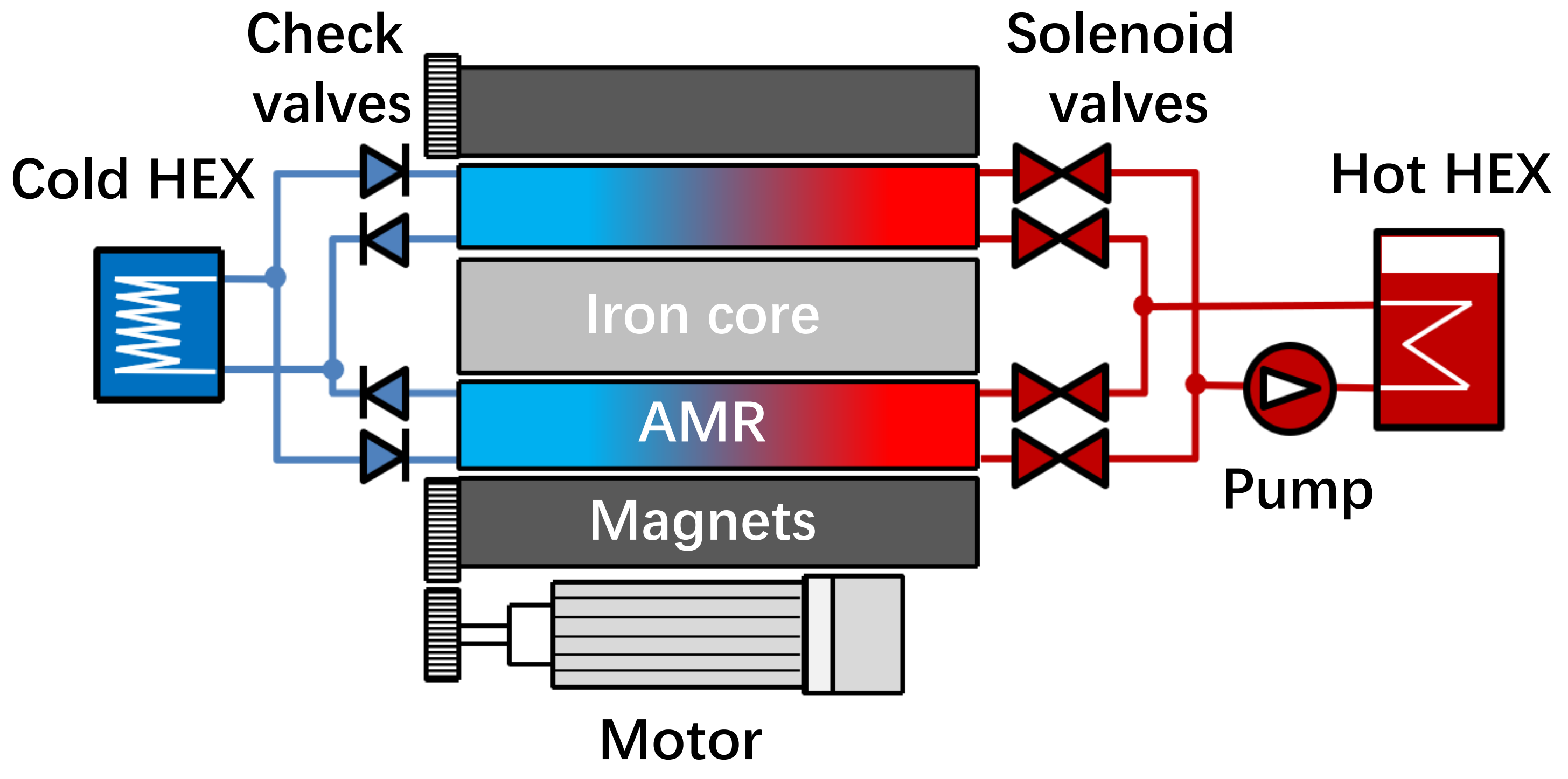


Fig.2 System schematic

Physical model

The laminar, porous media and local thermal non-equilibrium interfaces are used in the simulation. The governing equations are as follows:

$$\nabla \cdot \boldsymbol{u} = 0$$

$$\rho_f \frac{\partial \boldsymbol{u}}{\partial t} + \rho_f (\boldsymbol{u} \cdot \nabla) \frac{\boldsymbol{u}}{\varepsilon} + \varepsilon \nabla p + \mu \nabla^2 \boldsymbol{u} - \varepsilon \kappa^{-1} \mu \boldsymbol{u} = \boldsymbol{0}$$

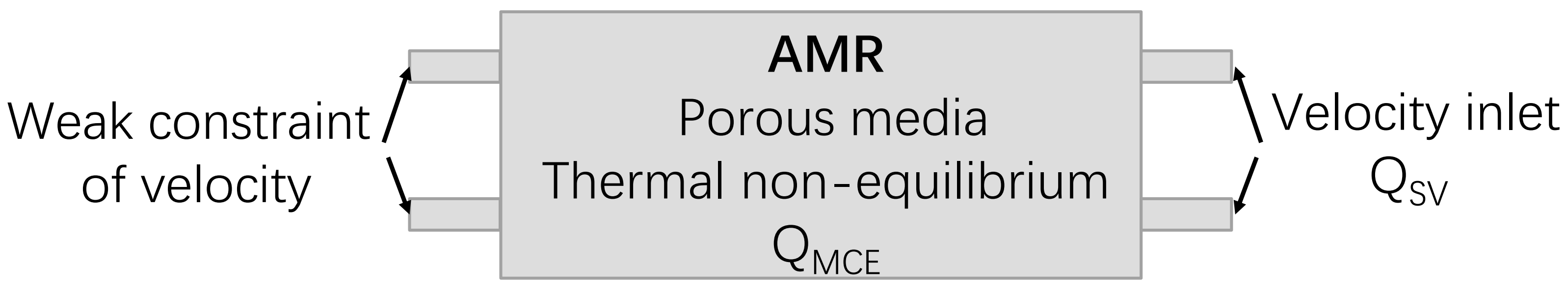
$$\rho_f c_{p,f} \frac{\partial T_f}{\partial t} + \rho_f c_{p,f} \boldsymbol{u} \cdot \nabla T_f = k_f \nabla^2 T_f + \frac{q_{sf}}{\varepsilon} (T_s - T_f) + Q_{\mathrm{SV}}$$

$$\rho_s c_{p,s} \frac{\partial T_s}{\partial t} = k_s \nabla^2 T_s + \frac{q_{sf}}{1-\varepsilon} (T_f - T_s) + Q_{\mathrm{MCE}}$$

$$Q_{\mathrm{MCE}} = \text{-} \rho_s \, T_s \frac{\partial s_m (T_s, \mu_0 H)}{\partial \mu_0 H} \cdot \frac{\partial \mu_0 H}{\partial t}$$

Q_{SV} and Q_{MCE} respectively means the heat generated due to the SV and MCE. A weak constraint is add to specify the velocity to simulate the switching of valves. Three cases are simulated:

Case A: Q_{SV}=0, without valves
Case B: Q_{SV}=0, with valves
Case C: Q_{SV}=3 W, with valves



Weak constraint of velocity

AMR
Porous media
Thermal non-equilibrium
Q_{MCE}

Velocity inlet
Q_{SV}

Fig.3 Interfaces and boundary conditions

Results and conclusion

As shown in fig.4, since there is no valve in Case A, the flow and temperature profiles are more uniform than case B and C. But the absence of valves has also introduced dead volume, which results in a reduction of 56% of the cooling power compared to case B and C. Besides, Case B and C have almost the same cooling power and temperature profile, which illustrates the eddy-current heat of SVs has little influence on the cold end and the AMR can be seen as a thermal buffer.

This study has clearly shown the mechanism of such a refrigerator and proved our improved valve system can effectively avoid the adverse impact of dead volume and eddy-current heat of SVs.

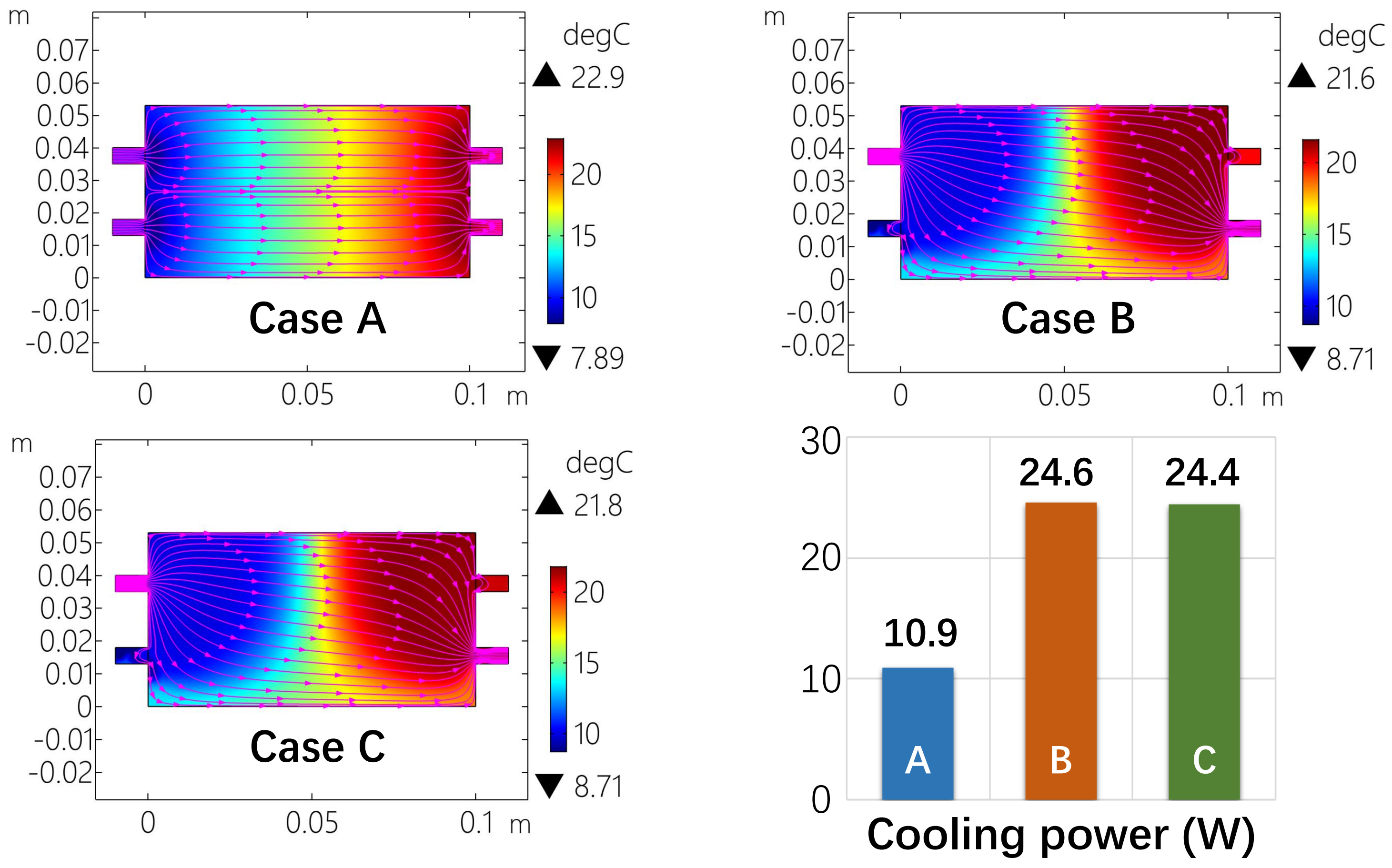


Fig.4 Temperature profile and cooling power

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