Transport characteristics of a transport device composed of two magnetically-driven systems using a temperature-sensitive magnetic fluid**

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Transport properties of a fluid transport device composed of two magnetically-driven systems utilizing a temperature-sensitive magnetic fluid were investigated experimentally. The two driving systems were connected in tandem (in series) or in parallel. Their flow rate in the parallel arrangement is larger than in the tandem arrangement. Not only in the case of a single driving system, but also in the case of the two systems connected in either way, the flow rate of the fluid transport device is maximized when the magnet is placed at an appropriate distance from the heating area. When the two systems are connected in tandem, a flow rate of 1.55 times that of the single driving system can be obtained, while in parallel a flow rate of 1.75 times that of the single driving system can be obtained. Using multiple driving systems for fluid transport is therefore a useful method to enhance flow rate.

Keywords: ferrofluid, magnetically-driven system, temperature-sensitive magnetic fluid, transport device

1. Introduction

Magnetic fluids are colloidal suspensions composed of ferromagnetic particles covered with surfactant and a mother liquid such as water or kerosene.[1] Temperature-sensitive magnetic fluids are sensitive to temperature as well as an applied magnetic field, i.e., their magnetization

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[1] Rosensweig, R.E. *Magnetohydrodynamics*. Cambridge: University Press (1985).

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strongly depends on temperature. The basic principle of the magnetically-driven system was proposed by Resler and Rosensweig.[2] The principle of energy conversion using this magnetically-driven system was also proposed.[3] When a nonuniform magnetic field is applied to a temperature-sensitive magnetic fluid by a permanent magnet, the magnetic body force proportional to the gradient of the magnetic field acts on the fluid. When heat is applied to the fluid at a position displaced from the centre of the arranged permanent magnet, a difference occurs in the balanced positive and negative magnetic body forces acting on the fluid, which produces a driving force and transports the fluid. This magnetically-driven system can be used as a heat transport system, and it is self-driven by applying both a magnetic field and heat, and its size can be reduced by adopting a simple structure.

In order to enhance the transport properties of the driving system, many researches have been undertaken.[4–14] Kamiyama et al. reported a magnetically-driven force enhancement method by mixing gas bubbles with the temperature-sensitive magnetic fluid in order to increase the difference of the magnetic forces.[4,5] They visualized the behaviour of the bubbles in the fluid and showed that the driving magnetic force is indeed enhanced. Shuchi et al. proposed a method utilizing a binary temperature-sensitive magnetic fluid in which a low boiling-point organic liquid is mixed with the temperature-sensitive magnetic fluid.[6–8] Iwamoto et al. examined the magnetic driving force and the heat transfer resulting from this method using n-hexane as the low boiling-point liquid.[9–12] Fumoto et al. confirmed that a magnetically-driven system using a temperature-sensitive magnetic fluid transfers heat stably.[13,14] Aursand et al.

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proposed a one-dimensional multiphase flow model[15] and demonstrated good performance predictions. In their own previous research, the present authors have shown that using such a system the fluid is self-driven by applying a nonuniform magnetic field and heat; the authors achieved heat transfer of 6000 mm.[16]

To enhance the transport properties, it is conceivable to use multiple magnetically-driven systems connected in tandem or in parallel. However, there has been no trial to investigate the fluid transport characteristics of such multiple magnetically-driven systems as far as the authors are aware. In this study, the fluid transport characteristics of a transport device composed of two magnetically-driven systems using a temperature-sensitive magnetic fluid are investigated experimentally. The flow rate is measured when the systems are arranged in tandem or in parallel.

2. Basic principle and experiments

When a nonuniform magnetic field is applied to a temperature-sensitive magnetic fluid, the magnetic body force $\boldsymbol{F}^m$ acting on the fluid is given by:[1]

$$\boldsymbol{F}^m = \mu_0 \boldsymbol{M} \cdot \nabla \boldsymbol{H}, \quad (1)$$

where μ_0 is the magnetic permeability in vacuum, $\boldsymbol{M}$ is the magnetization and $\boldsymbol{H}$ is the intensity of magnetic field. Under a relatively weak applied magnetic field, the magnetization can be considered to be parallel to the applied magnetic field and given by

$$\boldsymbol{M} = \chi_T \boldsymbol{K}_{\boldsymbol{H}} \boldsymbol{H}, \quad (2)$$

where χ_T is the magnetic susceptibility and $\boldsymbol{K}_{\boldsymbol{H}}$ is the thermomagnetic constant. The one-dimensional magnetic driving pressure Δp in the flow direction is given by integrating the above magnetic body force within the range of the magnetic field, that is,

$$\Delta p = \int \boldsymbol{F}^m \cdot \mathrm{d}x = \mu_0 \int (\boldsymbol{M} \cdot \nabla \boldsymbol{H}) \cdot \mathrm{d}x, \quad (3)$$

where x is the position vector and the integration is performed along the flow direction. Using the Darcy–Weisbach equation, the flow rate Q can be estimated as [16]:

$$Q = \frac{\pi a^3}{128 \eta l} \Delta p, \quad (4)$$

where a is the diameter of the pipe, l its length and η the viscosity of the magnetic fluid.

Fig. 1 shows the basic structure of our magnetically-driven system; Fig. 2 shows the distribution of the axial component of the magnetic field intensity along the centre line of the pipe; the position $x = 0$ corresponds to the centre of the magnet. When the fluid is not heated, the magnetic body force expressed by eqn (1) acts on the fluid in a balanced fashion and the fluid does not move. However, when the fluid is heated in the zone shifted from the centre of the magnets, the magnetic body force acting from the left-hand to the right-hand side becomes

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greater than the magnetic body force acting from the heated zone to the centre of the magnets. Then the magnetic body force acts on the fluid and the fluid is transported from the left-hand to the right-hand side.

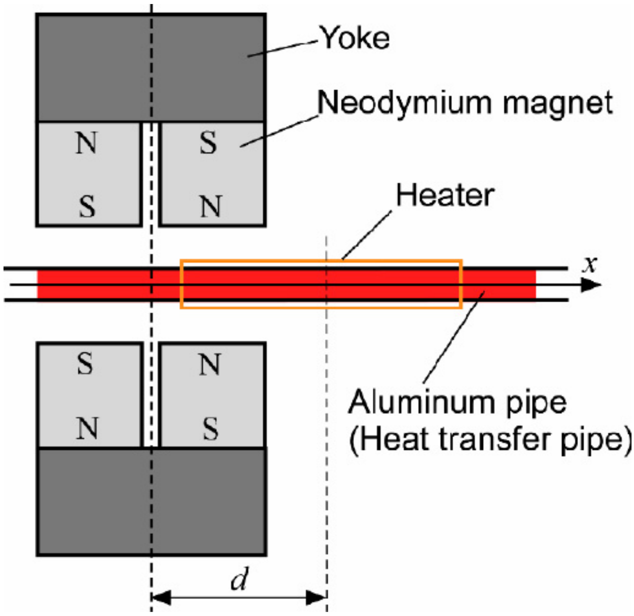

Figure 1. Magnetically-driven system using a temperature-sensitive magnetic fluid. Cross-section of a single system composed of magnets, heater and heat transfer pipe.

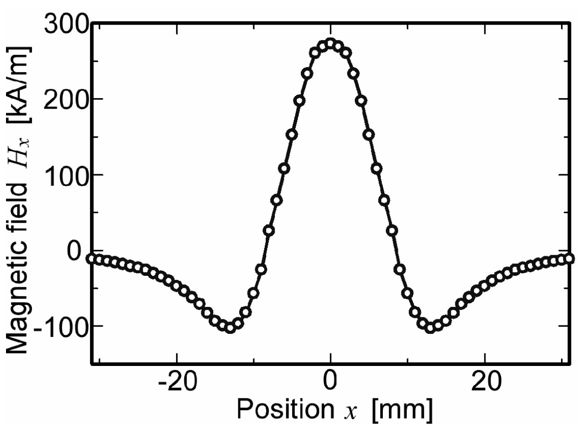

Figure 2. Distribution of axial direction component of the magnetic field intensity along the centre line of the pipe.

In our experiments, the magnet was composed of two neodymium permanent magnets and yoke. The dimension of each magnet was 22 mm (width) × 20 mm (depth) × 20 mm (height). A circular pipe with inner diameter 2.0 mm and outer diameter 3.0 mm was arranged in the centre between the two magnets. Part of the pipe was replaced by a heating transfer pipe made of aluminum (length 50 mm), in the centre of which a 30 mm wide and 30 mm long polyimide heater was wound. Let *d* be the distance between the centre of the heater and the centre of the magnets as shown in Fig. 1.

In this study, fluid transportation properties of twin magnetically driven systems were investigated experimentally. Fig. 3 shows the arrangements of the two systems. In our experiments, we combined them in three ways; as a single system, as twin systems in tandem and as twin systems in parallel. When the two systems were connected in parallel, Y- and T-shaped joints were prepared for the connexions, but there was almost no difference in the experimental results between them. Therefore, the Y-shaped joints were used for the parallel arrangement. As the fluid transport property, flow rate was measured using the flow meter, and effects of heat flux density q to the heater and the relative position of the magnets with respect to the heating area, i.e., distance d, were examined. d was 15, 20, 25 or 30 mm, and the heat flux density was the combination of 5.0 kW/m^2 and 3.0 kW/m^2.

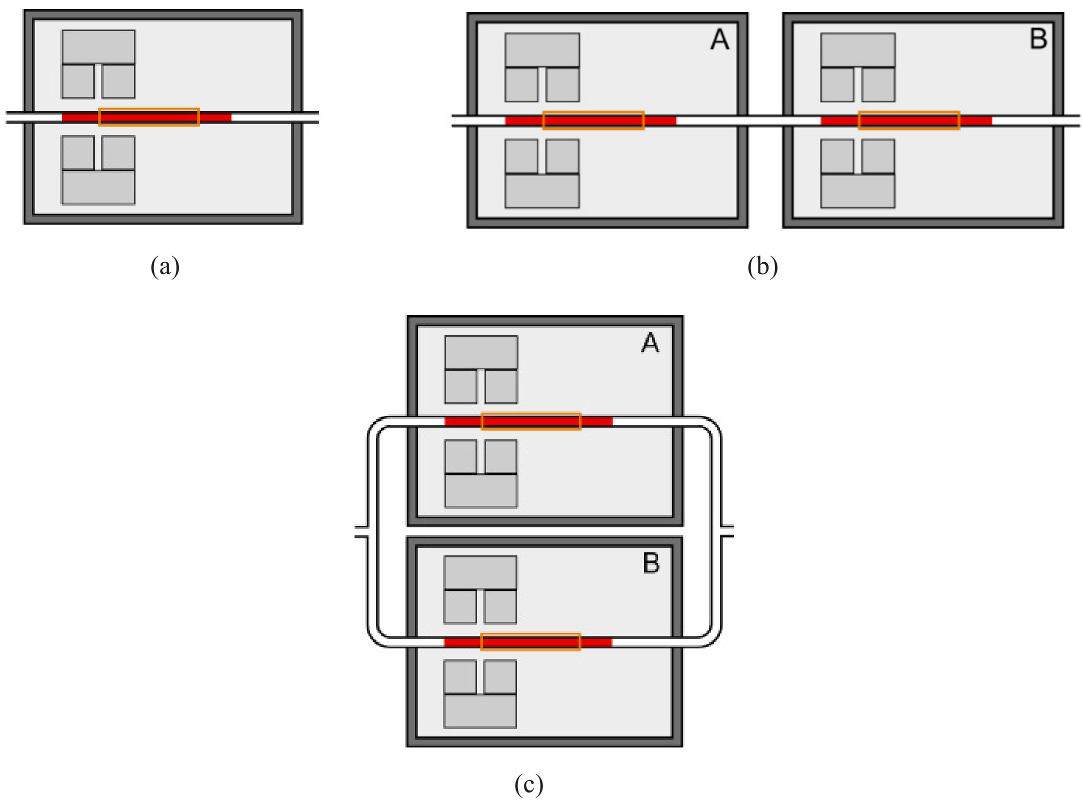

Figure 3. Arrangements of magnetically-driven systems. (a) Single system, (b) twin systems A and B in tandem arrangement and (c) twin systems A and B in parallel arrangement.

The experimental apparatus for investigating the transport properties mainly consisted of a fluid driving part, a fluid cooling part, and a flow-rate measuring part (Fig. 4). The test fluid was temperature-sensitive magnetic fluid TS-50K (Ichinen Chemical Co. Ltd), whose magnetization strongly depends on temperature within the normal range. It had a kerosene base in which were dispersed manganese zinc ferrite particles of average diameter 9.7 nm. The density of the test fluid was 1.37×10^3 kg/m^3, the viscosity 1.23×10^{-2} Pa s, and the saturated magnetization 41.1 mT. The heat transfer pipe was connected to a Teflon pipe of diameter 1.54 mm and total length 1730 mm. The maximum strength of the applied magnetic field was 273 kA/m. When there were two driving systems, d of one of them was fixed at 25 mm and the heat flux was 5.0 kW/m^2.

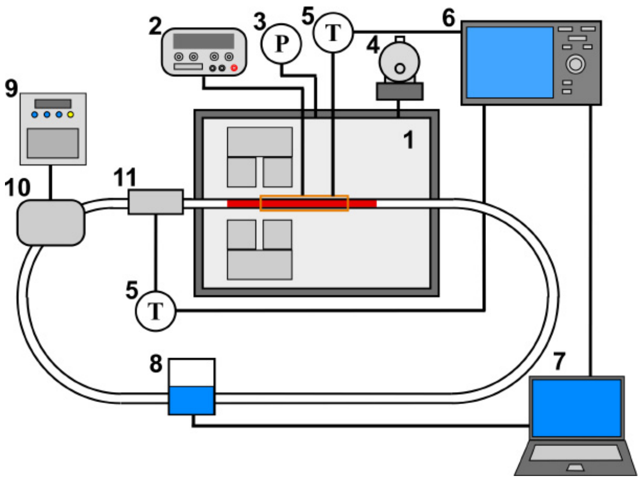

Figure 4. Schematic diagram of the experimental apparatus for a single system 1. 2, DC power supply; 3, pressure gauge; 4, vacuum pump; 5, thermocouple; 6, temperature recorder; 7, computer; 8, flow meter; 9, low temperature thermostatic tank; 10, cooling unit; 11, joint.

3. Results and discussion

3.1 Single system

First of all, the basic characteristics of the single magnetically-driven system were investigated. Fig. 5 shows the time history of the flow rate just after the fluid began to be heated. Fig. 6 shows the time history of the flow rate in the steady state and the effect of the heat flux intensity applied to the fluid by the heater. As can be seen in Fig. 5, the flow rate increases just after heat is applied to the fluid and about 150 s after fluid heating starts, the flow rate becomes steady. When the magnets are arranged at $d = 25$ mm and the heat flux q to the heater is 5.0 kW/m^2, the average flow rate is 264 ± 10 µL/min, while the flow rate is 161 ± 8 µL/min in case of $q = 3.0$ kW/m^2. Fig. 7 shows the effects of distance d on the flow rate; there is a distance at which the flow rate peaks. In our experiments, the flow rate was maximized at $d = 25$ mm. The peak value depends on the difference between the positive and negative magnetic body forces expressed by eqn (1), i.e. determined by the magnetization and the gradient of the magnetic field. The magnetization becomes small near the centre of the heating area due to the high temperature.

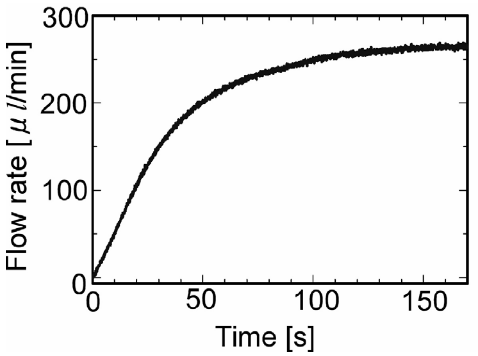

Figure 5. Time history of the flow rate of the single system immediately after the inition of heating. The distance *d* is 25 mm and the heat flux *q* is 5.0 kW/m^2.

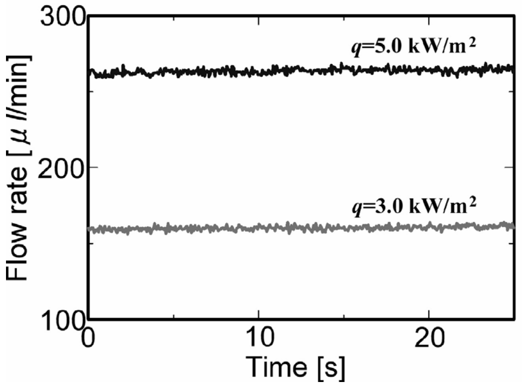

Figure 6. Time history of the flow rate produced by the single magnetically-driven system after transport becomes steady. The distance *d* is 25 mm.

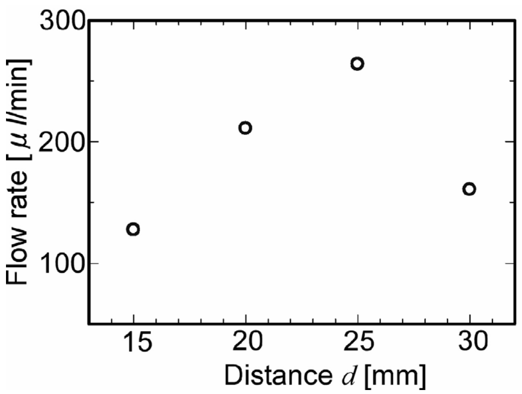

Figure 7. Flow rate produced by the single magnetically-driven system. Effect of the magnetic field producing by changing the distance between the central positions of the magnets and heating area.

3.2 Effect of heat flux on the flow rate

The flow rates produced by the fluid transport device composed of magnetically-driven systems are shown in Table 1. The distance between the centres of the heater and of the magnets is fixed at $d = 25$ mm. In the parallel arrangement, the flow meter was installed on the upstream side of each driving system. Table 1 shows the flow rate of each driving system and the total flow rate of the parallel systems. Comparing the flow rates for the conditions $d = 25$ mm and heat flux $q = 5.0$ kW/m^2, the tandem arrangement yields a flow rate of 1.55 times that of the single driving system, and the parallel arrangement yields a flow rate of 1.75 times that of the single driving system. Figure 8 shows the time history of the flow rate in the steady state when the driving systems are arranged in tandem, demonstrating the influence of the combination of heat fluxes given to the two driving systems. There is almost no difference in the flow rates when the combination of the heat fluxes applied to the upstream and downstream driving systems is either 5.0 and 3.0 kW/m^2 or 3.0 and 5.0 kW/m^2. In tandem, the flow rate is not simply twice the flow rate of the single driving system, because the temperature of the fluid rises due to the heat input at the upstream driving system, and the driving power in the downstream driving system decreases. On the other hand, when the driving systems are arranged in parallel, the flow rate of the fluid transport device is about 25 % lower than double the flow rate of the single driving system.

Table 1. Effects of heat flux on flow rate for $d = 25$ mm.

System	Heat flux/kW m^{-2}		Flow rate/μL min^{-1}
	A	B	
Single	5.0	---	264 ± 10
	3.0	---	161 ± 8
Tandem	5.0	5.0	409 ± 14
	5.0	3.0	317 ± 12
	3.0	5.0	320 ± 12
Parallel	Total		462 ± 15
	5.0	---	232 ± 8
	---	5.0	245 ± 10
	Total		437 ± 14
	5.0	---	238 ± 9
	---	3.0	211 ± 8
	Total		438 ± 14
	3.0	---	180 ± 7
	---	5.0	269 ± 10

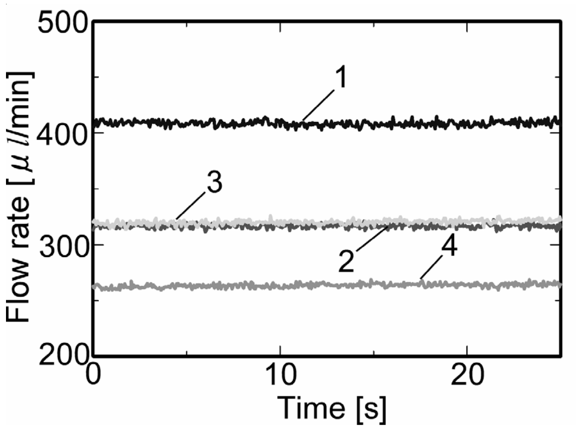

Figure 8. Flow rate produced by two magnetically-driven systems in tandem arrangement. The heat flux imposed to each system is: (curve 1) A and B, 5.0 kW/m^2; (curve 2) A, 3.0 kW/m^2 and B, 5.0 kW/m^2; (curve 3) A, 5.0 kW/m^2 and B, 3.0 kW/m^2; (curve 4) single system, 5.0 kW/m^2.

3.3 Effect of distance *d* on the flow rate

Figure 9 shows the flow rate of the twin driving systems in tandem arrangement when the distance *d* of one driving system is changed (panel (a) when the distance on the downstream side is changed and panel (b) when the distance on the upstream side is changed). It can be seen that the flow rates are approximately the same if the combination of the heat fluxes given to the upstream and downstream driving systems is the same.

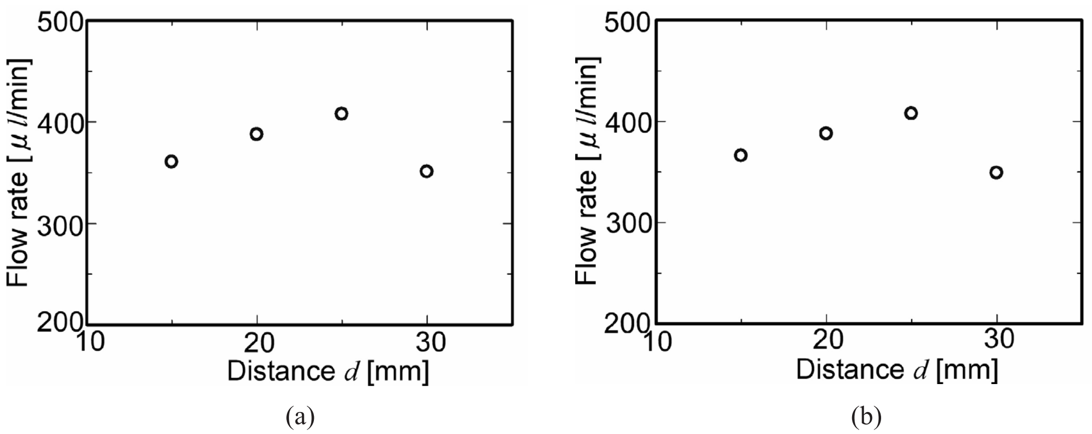

Figure 9. Flow rate produced by two magnetically-driven systems in tandem arrangement (Fig. 3). Effects of the magnetic field by changing the distance *d* between centres of the magnets and heating area. (a) system A; (b) system B. Heat flux $q = 5.0$ kW/m^2 and for the system not being varied, $d = 25$ mm.

Figure 10 shows the flow rate of the fluid transport device composed of twin driving systems in the parallel arrangement. Flow rate is maximal when the distance *d* of both driving systems is 25 mm. When the driving systems are connected in parallel, even if the conditions of the driving system A are constant, the flow rate of A changes if the conditions of the other driving system B change. With the parallel connexion, energy loss is generated at the junctions of the two flow paths, hence it is considered that the flow rate is smaller than twice that of the single driving system.

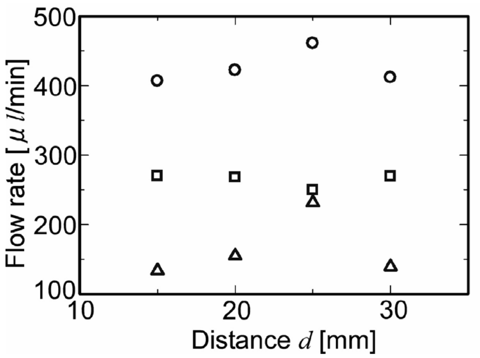

Figure 10. Effects of the distance *d* of the system B on the flow rate in parallel arrangement (Fig. 3). System A: *d* = 25 mm and the heat fluxes applied to the both systems are 5.0 kW/m^2. Open circles: total flow rate; open squares: flow rate of driving system A; open triangles: flow rate of driving system B.

Fig. 11 compares flow rates of the single driving system and two driving systems in tandem and in parallel. Two systems have a fluid transport capacity surpassing that of the single driving system, regardless of whether connected in tandem or in parallel; flow rate of the latter is larger than that of the former, because the temperature difference of the fluid due to the input heat can be generated more effectively in parallel.

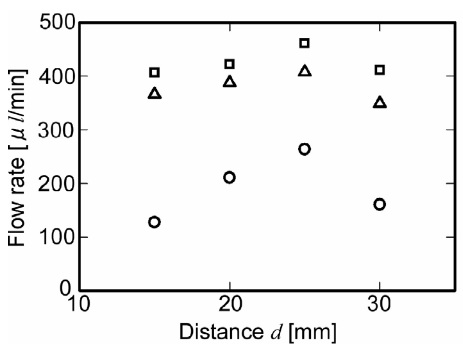

Figure 11. Flow rate of fluid transport devices composed of one (open circles) or two (open triangles, in tandem; open squares, in parallel) driving systems. With two systems, system A's *d* is fixed at 25 mm. Heat flux applied to the heater is 5.0 kW/m^2.

It is difficult to define the efficiency of the system because both fluid and heat are transported simultaneously. Basically, we anticipate constructing a cooling system for a CPU that transports heat from the high temperature region to the cooler part without an extra pump. Using this system, the flow is automatically produced and the heat is transported when it is applied to a temperature-sensitive magnetic fluid in the driven system.

Unfortunately, we do not yet have a proper theory to estimate the flow rates. Eqn (4) cannot be used, because it is obtained assuming a one-dimensional model of a straight pipe, and the temperature distribution in the driving system cannot be measured.

4. Concluding remarks

It has been found that the amount of fluid transportation is increased when two driving systems are provided compared with only one. In the case of using two, the flow rate is larger if they are connected in parallel than in tandem; the flow rate is 1.55 times that of the single driving system for the latter, and 1.75 times that of the single driving system for the former. Thus, the fluid transport device composed of multiple driving systems in parallel is useful for enhancing flow rate.