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# Studies on fluid dynamics and heat transfer characteristics of solid-state caloric cycles using new electric heating apparatus

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## ABSTRACT

This research conducted an experimental and numerical study on fluid dynamics and heat transfer phenomena of a solid-state caloric cycle. Regenerative caloric cycles have a complex structure, and the caloric material constituting the regenerator is very expensive. Since the purpose of this research is to study fluid dynamics and thermal characteristics of oscillatory flow inside the system, a reciprocating flow is created using a motor and a linkage system. A new electric heating apparatus capable of simulating a caloric effect is implemented. Stainless steel, which has thermal properties similar to those of gadolinium most commonly used in the magnetocaloric cycle, is used to create a realistic regenerator behavior as much as possible. Although the cooling effect cannot be generated by using current equipment, heat transfer in single-phase flow is essentially identical between the cooling and heating processes. Therefore, the new heating apparatus can simplify the structure of the experimental equipment, reduce costs significantly to manufacture the experimental facility, and conduct research on the fluid flow and heat transfer inside the regenerator.

The experimental equipment can stably adjust the heating power applied to the regenerator using a potentiometer, thereby easily simulating different field intensities. The flow profile, flow velocity, and displacement ratio can be easily and accurately controlled by utilizing the linkage system and the servo motor. Through this experimental equipment, a new modeling approach for the solid-state caloric cycle could be verified. The new model considers developing region which is created by oscillatory flow. This developing region is added not only to the regenerator model but also to the heat exchanger models in this research. The new experimental approach has shown that the model can more accurately predict the results under different displacement ratios.

## 1. INTRODUCTION

A typical alternative experimental equipment, which is designed to study fluid dynamics and heat transfer characteristics inside a solid-state caloric system, is the passive regenerator test apparatus (Lei *et al.*, 2018). “Passive” means that caloric effect is not used in the cycle which is the opposite term of “active”.

Since the caloric effect is not used in the passive cycle, it is not possible to make a realistic temperature difference between caloric material and liquid generated in an actual active regenerative refrigeration system. For example, the temperature of the caloric material in the magnetocaloric cycle is 3 - 4 °C higher than that of the heat transfer fluid due to the caloric effect after the magnetization process. However, the temperature difference between the two objects caused by the only fluid flow is quite small.

Chen et al. (2014) created an intermittent heating apparatus using the microelectromechanical system (MEMS) technique to generate a more realistic temperature difference between the solid and liquid. A MEMS wafer is composed of a nichrome film layer, a silicon layer, and a $SiO_2$ layer. DC power is applied to the nichrome film to generate intermittent heating. However, the thermal properties of silicon and $SiO_2$ which mainly constitute the MEMS wafer, such as thermal conductivity, and thermal diffusivity, are significantly different from the thermal properties of caloric material.

These can make a difference in heat transfer characteristics between the MEMS regenerator and the active regenerator. Therefore, this research used stainless steel with thermal properties similar to the thermal properties of caloric material to manufacture a regenerator with thermal characteristics similar to the actual regenerator system. In addition, the caloric effect was simulated, and a temperature difference was generated between the solid material and the heat transfer fluid using an electric resistance heating system composed of stainless steel. Using the new electric heating apparatus, the fluid dynamics and heat transfer characteristics inside the regenerator were investigated. In addition, the experimental results and modeling results were compared, and the model for the solid-state caloric system was verified with the experimental data.

## 2. ELECTRIC HEATING APPARATUS

This study is to design an experimental facility for studying fluid dynamics and heat transfer characteristics inside the regenerator. Therefore, instead of generating caloric effects using expensive caloric materials, a temperature difference between caloric materials and heat transfer fluid is generated using an electric heating system. The regenerator was manufactured using stainless steel because the thermal properties of stainless steel are similar to those of caloric materials such as gadolinium, as shown in Table 1.

In addition, stainless steel has relatively high electrical resistivity, so electric heating power applied to the regenerator can be easily generated. Using stainless steel instead of caloric material significantly reduced the cost of manufacturing the regenerator system. Although the cooling effect cannot be created using a new experimental facility because heating is implemented through electricity, the heating and cooling processes are essentially the same in single-phase flow. Therefore, the fluid dynamics and heat transfer characteristics inside the regenerator can be studied using this equipment.

### 2.1 New Electric Heating System

Figure 1 shows the schematics of the new electric heating system. The system consists of four steps. Step1 is the process of applying electric heating to the regenerator, which corresponds to the magnetization process in the magnetocaloric refrigeration system. Step2 activates the pumping system to move the heat transfer fluid from cold to hot, which corresponds to the hot flow period in the magnetocaloric system. Step3 has no heating and no fluid flow. This step corresponds to the demagnetization process. Step4 inversely operates the pumping system to allow the heat transfer fluid to flow from the hot side to the cold side in the regenerator, which is the cold flow period. Figure 2 represents the heating and fluid flow processes for each step. The relay adjusts the electric heating applied to the regenerator and the servo motor regulates the fluid flow. One controller controls both relay and servo motor, simultaneously. Figure 3 shows a picture of the new electric heating system. The test equipment is largely composed of a heating part, pumping part, and cold and hot exchangers. The water heater and cooler are connected to cold and hot heat exchangers, respectively. A flow meter measures the mass flow rate of heat transfer fluid after the pumping system, and a differential pressure transducer is installed in the front and end of the regenerator to measure the pressure drop of the regenerator. Four check values control the direction of the flow at each step, and three thin thermocouples are installed inside the regenerator. Six thermocouples are installed at the front and end of the regenerator and cold and hot heat exchangers. An air collector installed at the end of the pumping system prevents the air from flowing into the system.

**Table 1:** Properties of gadolinium and stainless steel

| Pure material | Gadolinium | Stainless steel (304) |
|---|---|---|

| | | |
|---|---|---|
| Thermal conductivity (W/m-K) | 10.6 | 16.2 |
| Thermal diffusivity (mm2/s) | 5.2 | 4.1 |
| Specific heat (J/kg-K) | 260 | 510 |
| Electrical resistivity (Ω-m) | - | $7.30 \times 10^{-7}$ |

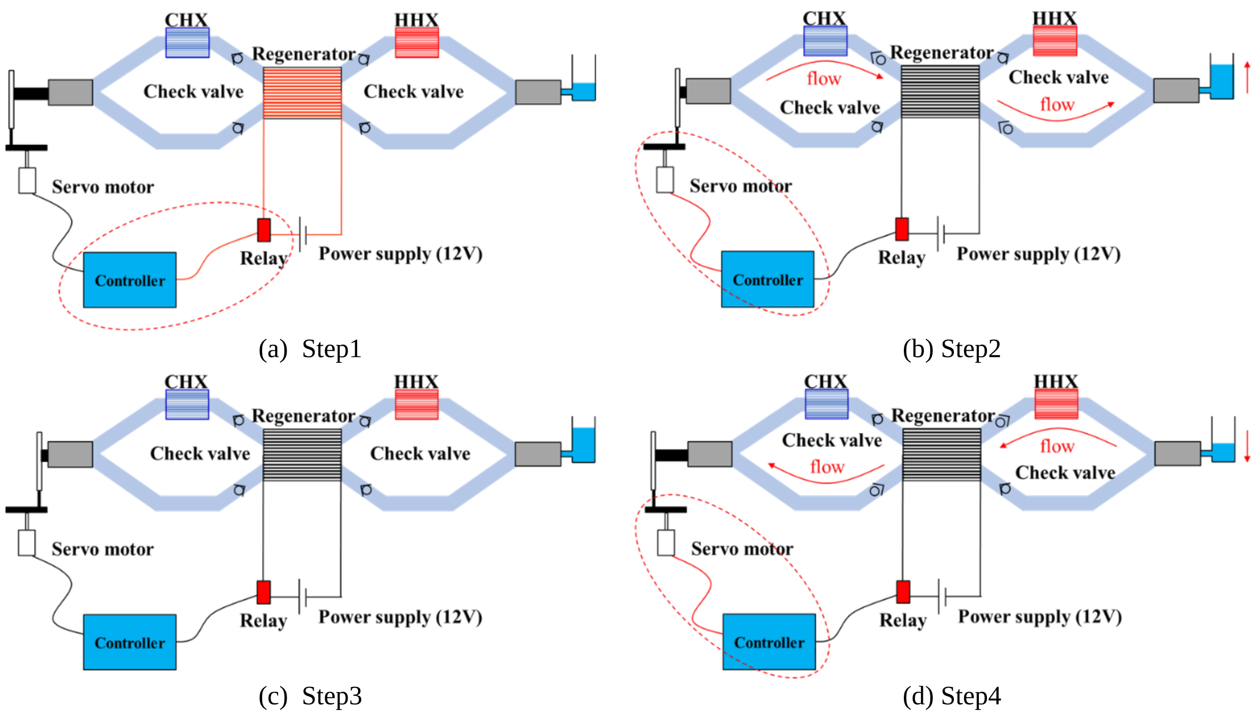



**Figure 1:** Schematics of new electric heating system

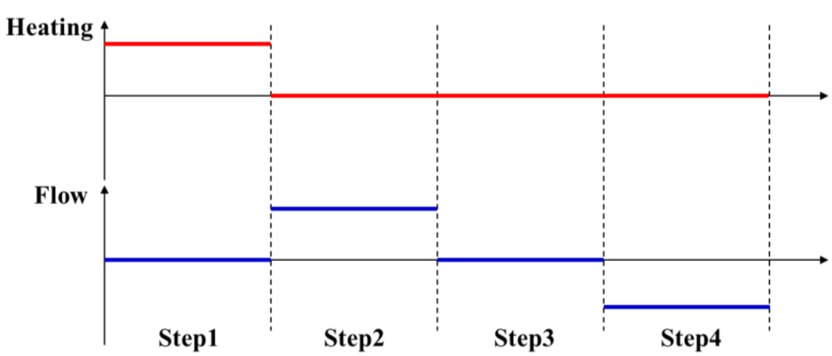



**Figure 2:** Heating and fluid flow of new electric heating system

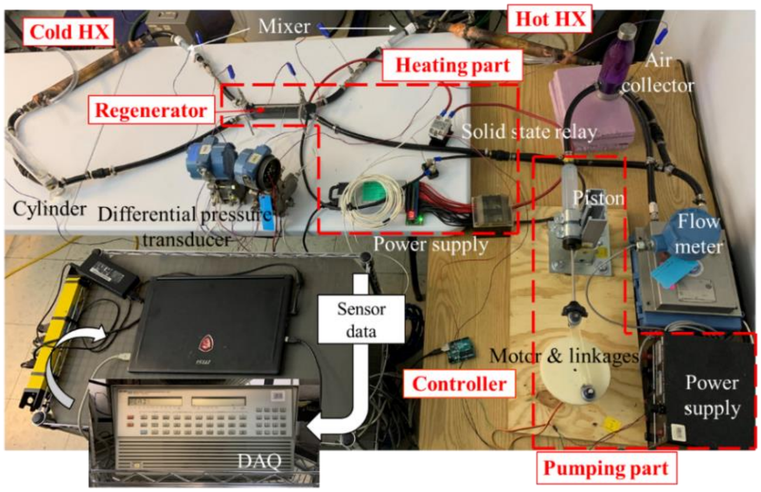
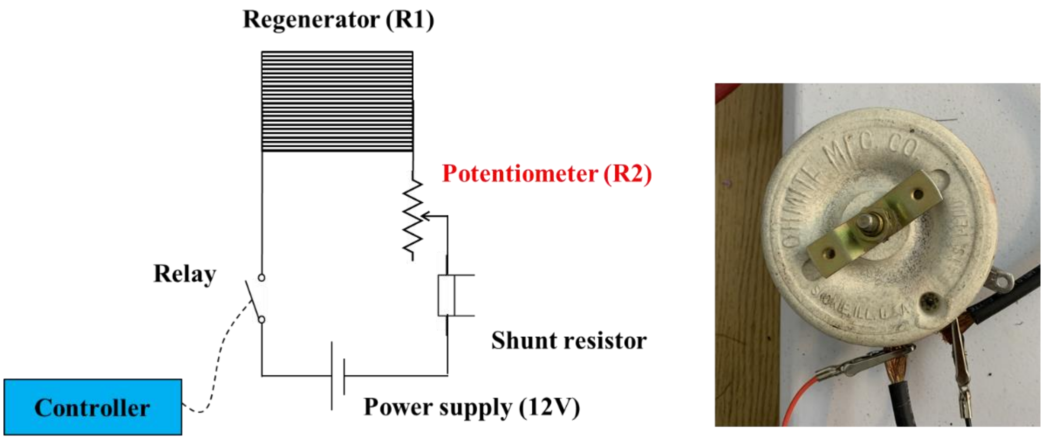



**Figure 3:** Picture of new electric heating system




(a) (b)

**Figure 4:** (a) Electric circuit of heating part and (b) photo of potentiometer

## 2.2 Heating Part

Figure 4 shows (a) the electric circuit of the heating part and (b) the photo of the potentiometer. The electric circuit of the heating part consists of a regenerator, relay, controller, power supply, shunt resistor, and potentiometer. The controller controls the relay. The shunt resistor is used to measure the current of the system and the potentiometer is used to adjust the electric heating power applied to the regenerator.

The heating power ($P_1$) applied to the regenerator is calculated by Equations (1) – (4).

$$R_t = R_1 + R_2 \tag{1}$$

$$I = \frac{V}{R_t} \tag{2}$$

$$V_1 = I \times R_1 \tag{3}$$

$$P_1 = I \times V_1 \tag{4}$$

# 3. NUMERICAL MODEL

A numerical simulation for the new electric heating system was performed. The 1D time-dependent model was used, and there is a detailed description of the model in Kang & Elbel (2018). To consider the hydrodynamic and thermal developing regions caused by the oscillatory flow, the Nu correlation of Nicolay and Martin (2002) and the friction factor correlation of Shah (1978) were applied to the model. In this study, these developing regions were applied not only to the regenerator model but also to the heat exchanger models.

There is a reservoir tank1 for installing the pressure sensor and the thermocouple between the regenerator and the hose, as shown in Figure 5. This reservoir tank 1 does not allow some volume of the heat transfer fluid exiting from the regenerator to enter the heat exchanger and the fluid returns to the regenerator, which is called dead volume. To consider the dead volume, the model was constructed as shown in Figure 6. In actual experimental equipment, heat transfer fluid from the regenerator flows into reservoir tank 1. The fluid from reservoir tank 1 goes to reservoir tank 3 through reservoir tank 2, and the heat exchanger. Then, the fluid from reservoir tank 3 enters the regenerator again through reservoir tank 1. To model this process, the temperature of reservoir tank 1 is calculated in the half-cycle process and then, the temperature of reservoir tank 1 is calculated again after reservoir tank 3 model in the after process using the final temperature of reservoir tank 1 in the half-cycle process.

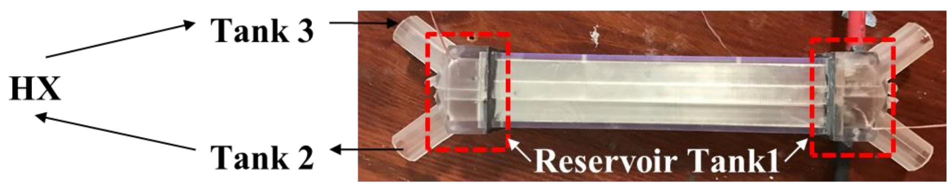



**Figure 5:** Route of fluid flow

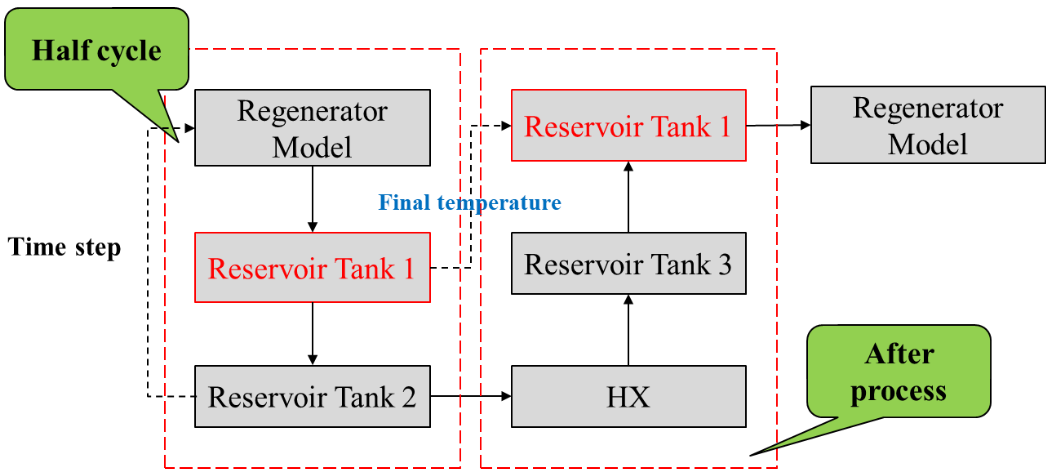



**Figure 6:** Flow chart of model for new electric heating system

## 4. RESULTS AND DISCUSSION

### 4.1 Controlling Heating Power

The electric heating power applied to the regenerator is controlled by the resistance of the potentiometer. Figure 7 shows the system voltage and shunt resistor voltage according to the change in the electric resistance of the potentiometer. As the resistance of the potentiometer increases from 0 to 2, the system voltage value is almost constant at 12 V, and the shunt resistor voltage gradually decreases from 0.035 to 0.005V. The heating power obtained through test results and the heating power calculated using Equations (1) - (4) are shown in Figure 8. As a result of the comparison, the tested and calculated heating power showed less than a 4 % error. Therefore, the electric heating power of the regenerator can be stably and accurately controlled. Using this new experimental equipment, a heating effect due to the caloric effect can be easily simulated.

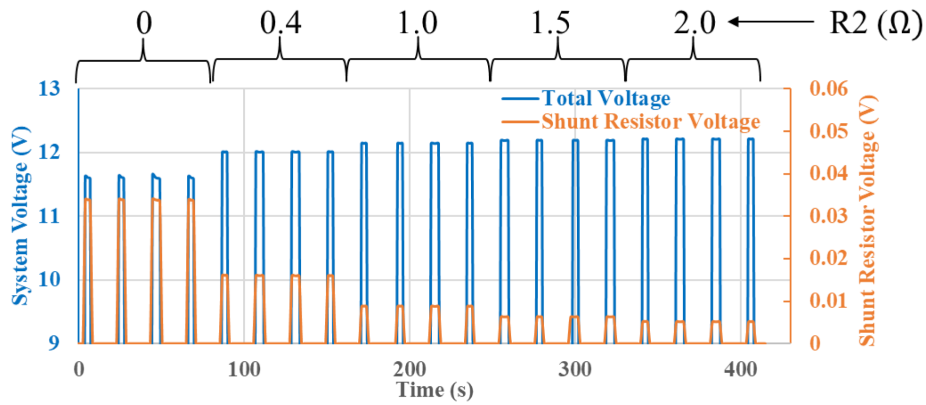



**Figure 7:** System voltage and shunt resistor voltage according to the electric resistance of the potentiometer

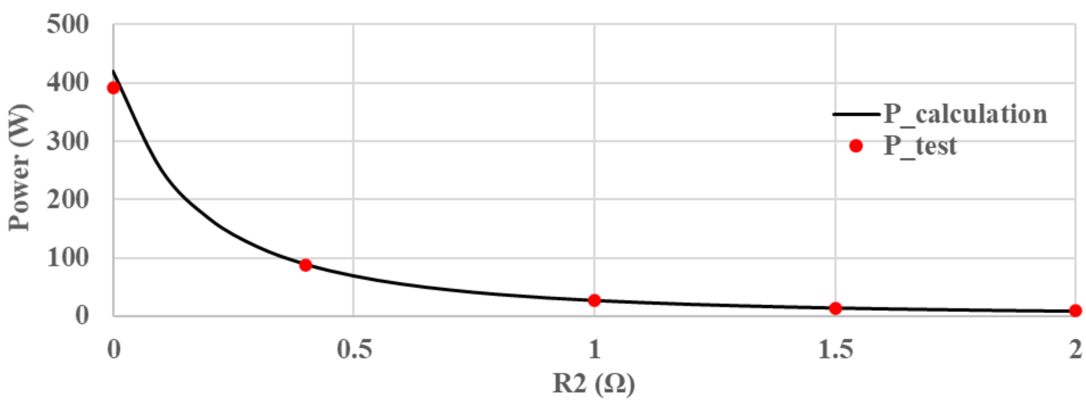
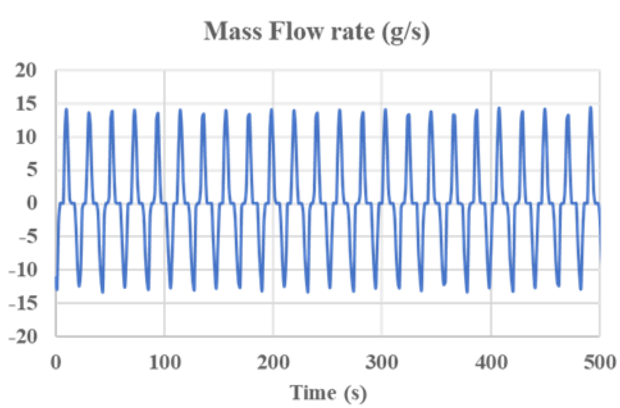


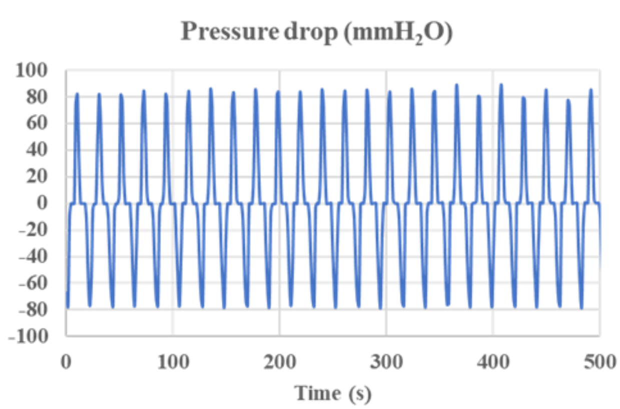

**Figure 8:** Calculated and tested heating power

### 4.2 Stability of New Heating Apparatus

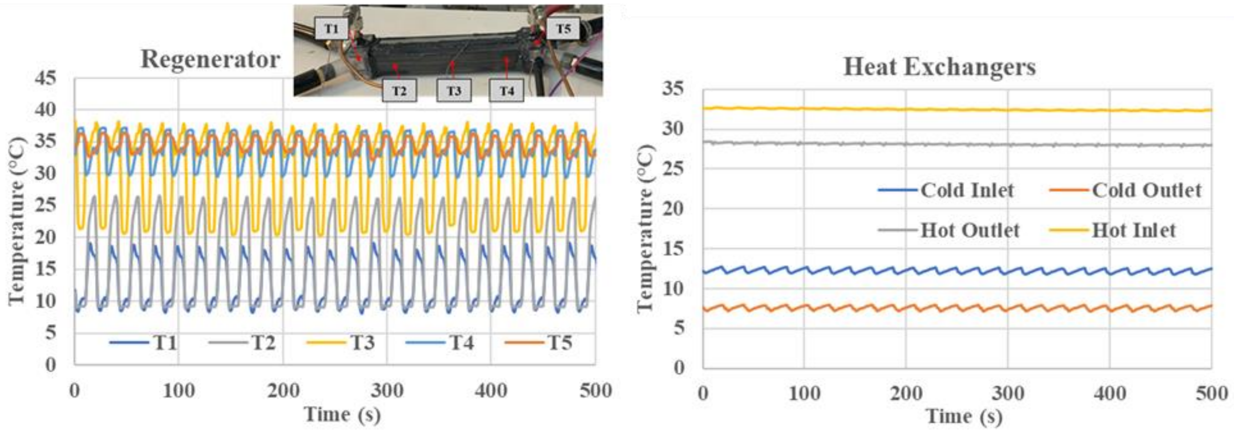
The stability of the new electric heating facility was checked using the conditions of 20 seconds total cycle time and 0.6 displacement ratio. Figure 9 shows the results of mass flow rate, pressure drop, the internal temperature of the regenerator, and inlet and outlet temperature of heat exchanges after the experimental equipment reaches cyclic steady-state condition. After reaching cyclic steady-state condition, the new heating apparatus has shown stable operation.




(a)




(b)




(c) (d)

**Figure 9:** (a) mass flow rate (b) pressure drop of regenerator
(c) internal temperature of regenerator (d) inlet and outlet temperature of heat exchangers

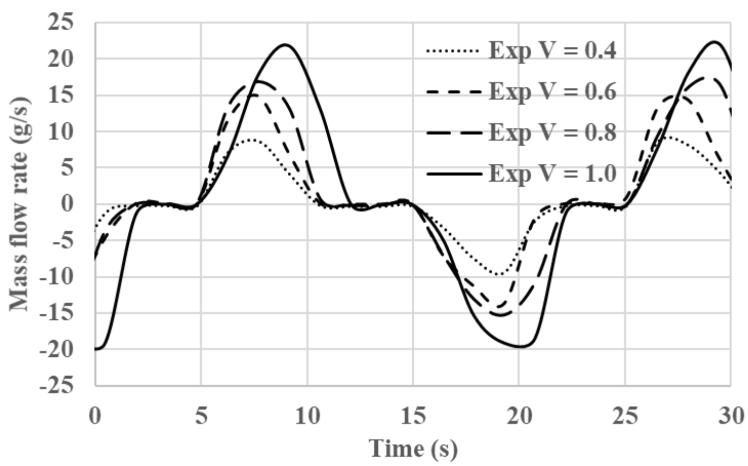
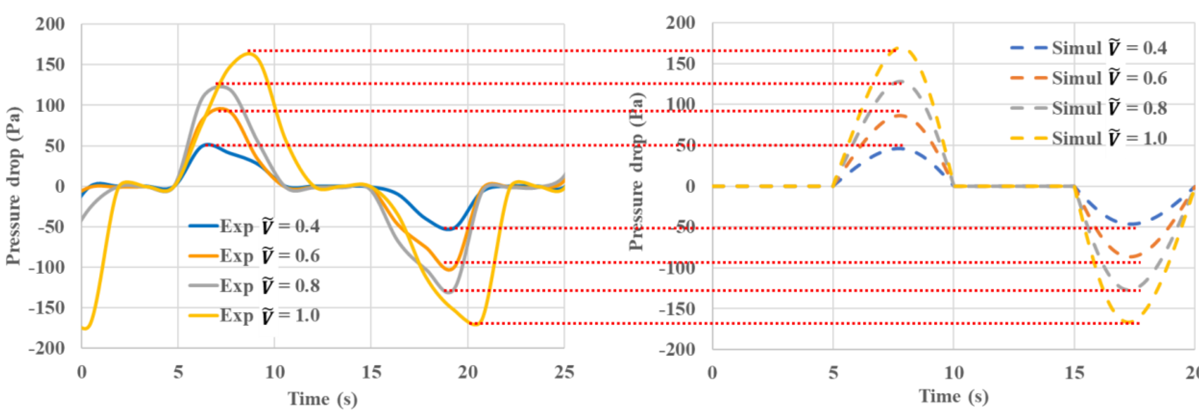



**Figure 10:** Mass flow rate for different displacement ratio




(a) (b)

**Figure 11:** Comparison of pressure drop of (a) experiment and (b) simulation

## 4.3 Mass Flow Rate & Pressure Drop

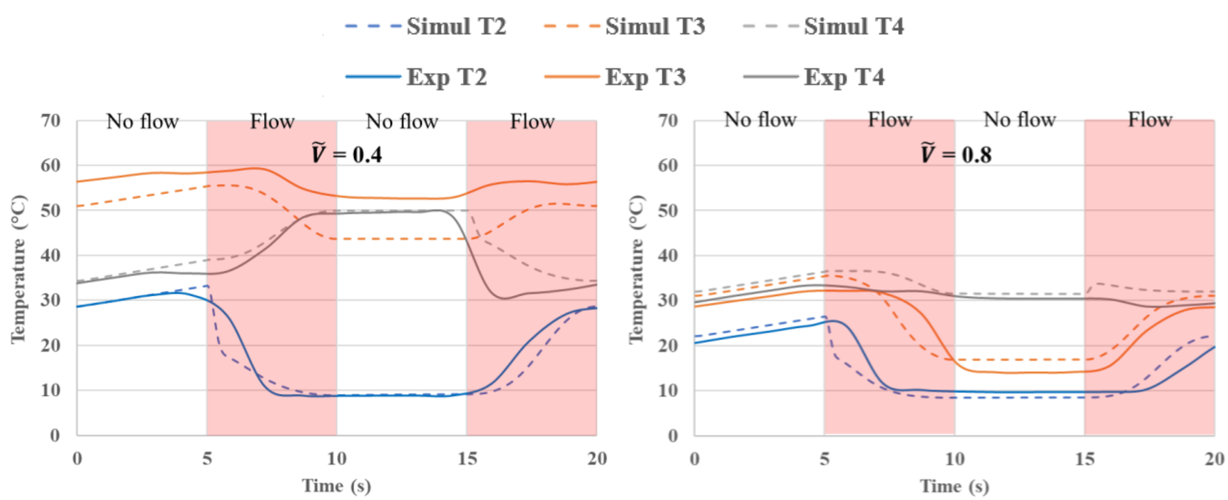
Figure 10 shows the mass flow rate when different displacement rates are applied to the new electric heating system. Figure 11 shows the pressure drop of experimental results and simulation results according to the different displacement ratios. The experimental pressure drop of the regenerator agrees well with the simulated pressure drop of the regenerator. Cold flow and hot flow have slightly different pressure drop shapes because they have different flow routes. As displacement increases, there is a time lag because of higher pressure drop.

### 4.4 Internal Temperature & Effectiveness of Regenerator

Figure 12 compares the simulated and experimental internal temperature of the regenerator for 0.4 and 0.8 displacement ratios. Actual temperature profiles inside the regenerator agree well with simulation results. When $\tilde{\boldsymbol{V}}$ is 0.4, the middle of the regenerator has the highest temperature along the length. This result is caused by the heat transfer fluid in the middle of the regenerator failing to escape the regenerator when the displacement ratio is small. Therefore, the temperature change trend of T4 is different from those of T2 and T3.

Equation (4) shows the definition of the regenerator effectiveness for the high side. Figure 13 shows the simulated and experimental regenerator effectiveness for different displacement ratios. The regenerator effectiveness of experiment and simulation shows similar trends in change.

$$\eta_H = \frac{T_{H,Outlet} - T_{C,Intlet}}{T_{H,Inlet} - T_{C,Inlet}} \tag{4}$$




(a) (b)

**Figure 12:** Comparison of internal temperature of regenerator of (a) experiment and (b) simulation

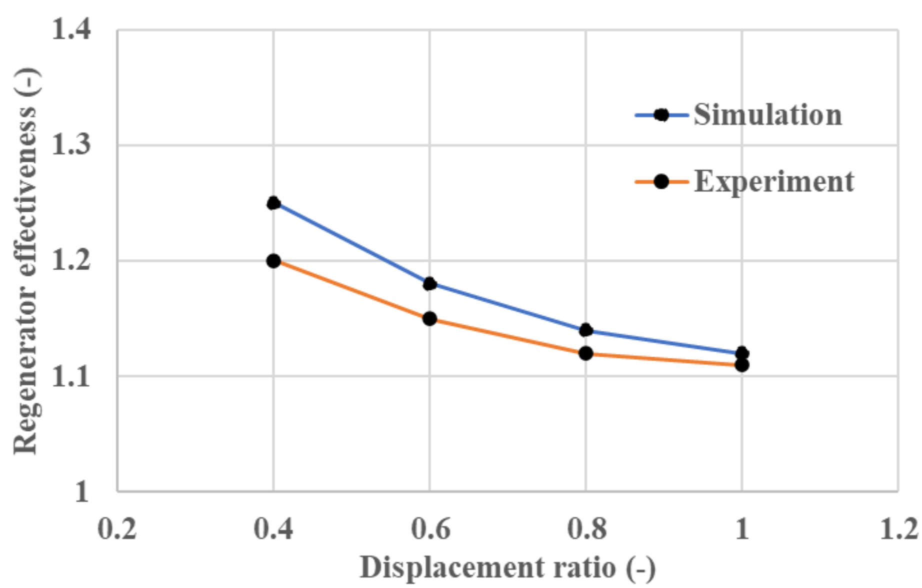


**Figure 13:** Simulated and experimental regenerator effectiveness for different displacement ratios

According to the above results, the pressure drop, internal temperature, and regenerator effectiveness of the experiment and simulation are quite similar. Therefore, the new model with developing regions caused by the oscillatory flow can accurately simulate the flow and the heat transfer phenomenon in the oscillatory flow.

## 4. CONCLUSIONS

In this study, alternative experimental equipment was built using the new electric heating apparatus for studying the fluid flow and heat transfer phenomenon inside the regenerator of the solid-state caloric cycle. Since this equipment does not use expensive caloric materials, the cost of making experimental equipment could be significantly reduced. In addition, unlike a passive regenerator system, the temperature difference between the solid material and the heat transfer fluid could be generated, which is similar to the actual regenerator. Using stainless steel which has thermal properties similar to the thermal properties of caloric material, a more realistic regenerator with heat transfer characteristics similar to the actual regenerator system could be manufactured.

The electric heating power applied to the regenerator can be adjusted using a potentiometer and showed an error of less than 4% compared to the calculated electric heating power. Therefore, the new facility can easily and accurately simulate the different field intensities.

To simulate new experimental equipment, the new model was created considering hydrodynamic and thermal developing regions caused by the oscillatory flow and the dead volume. The results of the modeling are almost the same as the pressure drop, internal temperature profile of the regenerator, and regenerator effectiveness obtained through the experimental test. Therefore, the new model simulates the fluid flow and heat transfer phenomenon for the oscillatory flow accurately.

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## ACKNOWLEDGEMENT

The authors would like to thank the member companies of the Air Conditioning and Refrigeration Center at the University of Illinois at Urbana-Champaign for their financial and technical support. The authors would like to thank Creative Thermal Solutions, Inc. (CTS) for providing technical support and equipment.