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Numerical study of novel regenerator design for solid-state caloric cycles

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ABSTRACT

A numerical study was investigated to apply a bare-rod type of regenerator to solid-state caloric cycles. The bare-rod type of regenerator has many advantages over various microchannel types of the regenerator, which are general regenerator designs commonly used for the solid-state caloric cycles. Firstly, the bare-rod type of regenerator interferes with the flow, thereby leading to an increase in the convective heat transfer. Secondly, the heat transfer area of the regenerator with the same porosity is increased compared to the microchannel type. Thirdly, the high thermal conductivity of caloric materials generally improves the convective heat transfer while reducing the temperature gradient of the regenerator due to an increase in the heat conduction in the caloric material. However, the bare-rod regenerator reduces the conduction loss and increases the temperature gradient in the regenerator since the caloric material of the regenerator is separated along the longitudinal direction. Finally, a regenerator with a small hydraulic diameter can be easily produced because the newly proposed novel design for a caloric cycle is in the form of a simple rod rather than a tube.

In this study, the circular and elliptical types of the bare-rod regenerator were compared with the plate type design known to have the highest heat transfer performance among microchannel types of the regenerator. Using 2D CFD simulation, the correlations for Nusselt number and friction factor of the bare type of regenerator were obtained. When the Reynolds number is between 20 and 80, the circular and elliptical designs increase the Nusselt number by about 75 - 90% and 25 - 50%, and the friction factor by about 230 to 285%, and 55-105% compared to the plate type, respectively. As a result of applying these Nu and friction factor correlations to the system model, the circular type increased the COP by 9.1% and the elliptical type by 10.6%. These positive results are mostly achieved due to substantially higher heat transfer coefficients of the bare-rod type regenerator.

1. INTRODUCTION

Due to the recent development of manufacturing technologies, such as 3D metal printing, researchers are researching and developing a novel heat exchanger in diverse fields (Lee *et al.* (2012), Rajagobal *et al.* (2019), & Han *et al.* (2019)). The solid-state caloric cooling cycle mostly uses a packed bed of spherical particles and a microchannel type of regenerator.

This study aims to develop a novel regenerator using the bare-rod type of heat exchanger that can increase the efficiency of the solid-state caloric cycle compared to the conventional regenerator design. As an advantage of the new regenerator design, it is easy to manufacture a regenerator with a small hydraulic diameter since a simple rod is used. In addition, since caloric materials are separated from each other in the longitudinal direction, conduction loss of solid material can be reduced in the regenerator. These rods interfere with the fluid flow and develop turbulent flow, increasing the heat transfer coefficient. Finally, the heat transfer area can be increased when using an elliptical rod of the regenerator with the same porosity.

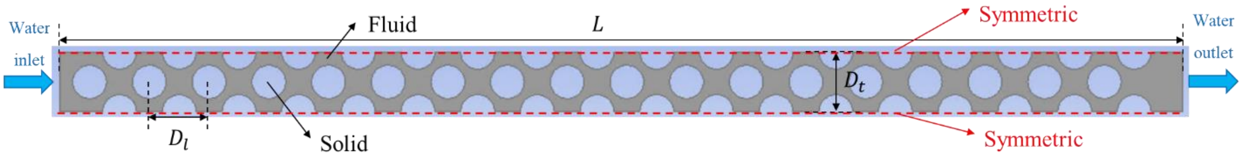
2. NUMERICAL SIMULATION

This study compared the performance of circular bare-rod type and elliptical bare-rod type regenerators with the plate type regenerator. Numerical simulation for the novel regenerator designs was performed. Ansys Fluent was used to calculate the heat transfer rate and pressure drop of the bare-rod type of regenerator. From the CFD results, the Nu number and friction factor of each regenerator were compared, and Nu and friction factor correlations in terms of the Re were obtained. These correlations were applied to the model for the solid-state caloric cycle, and the effect of the new regenerator on cycle performance was examined.

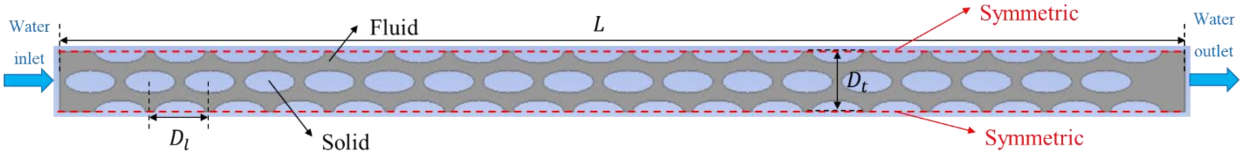
2.1 CFD Model

Figure 1 shows the geometry of (a) the circular bare-rod type of the regenerator and (b) the elliptical bare-rod type of the regenerator. The bare-rod regenerators have a staggered arrangement. Transverse pitch (D_t) and longitudinal pitch (D_l) of the rods are the same as 0.53 mm, and the porosity is 0.5. The elliptical regenerator uses an aspect ratio of 2. The heat transfer fluid enters from the left, exchanges heat with the solid material, and exits to the right. The total length of the regenerator is 10 mm. Solid wall temperature is 350 K and fluid inlet temperature is 300 K. Fluid inlet velocity changed from 0.1 to 0.6 m/s. Geometric and operating conditions are shown in Table 1.

The two-equation realizable k-epsilon model with an enhanced wall treatment was used. Water was used as the heat transfer fluid, and steel was used as the solid material. The top and bottom of the model were set as symmetric conditions.



(a)



(b)

Figure 1: Geometry of (a) circular bare-rod type and (b) elliptical bare-rod type of regenerator.

Table 1: Geometric and operating conditions of CFD

Condition	**Value**
Transverse pitch, D_t (mm)	0.53
Longitudinal pitch, D_l (mm)	0.53
Regenerator Length, L (mm)	10
Solid wall temperature (K)	350
Fluid inlet temperature (K)	300
Fluid inlet velocity (m/s)	0.1 – 0.6

Table 2: Geometric and operating conditions of caloric cycle model

Condition	Value
Regenerator Length, L (mm)	200
Porosity (-)	0.5
Cycle frequency (Hz)	0.38 – 0.45
Mass flux (kg/s-m^2)	95 - 100

2.2 Caloric Cycle Simulation

The effect of the new regenerator on the solid-state caloric cycle was simulated. In this study, the 1D time-dependent model was used, and there is a detailed description of the model in Kang and Stefan (2018). Table 2 shows the geometric and operating conditions for the model. Length of the regenerator is 200 mm, porosity 0.5, cycle frequency 0.38 - 0.45 Hz, and mass flux 95 - 100 kg/s-m^2.

3. MESH INDEPENDENCE

The mesh independence was checked by changing the number of mesh elements. Figure 2 shows the mesh of the elliptical type of the regenerator with about 110,000 mesh elements. 5 inflation mesh layers were applied to the space near the solid wall to increase the accuracy of the calculation of the fluid flow and heat transfer near the wall. Figure 3 represents the outlet temperature and pressure drop depending on the number of mesh elements. As the number of mesh elements increases, the outlet temperature decreases, and the pressure drop increases. The results rapidly change until the number of mesh elements reaches about 50,000 meshes. The output temperature and pressure drop hardly change after the number of mesh elements exceeds 100,000. Therefore, about 110,000 mesh elements were used in this study.

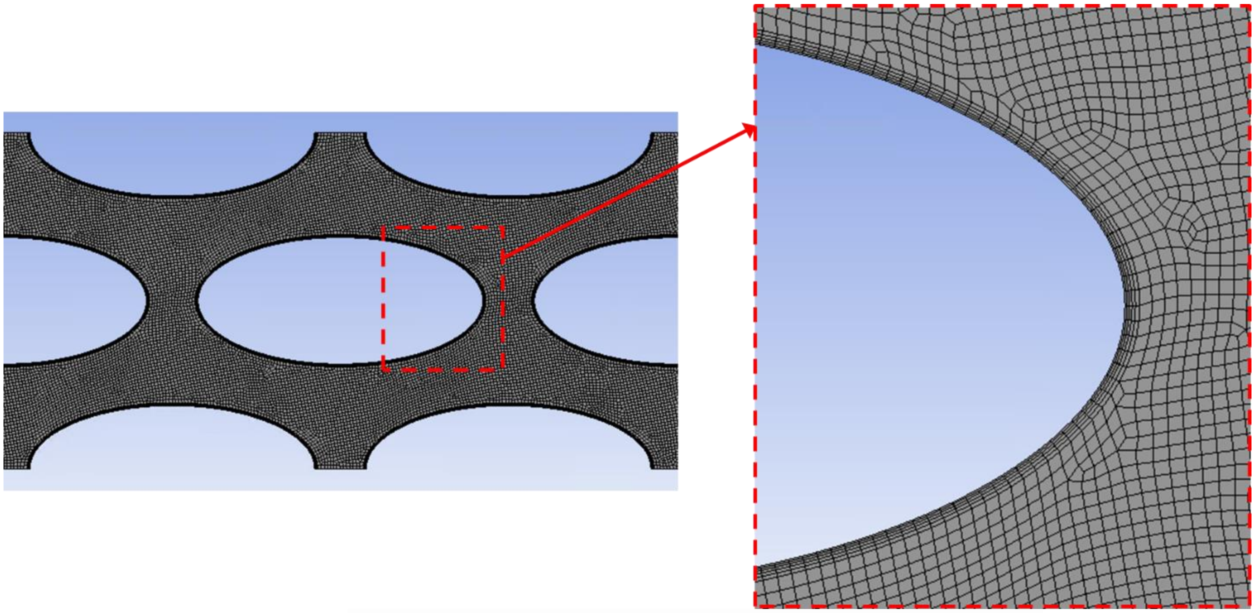


Figure 2: Mesh for elliptical regenerator (about 110,000 mesh elements case)

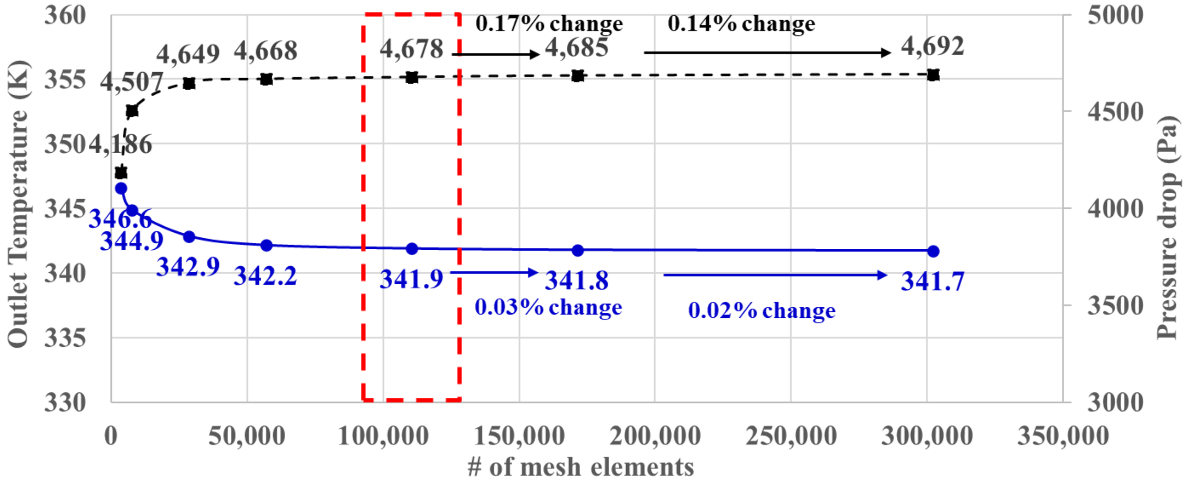
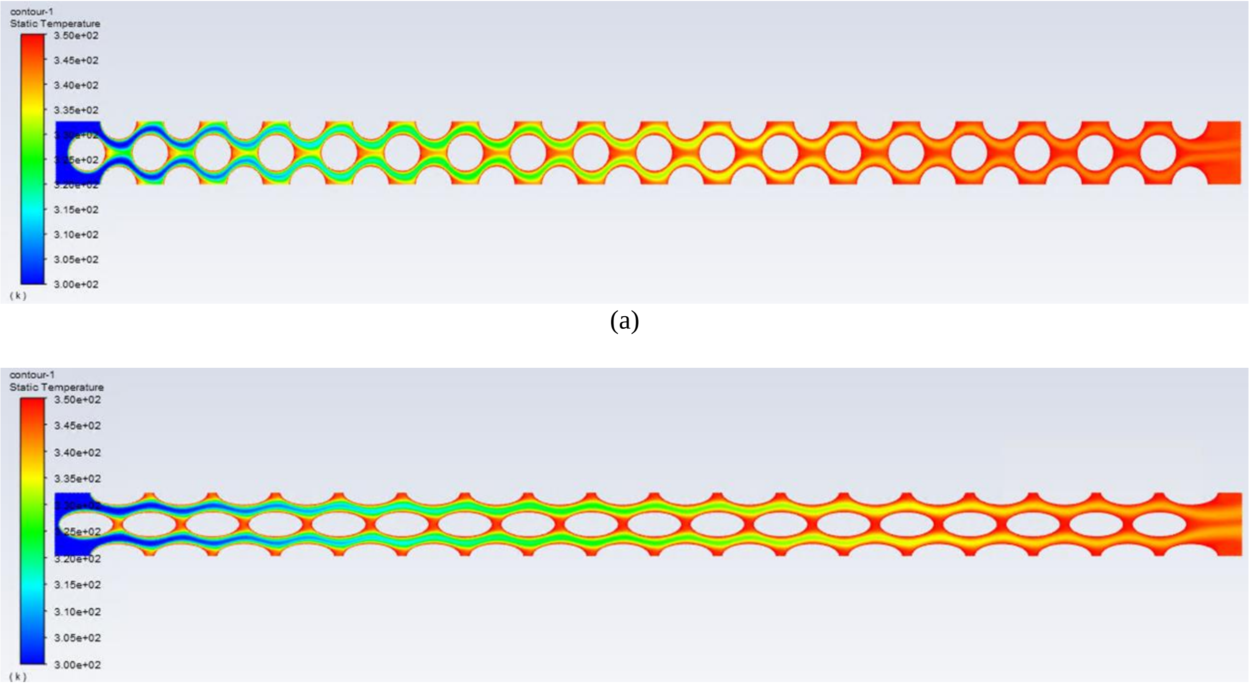


Figure 3: Outlet temperature and pressure drop depending on the number of mesh elements

4. RESULTS AND DISCUSSION

4.1 CFD Results

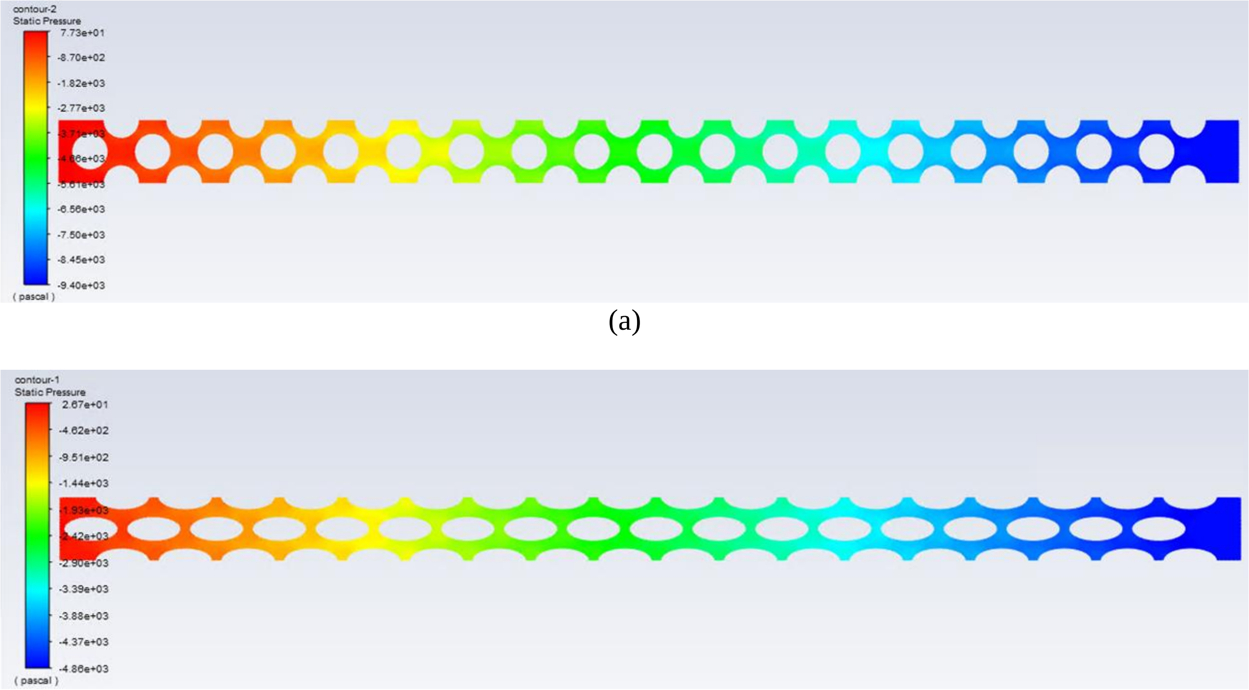
Figure 4 shows the temperature profile of (a) circular bare-rod type and (b) elliptical bare-rod type when the fluid inlet velocity is 0.2 m/s. The average outlet temperature of the circular type is about 344.8 K, which is higher than 341.9K for the elliptical type. Therefore, higher heat transfer is performed in the circular type. Figure 5 shows the pressure profile of (a) circular bare-rod type and (b) elliptical bare-rod type when the fluid inlet velocity is 0.2 m/s. The pressure drop of the circular type is 9,210 Pa, which is about twice as high as 4678 Pa of the elliptical type. The phenomenon is because a relatively narrow flow path is formed and the flow is more interfered with in the circular type of the regenerator as shown in figure 6, the velocity profile of (a) circular bare-rod type and (b) elliptical bare-rod type when the fluid inlet velocity is 0.2 m/s.



(a)

(b)

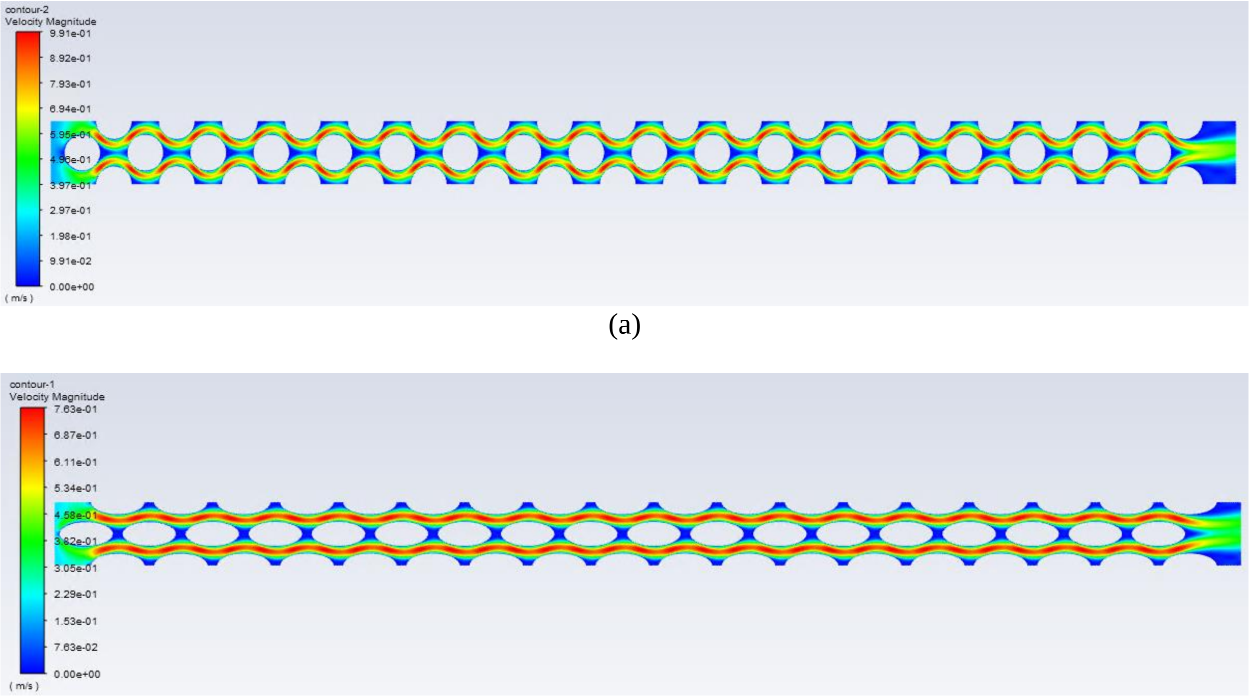
Figure 4: Temperature profile of (a) circular bare-rod type and (b) elliptical bare-rod type using fluid inlet velocity is 0.2 m/s



(a)

(b)

Figure 5: Pressure profile of (a) circular bare-rod type and (b) elliptical bare-rod type using fluid inlet velocity is 0.2 m/s



(a)

(b)

Figure 6: Velocity profile of (a) circular bare-rod type and (b) elliptical bare-rod type using fluid inlet velocity is 0.2 m/s

Table 3: Averaged outlet temperature of fluid and pressure drop inside regenerator for different inlet velocities

	Inlet velocity (m/s)	Outlet Temperature (K)	Pressure drop (Pa)
Circular	0.1	349.3	3960
	0.2	344.8	9210
	0.4	343.5	25755
	0.6	341.6	51298
Elliptical	0.1	348.5	2209
	0.2	341.9	4678
	0.4	331.5	10289
	0.6	329.6	17243

Table 3 represents the averaged outlet temperature of fluid and pressure drop inside the regenerator for the different fluid inlet velocities. In both types of regenerators, as the inlet velocity increases, the fluid outlet temperature decreases, and the pressure drop increases. The circular type always shows a higher averaged outlet temperature and pressure drop compared to the elliptical type when using the same velocity.

4.2 Data Reduction

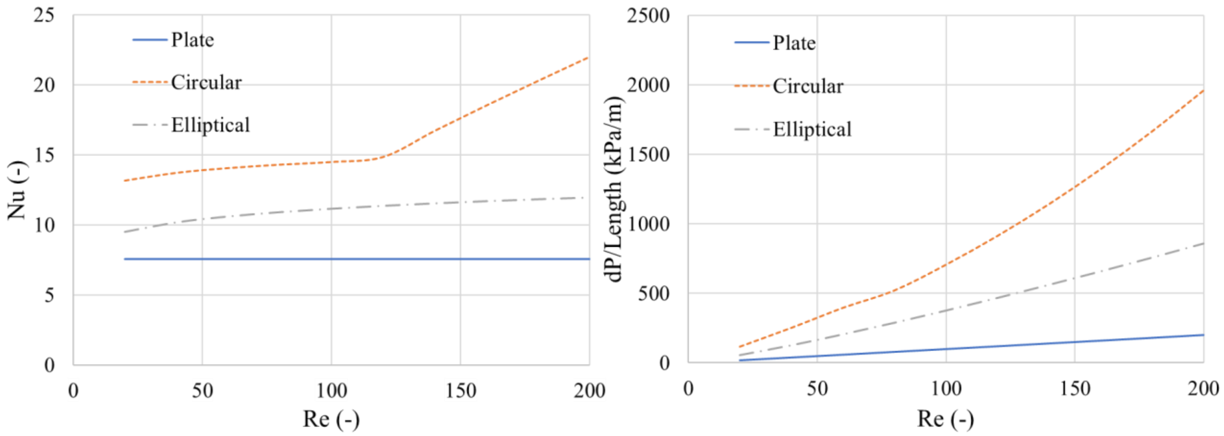
Using the results of Table 3, Figure 7 shows the Nu number and pressure drop per length as a function of the Re for circular and elliptical bare-rod regenerators and plate type of regenerator. In the cases of the bare-rod type, as Re increases, Nu and pressure drop per length tend to increase. In the case of the plate regenerator, Nu is constant and pressure drop per length tends to increase. In both Nu and pressure drop per length, the circular type is the highest, the elliptical type is the second highest and the plate regenerator is the lowest. For the circular type, as Re exceeds 120, the fluid flow changes to transition, and Nu and pressure drop tend to increase more rapidly.

The Re of the regenerator in the solid-state caloric cycle is usually less than 80. In this range of Re, circular and elliptical regenerators increase Nu by 75 - 90% and 25 - 45%, respectively. Also, circular and elliptical regenerators increase the Darcy friction factor by 230 - 285% and 55 - 105%, respectively. Figure 8 shows the Colburn j-factor and Darcy friction factor as a function of Re using Equations (1) and (2). In all three types of regenerators, the Colburn j-factor and Darcy friction factor decrease, as Re increases.

The Colburn j-factor of the circular type has about twice the j-factor of the plate type, and the Colburn j-factor of the elliptical type has about 1.5 times the j-factor of the plate type, which is similar to Nu. In the case of the Darcy friction factor, the circular type has about 3.5 to 4 times the plate type, and the elliptical type has about 2 times the plate type. Table 4 shows the correlation of Nu and friction factor as a function of Re for different regenerator designs.

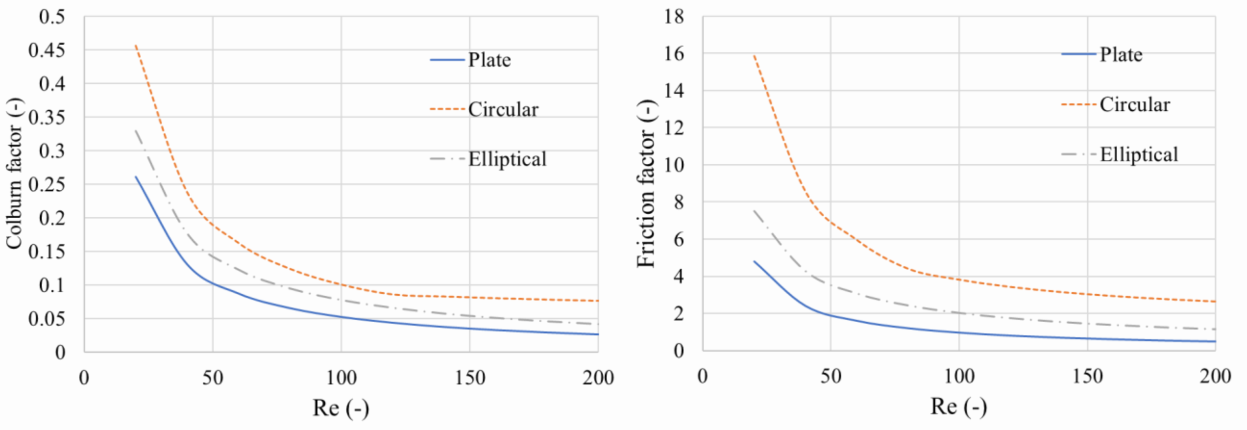
$$j = \frac{Nu}{Re\, Pr^{1/3}} \tag{1}$$

$$f = \frac{\Delta P}{L}\frac{2D_h}{\rho \bar{v}^2} \tag{2}$$



(a) (b)

Figure 7: (a) Nu and (b) pressure drop per length as a function of the Re number for different types of regenerators



(a) (b)

Figure 8: (a) Colburn j-factor and (b) Darcy friction factor as a function of the Re number for different types of regenerators

Table 4: Nu and friction factor correlations for different types of regenerators

	Nusselt correlation	Friction factor
Plate	$Nu = 7.45$	$f_D = \frac{96}{Re}$
Circular	Re < 120: $Nu = 11.0Re^{0.06}$ Re > 120: $Nu = 0.24Re^{0.77}Pr^{0.4}$	Re < 120: $f_D = \frac{228.2}{Re^{0.89}}$ Re > 120: $f_D = 1.48 + \frac{235}{Re}$
Elliptical	$Nu = 7.04Re^{0.1}$	$f_D = \frac{85}{Re^{0.81}}$

Table 5: COP, Nu, pumping power of different regenerator systems

	Plate (base)	Circular	%	Elliptical	%
COP (-)	2.25	2.45	9.1	2.48	10.6
Nu (-)	7.60	13.35	75.7	9.76	28.4
Wpump (W)	0.39	0.83	114.1	0.57	46.0

4.3 Comparison of Performance of Caloric Cycle

The Nu and friction factor correlations for circular and elliptical bare-rod regenerators in Table 4 were applied to the solid-state caloric cycle model to compare their performance with the performance of the plate regenerator system. A 1kg regenerator and the conditions generating a cooling capacity of 100 W were used.

As shown in Table 5, the COPs are 2.25 for the plate regenerator system, 2.45 for the circular regenerator, and 2.48 for the elliptical regenerator. Therefore, the circular type of the regenerator improves the COP by about 9.1 % and the elliptical type of the regenerator by about 10.6 % compared to the plate type of the regenerator. The increase in COP in bare-rod type regenerator is caused by the increase in Nu and heat transfer area and the decrease in the conduction loss. The circular type and elliptical type increase Nu by about 75.7 % and 28.4 % compared to the plate type, respectively. In addition, the elliptical type increases the heat transfer area by about 10 %. The circular regenerator has the highest Nu, but its much larger friction factor significantly increases pumping work, resulting in a relatively smaller COP compared to the elliptical regenerator.

5. CONCLUSIONS

This study developed a novel regenerator design for a solid-state caloric cooling cycle. The circular and elliptical bare-rod type regenerators were applied to caloric cycles, and their effect on the caloric cycle was investigated. 2D CFD simulation was performed, and the heat transfer performance of the bare-rod type of the regenerator was compared with the plate type of regenerator. Based on the CFD results, Nu and friction factor correlations for bare-rod types were obtained and COP was calculated by applying these correlations to the caloric cycle model. Bare-rod type regenerator can bring many advantages to the caloric cycle. First, it interferes with the fluid flow and increases the convective heat transfer. Second, unlike the microchannel type of the regenerator, each bare-rod is separated in the longitudinal direction, so that conduction loss in caloric material can be reduced. Also, since it uses a simple rod, the manufacturing process is simple and easy even with a small hydraulic diameter. Finally, the elliptical bare-rod regenerator increases the heat transfer area.

After checking the mesh independency, about 110,000 mesh elements for the CFD were used, and 5 inflation mesh layers were applied near the solid wall to increase the calculation accuracy near the wall. The two-equation realistic k-epsilon model with enhanced wall treatment was used. As fluid inlet velocity increases from 0.1 to 0.6 m/s, the fluid averaged outlet temperature decreases, and pressure drop inside the regenerator increases rapidly. When using the same inlet velocity, the circular regenerator always has a higher outlet temperature, and pressure drop compared to the elliptical regenerator. This is because the circular type forms a narrower flow path and more interferes with the flow.

With the CFD results, Nu and pressure drop as a function of Re were calculated. In the case of bare-rod, Nu and pressure drop per length tend to increase as Re increases. In the case of plate regenerator, Nu is constant, and pressure drop per length increases. For Re below 80, the circular regenerator increases Nu by 75 - 90% and the elliptical regenerator by 25 - 45%. The circular regenerator and elliptical regenerator increase the Darcy friction factor by 230 - 285% and 55 - 105%, respectively.

With the results obtained, Nu, Darcy friction factor correlations for circular and elliptical types were obtained and applied to the caloric cycle model. The circular regenerator improved the COP by about 9.1 % and the elliptical regenerator increases the COP by about 10.6 % compared to the plate regenerator system. This increase in COP was caused by increased Nu and heat transfer area and reduced conduction loss in caloric material.

REFERENCES

Han, U., Kang, H., Lim, H., Han, J., & Lee, H. (2019). Development and design optimization of novel polymer heat exchanger using the multi-objective genetic algorithm. *Int. J. Heat Mass Transf., 144,* 118589.

Kang, M., & Elbel, S. (2018). Performance Analysis of Active Magnetic Regenerative Refrigeration Cycle using Transient Modeling, *17th International Refrigeration and Air Conditioning Conference at Purdue,* Paper 2156.

Lee, H., Saleh, K., Hwang, Y., & Radermacher, R. (2012). Optimization of novel heat exchanger design for the application to low temperature lift heat pump. *Energy, 40*, 204-212.

Rajagopal, M., Chang, H., Man, T., Kuntumalla, G., Meng, Y., Sundar, S., Zhao, H., Salapaka, S., Shao, C., Ferreira, P., Miljkovic, N., & Sinha, S. (2019). Materials-to-device design of hybrid metal-polymer heat exchanger tubes for low temperature waste heat recovery. *Int. J. Heat Mass Transf., 143,* 118497.

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