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Measurement and numerical simulation on the heat transfer characteristics of reciprocating flow in microchannels for the application in magnetic refrigeration

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HIGHLIGHTS

- Two types of microchannel were proposed.
- The experimental and calculation results were in good agreement with each other.
- There is an optimum ratio of amplitude to flow channel length ($\Delta L/L$).
- Heat transport enhancement could be realized by using staggered mini-plates type.

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ABSTRACT

Experimental and numerical studies were conducted on the heat transfer characteristics of reciprocating flow in different types of microchannels for the application in the active magnetic regenerator (AMR) of magnetic refrigeration systems. Experimental measurements were performed for a flat plate type microchannel fabricated using MEMS technique, and with intermittent heating as the boundary condition. The results of the experiments are in good accordance with those of 2-D numerical simulations conducted using the same conditions as the experiments. Therefore, it is considered that the numerical mode is effective for evaluation of the heat transfer for reciprocating flow. Furthermore, numerical simulations on two types of microchannel (flat plate type and staggered mini-plates type) were conducted with alternative heating and cooling conditions which corresponding to the volumetric temperature rise/drop of solid material as a result of magnetocaloric effect. The influence of various factors on the heat transport of reciprocating flow was analyzed. It was found that enhancement of the heat transport could be realized by utilizing the microchannel of staggered mini-plates type, and there is an optimum ratio of amplitude to flow channel length ($\Delta L/L$) to achieve high efficiency heat transport.

1. Background and introduction

Recent research has revealed that heat transfer enhancement could be realized by utilizing reciprocating flow in pipe or parallel channels, especially for high frequency conditions, because a thinner boundary layer is formed with a higher temperature gradient. Numerical studies [1–5] have been conducted on the heat transfer of reciprocating flow in pipes or in 2-D channels in recent years. Ozawa et al. [1] conducted a numerical simulation on the convective heat transfer induced by fluid oscillation and the characteristics of flow field and heat transfer were studied. For the condition of relative higher frequency (10 Hz), an explicit velocity boundary layer forms near the channel wall, heat transport in the flow direction is mainly through the region near the channel wall, rather than through the bulk liquid region. This indicates that the heat transport is mainly dependent on the thin boundary layer rather than the bulk region for high frequency reciprocating flow. A numerical study on the laminar forced convection of periodically reversing flow in a pipe heated at constant temperature was performed by Zhao and Cheng [2]. They reported that the average heat transfer rate increases with both the kinetic Reynolds number and the dimensionless oscillation amplitude, but decreases with an increase in the length to diameter ratio. Studies on the heat transfer of reciprocating flow in 2-D channels with uniform heat flux and constant temperature boundary conditions were also conducted by a group of researchers [3–5]. Sert and Beskok [3], and

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Nomenclature

Variables

c	heat capacity (J/kg K)
f	frequency (Hz)
h	thickness of MEMS wafer (mm)
L	length of MEMS wafer (mm)
L'	length of staggered mini-plates (mm)
ΔL	amplitude (mm)
p	pressure (Pa)
p_c	set value of pressure (Pa)
ΔP_{loss}	pressure loss (Pa)
Q_c	cold energy transported to the low temperature reservoir (J)
Q_m	enthalpy drop at the beginning of cooled flow half cycle (J)
r	width of microchannel (mm)
S	source term of energy equation
t	time (s)
Δt	time step (s)
T	temperature (K)
ΔT_{rs}	temperature difference between high and low temperature reservoir (K)
ΔT_m	temperature change of solid microchannel material (K)
u	velocity in x direction (m/s)
v	velocity in y direction (m/s)
v_x	velocity of fluid in x direction (mm/s)

Greek

α	thermal diffusivity (m^2/s), Womersley number
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
η	efficiency of heat transport
τ_c	cycle of reciprocating flow (s)

Subscript

l	left side
m	middle
r	right side
H	high temperature side
L	low temperature side
f	fluid
s	solid

Shokouhmand et al. [4] conducted numerical simulations on the heat transfer of reciprocating flows in 2-D channels with uniform heat flux and constant temperature zone on the channel wall. The reciprocating flow Nusselt numbers are comparable to or higher than those for the corresponding unidirectional flow, and at high values of α (Womersley number, which specifies the velocity profile shape), the Richardson annular effect (which results in near-wall velocity overshoots, where the maximum velocity no longer occurs at the symmetry plane) becomes important and heat transfer will be enhanced. The optimum frequency and geometry for maximization of the heat transfer rate was also investigated. Similar calculations were performed by Habibi et al. [5] and the effect of introducing a porous medium on the flow regime of a 2-D channel was investigated. Enhancement of the heat transfer rate could be achieved by introducing a porous material adjacent to the channel wall.

Studies [6–16] on the application of reciprocating flow in some heat transfer devices have also been conducted, especially for the active magnetic regenerator (AMR) of magnetic refrigeration systems. A magnetic refrigeration (Brayton) cycle is comprised of four sequential processes: adiabatic magnetization, heat exchange (heating of fluid), adiabatic demagnetization, and heat exchange (cooling of fluid). In the adiabatic magnetization/demagnetization processes, the temperature of solid material increases/decreases induced by the magnetocaloric effect. The application of reciprocating flow in an AMR is expected to achieve a larger temperature span and higher efficiency (COP: coefficient of performance) of the magnetic refrigeration system by utilizing the combination of processes of thermal storage and regeneration. In these studies, boundary conditions corresponding to the temperature variation of a solid material of a flow channel induced by the magnetocaloric effect should be applied, not uniform heat flux or constant temperature boundary conditions. 1-D numerical simulations [6–12] that have involved parametric investigations on the temperature profiles [6,10,11], temperature spans [6,7,9–11], COP [8,9,11,12], and cooling power [7–10,12] have been performed for reciprocating flow in the AMR of magnetic refrigeration systems. In particular, these studies have focused on the effects of changing a few key parameters, such as the fluid mass flow rate, the operating frequency, and the utilization factor (UF), which represents the ratio of the heat capacity of the fluid to the heat capacity of the magnetocaloric material. In these 1-D simulations, convective heat transfer between the solid surface and fluid was simplified by using empirical correlations. 2-D numerical studies have also been conducted for different types of AMRs, such as spherical particle [13] and parallel plate types [14–17]. A 2-D model of a reciprocating flow AMR with a parallel plate was developed by Petersen et al. [14]. The preliminary results indicate that the model has the ability to evaluate the temperature span and it is necessary to use 2-D methods to investigate the reciprocating flow in parallel channels. Nielsen et al. [15] developed a new 2.5D model including parasitic thermal losses and conducted research on the reciprocating flow in parallel channels. It is concluded that the ideal 2D model can be used to explore the performance of a linear reciprocating parallel-plate based AMR, while the 2.5D model can be used to explore the expected experimental performance in more detail. A comparison of the experimental and numerical results using the 2.5D model was performed by Tura et al. [16]. A 2-D simulation on the performance of a porous media model (spherical particle type) AMR was performed by Li et al. [13] and the cooling capacity was discussed. Experimental study on a Gd-based linear reciprocating AMR was conducted by Trevizoli et al. [17], where the relations of cooling capacity, temperature difference between the sources and UF were observed.

The heat transfer enhancement is essential for improving the performance of the AMR. One of the effective approaches is to utilize the reciprocating flow in microchannel with enhanced heat transfer system. The fundamental knowledge of the heat transfer characteristics of the reciprocating flow in microchannel is essential for the application in AMR. In this study, experimental studies and 2-D numerical simulations were conducted to examine the heat transfer characteristics of reciprocating flow in microchannels. Experiments were performed under intermittent heating conditions on the wall of microchannels. In order to assess the validity of the numerical calculation model, numerical simulations were also conducted with the same conditions as the experiment. Furthermore, in order to simulate the magnetic refrigeration cycle in which both heating and cooling processes exist by the magnetocaloric