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Tracking Control of a Spool Displacement in a Direct Piezoactuator-Driven Servo Valve System

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This paper presents tracking control performances of a piezostack direct drive valve (PDDV) operating at various temperatures. As a first step, a spool valve and valve system are designed to be operated by the piezoactuator. In this study, the stacked piezoelectric actuator, which is lead–zirconate–titanate (PZT) ceramic is used for control of spool displacement. An aerogel is used for heat insulation since the PZT piezoelectric actuator has low Curie temperature. After briefly describing the operating principle, the governing equation of the proposed valve system is driven including the piezostack actuator. Subsequently, an experimental apparatus for investigating the effect of temperatures on the performances is set up. The PDDV is installed in a large-size heat chamber equipped with electric circuits and sensors. A classical proportional-integral-derivative (PID) controller is designed and applied to control the spool displacement. In addition, a fuzzy algorithm is integrated with the PID controller to enhance the performance of the proposed valve system. The gain of PID changes to satisfy the target frequency and displacement according to input frequency and operating temperature. Therefore, fuzzy algorithm with two input variables that are frequency and temperature can determine the gain of PID controller. The tracking performance of a spool displacement is tested by increasing the temperature and exciting frequency up to 150°C and 200 Hz, respectively. It is shown that the tracking performance heavily depends on both the operating temperature and the excitation frequency.

Keywords: piezoelectric, servo systems, tracking control, temperature, flow rate

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INTRODUCTION

Currently, many types of actuator using smart material are studied and implemented to industrial fields such as valves, shock absorbers, and so on (Proch and Trickl, 1989; Choi et al., 1999; Ahn and Jeon, 2002). Especially, the piezoelectric actuator is used for many control applications because the piezoelectric actuator has salient features such as fast frequency response, high actuating force, and infinite control resolution (Niezrecki et al., 2001). However, the piezoelectric actuator, especially made with lead–zirconate–titanate (PZT) material, is susceptible with temperature variation because the piezoelectric has low Curie temperature (Choi and Han, 2010). The PZT type of piezoelectric actuator is most widely used in mechanical system because the actuator has the best mechanical properties such as charge coefficient of d_{33} and d_{31} (Uchino, 1986). Therefore, many researches of piezoelectric actuator and applications with high temperature conditions are studied actively. Li et al. (2010) studied the property of ferroelectric ceramic under temperature conditions from 25 to 180°C. Choi et al. researched temperature-dependent dynamic characteristics and control performance of a piezostack actuator with high temperature conditions up to 180°C (Han et al., 2015). Furthermore, Choi et al. proposed a valve system actuated by piezoelectric actuator and evaluated the valve system at high temperature. However, the used piezoelectric actuator is not the normal stack actuator, which is made for high temperature up to 125°C (Jeon et al., 2015).

The hydraulic valve system is widely used for control mechanical system since the system has high power density and changes hydraulic energy to mechanical power easily. The performance of mechanical system with hydraulic valve system is seriously influenced by performance of the valve system. A servo valve system uses solenoid type actuator, but the solenoids cannot provide fast response and high precision (Paul et al., 1994; Li and Song, 2007). One approach to resolve the problems is to use the piezoelectric actuators for hydraulic servo valve (Jeon et al., 2013).

Consequently, the main contribution of this work is to design and investigate the hydraulic servo valve system driven by piezoelectric actuator in high temperature. This is accomplished by evaluating the tracking performance of a spool displacement at various operating temperatures and excitation frequencies. In order to undertake this test, the valve system is installed in a heat chamber with a hydraulic circuit and electric devices such as the pneumatic hydraulic cylinders and the high temperature resistant sensors. The performance of tracking control of the spool displacement is experimented using two types of controller, which are a typical proportional-integral-derivative (PID) controller and PID controller integrated with a fuzzy algorithm. The tracking control results are evaluated and presented in time domain by increasing the temperature and exciting frequency up to 150°C and 200 Hz, respectively.

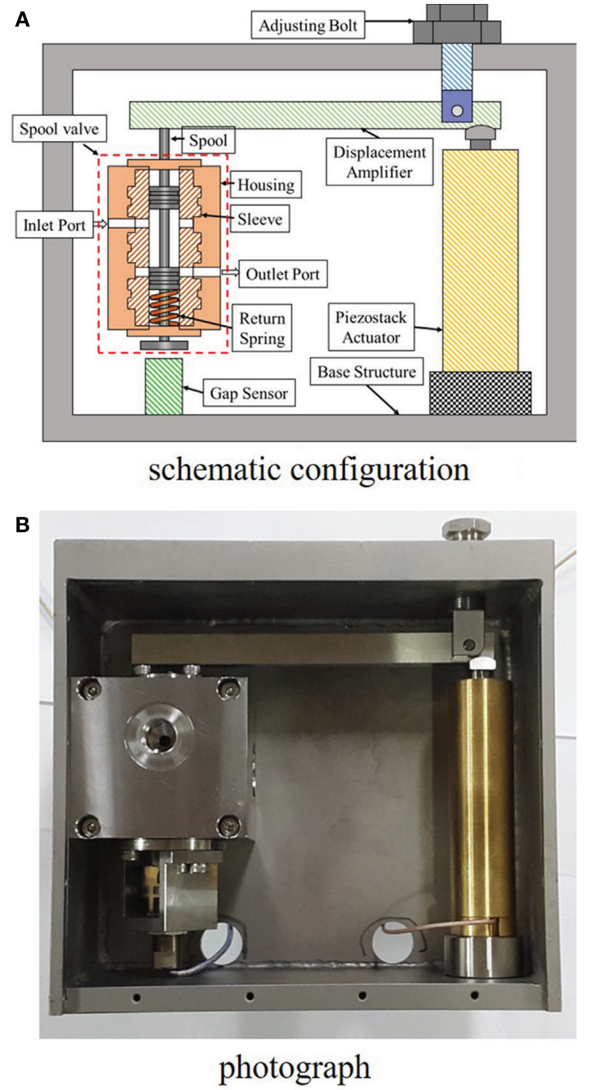

FIGURE 1 | Schematic configuration and photograph of servo valve system. **(A)** Schematic configuration and **(B)** photograph.

PIEZOSTACK DIRECT DRIVE VALVE

The hydraulic direct drive valve system driven by piezoelectric actuator providing high accuracy and fast response is devised in this work. A spool valve is applied for the flow rate control with high precision. The spool valve can control the flow rate by moving the position of spool. The pressure of inlet port is always kept and the pressure of outlet port is changed with open area. The spool valve system is designed in which the spool is directly driven by the stacked piezoelectric actuator to provide fast response. **Figure 1** shows the schematic diagram and photograph of the proposed piezostack direct drive valve (PDDV) system. As shown in the **Figure 1A**, the proposed valve system consists of a spool valve, a piezostack actuator, a displacement amplifier, a gap sensor, an adjust bolt, and base structure. One of the weaknesses, small displacement of piezostack actuator, is overcame through a displacement amplifier. The displacement amplifier that utilizes a lever-hinge mechanism can magnify a displacement generated from the piezostack. The spool displacement is measured by a gap sensor, which is non-contact method sensor because a non-contact sensor does not have any effects on the system. Furthermore, an adjusting bolt is adopted to compensate the thermal expansion, and all systems are fixed by the base structure at the inside of the structure. The spool valve consists of the housing, spool, sleeve, and return spring. The sleeve has two ports that are circular input port and rectangular output port. The reason why using rectangular output port is that rectangular shape can change output area linearly through spool location. The return spring is used to bring back the initial position of the spool because considered piezostack actuator is unipolar type actuator. **Figure 1B** shows a photograph of the manufactured PDDV system.

Figure 2 shows the schematic diagram of PDDV mechanical model, which is consisted of the piezostack, lever-hinge, and spool valve. The dynamic equations of the piezostack actuator and the spool can be obtained as follows:

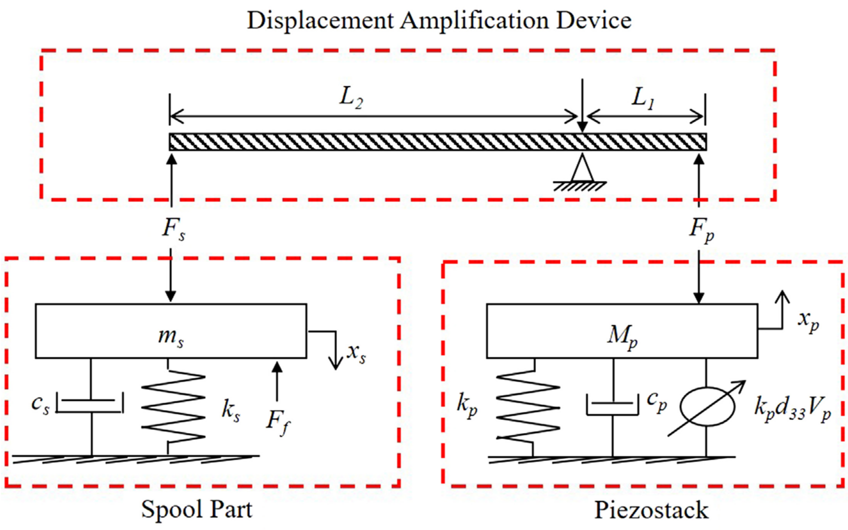

FIGURE 2 | Schematic configuration of mathematical model.

$$\begin{aligned} m_p \ddot{x}_p + c_p \dot{x}_p + k_p x_p &= k_p d_{33} V_p - F_p \\ m_s \ddot{x}_s + c_s \dot{x}_s + k_s x_s &= F_s - F_f \end{aligned} \tag{1}$$

where x_p and x_s are the displacement of the piezostack and spool. V_p, m_p, c_p, and k_p are the input voltage to the piezostack, the mass, damping coefficient, and stiffness of the piezostack, and m_s, c_s, and k_s are the mass, damping coefficient, and stiffness of the spool, respectively. d_{33} is the charge constant of the piezostack. F_p is the acting force from a piezostack, and F_s is the transmitted force from the displacement magnification device can be obtained as follows:

$$F_s = d_r^{-1} F_p - \frac{I_L}{L_2} \cdot \frac{\ddot{x}_s}{L_2} \tag{2}$$

where $d_r(=L_2/L_1)$ is the amplification ratio of the lever-hinge system. I_L and $\ddot{x}_s / L_2$ are the mass moment of inertia and the approximated angular acceleration of the lever. F_f is a steady flow force calculated by

$$F_f = 2\Delta P C_d^2 A_o \cos(\theta) \tag{3}$$

where ΔP is the pressure drop and C_d value is selected from 0.6 to 0.65 and it is a function of Reynolds number and cavitation number (Han et al., 2015). θ is the jet angle and A_0 is the open area of outlet port calculated by $2 D_s x_s \sin^{-1}(H_s / D_s)$, where D_s and H_s are the diameter of the spool and the height of the outlet port. Finally, the dynamic equation of proposed PDDV system can be expressed as follows:

$$\begin{aligned} &\left\{ m_s + m_p d_r^{-2} + \frac{I_L}{L_2^2} \right\} \ddot{x}_s + \left\{ c_s + c_p d_r^{-2} \right\} \dot{x}_s \\ &+ \left\{ k_s + k_p d_r^{-2} + 4\Delta P C_d^2 D_s \cos(\theta) \sin^{-1}\left(\frac{H_s}{D_s} \right) \right\} x_s \\ &= d_r^{-1} k_p d_{33} V_p(t) \end{aligned} \tag{4}$$

TABLE 1 | Mechanical and dimensional properties of the piezostack actuator.

Specifications	Symbol	Value
Damping coefficient	c_p	150 N s/m
Stiffness	k_p	70 MN/m
Mass	m_p	0.317 kg
Piezoelectric charge constant	d_{33}	6 × 10^{-7} m/V
Length	l_p	0.1 m
Maximum operating temperature		80°C

TABLE 2 | Mechanical properties and dimensions of the spool-sleeve.

Specifications	Symbol	Value
Mass of the spool	m_s	0.01 kg
Damping coefficient of the spool	c_s	200 N s/m
Spring coefficient of the return spring	k_s	80 kN/m
Diameter of the spool	D_s	7.145 mm
Height of the outlet port	H_s	4 mm
Overlap length	ε	0.01 mm
Width of the outlet port	A	2 mm
Discharge coefficient	C_d	0.611
Jet angle	θ	61°

In this study, the positive and normal closed spool valve is considered. The flow rate can be controlled by effective open area. Consequently, flow rate (Q_S) can be expressed as follows:

$$Q_s = C_d A_O \sqrt{2\Delta P / \rho} \tag{5}$$

where ρ is a density of hydraulic oil. In this work, VG 46 is used for actuating fluid and ρ of VG 46 is 879 kg/m^3. The commercial piezostack actuator (pst150/20/80/V25, PIEZOMECHANIK) is considered to control the valve system, and guaranteed working temperature is 80°C because of PZT type piezoelectric material. The displacement from piezostack is magnified by lever-hinge amplifier whose amplification ratio is 21. The mechanical and dimensional properties of the valve system are shown in **Tables 1** and **2**. The valve system is designed in which the maximum operating frequency of the PDDV is chosen up to 50 Hz. The frequency response of the valve is experimentally obtained by the sinusoidal sweep test. **Figure 3** shows the frequency response results obtained from simulation and experiment, respectively.

EXPERIMENTAL APPARATUS AND RESULTS

In order to test the performance of the proposed valve system with high temperature conditions, an apparatus is set up in the large size of the heat chamber. **Figure 4** shows the schematic configuration of experimental flow chart to undertake the test. A heat chamber (BK-HTDO-8100, Bookwang C&C co., Ltd.) is used for control the environment temperature and can regulate the temperature from room temperature to 300°C. First, the computer generates low input signal and the generated signal is transferred to voltage amplifier (EC750SA, NF Corporation) through D/A converter (DS1104 R&D Controller Board, dSPACE). The voltage amplifier can magnify the voltage up to 200 V to be applied to the piezostack. The displacement amplifier can generate spool position from the displacement of piezostack. The gap sensor (KD-2306 2SMT, KAMAN) can detect the spool, and the position signal is transferred into the computer through A/D converter (DS1104 R&D Controller Board, dSPACE). Second, nitrogen pressure vessel is used to make the input pressure, and the pressure can be changed to hydraulic pressure by pneumatic-hydraulic cylinder. The cylinder has two rooms and the rooms are separated by the moving piston. The cylinder has 1 l of hydraulic volume, and three cylinders are used for this research. The outlet port of the cylinder is connected to the inlet port of the valve system through inlet pressure sensor (210-40-011-04, Paine Electronics, LLC). The outlet port of the valve is connected to another pressure sensor and flow meter (FT-08AEYB-LEA-3), and the passed fluid goes to the reservoir tank. The sensor signals are saved by the computer using A/D convertor. After the experiment, the cylinders are filled with fluid again using a pump and a valve. All of the sensors, three pneumatic-hydraulic cylinders, and piezostack actuator are in the heat chamber. Furthermore, the valve system is surrounded by aerogel, which is a heat insulator. **Figure 5** shows the photograph of established experimental apparatus.

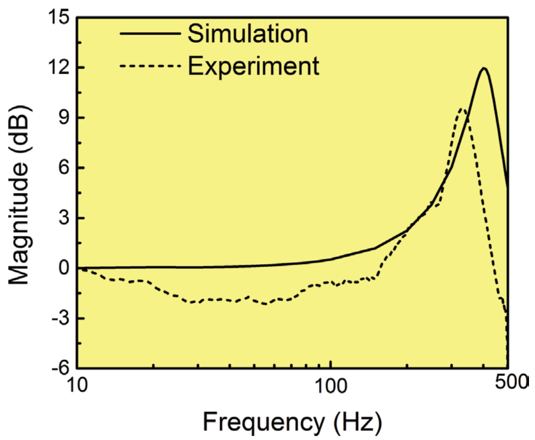

FIGURE 3 | **Frequency responses of the PDDV system**.

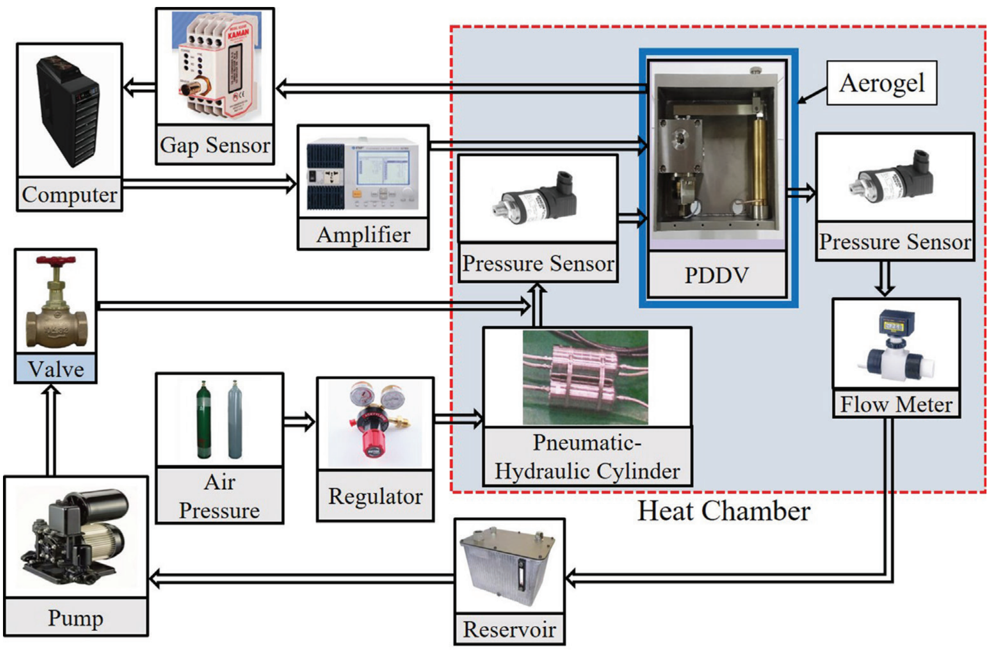

FIGURE 4 | **Configuration of experimental apparatus for the tracking control**.

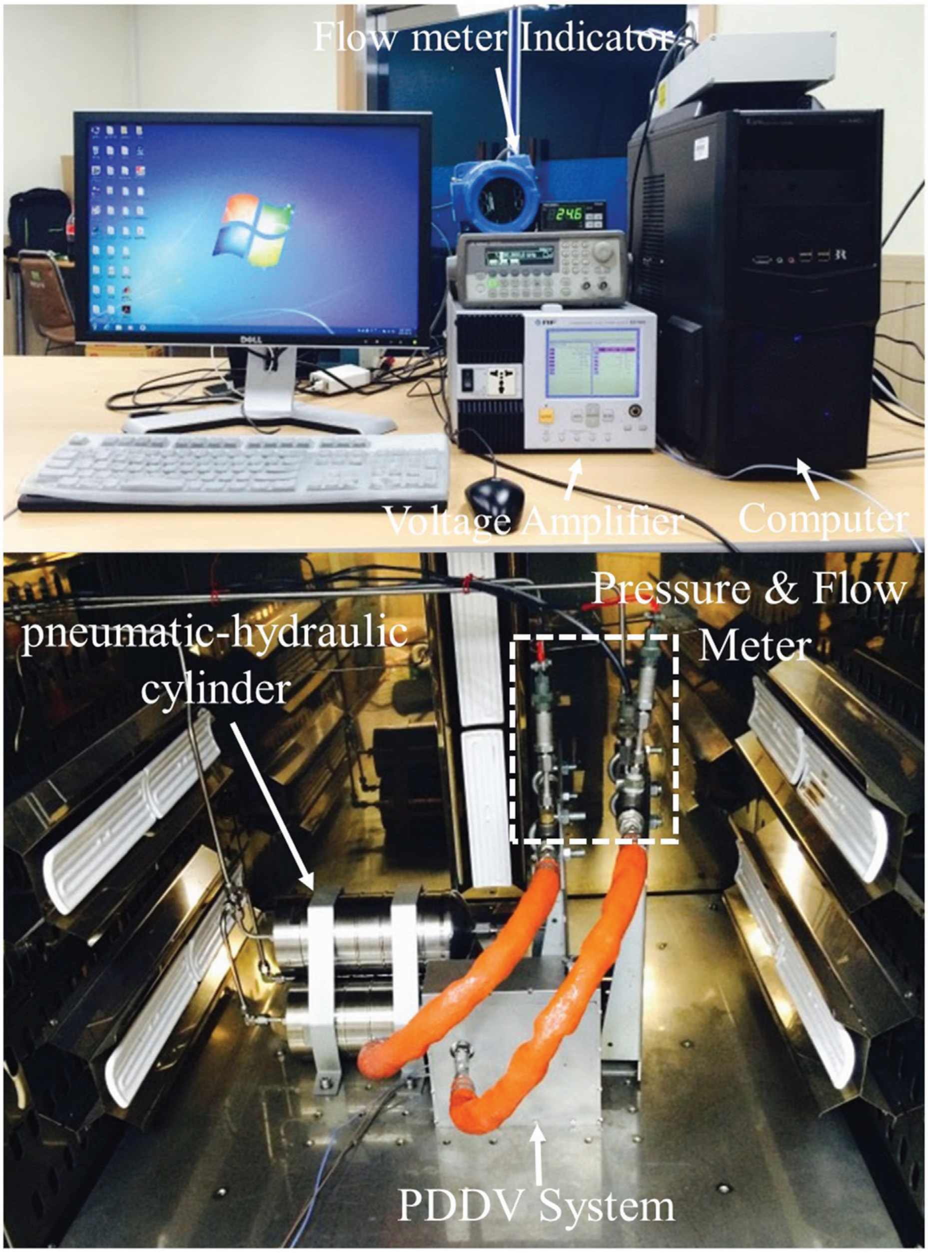

FIGURE 5 | **Photo of the setup of the experiments**.

In this work, the PZP type of piezostack, guaranteeing its performance at the temperature up to 80, is used. Therefore, the temperature effects on the valve system are firstly investigated in terms of the spool displacement. It is well known that the blocking force of the piezostack actuator is dramatically decreased as the temperature increases (Choi et al., 1999). **Figure 6** shows the driving voltage required to reach 0.3 mm of the spool displacement. The PID controller is used for displacement control of spool, and the gain of P, I, and D are chosen by the trial and error method. As shown in the figure, the 90 V is applied to the piezostack at room temperature. However, 150 V is required to get 0.3 mm of the spool displacement at 120°C environment. Therefore, the heat insulator should be used around the piezostack actuator to achieve up to 150°C as shown in the **Figure 7**. The flow rate according to displacement of the spool is measured by the flow meter shown in **Figure 8**. **Figure 8A** shows the result of the flow rate at excitation frequency of 1 Hz. The flow rate data under 3.78 LPM have some errors because the flow meter can detect only the range from 3.78 to 37.8 LPM. In spite of the errors, the flow rate data fairly follows the displacement of the spool as seen. It is seen from **Figure 8B** that the flow rate data has relatively large error and phase delay because the flow meter

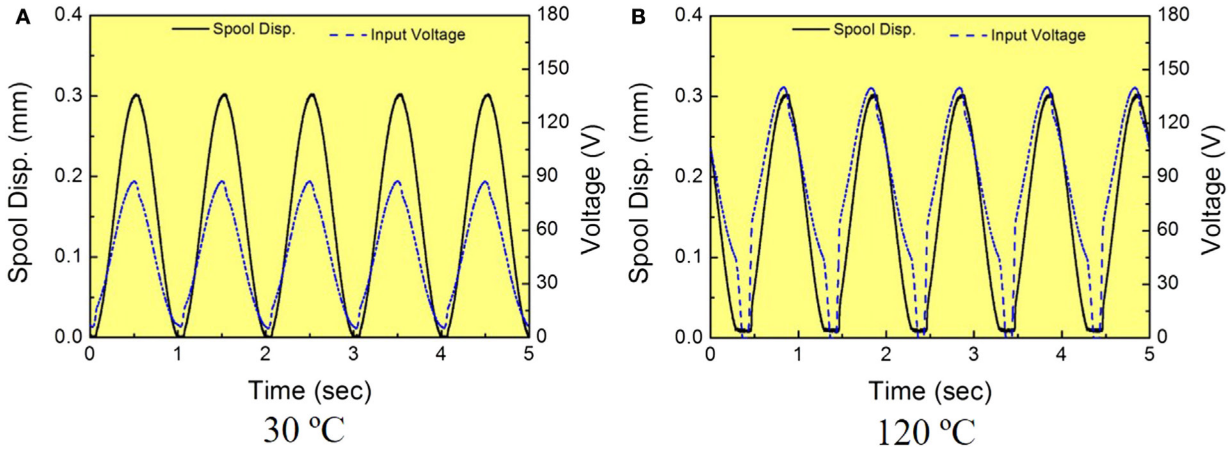

FIGURE 6 | **Spool displacement and input voltage at two different temperatures**. **(A)** 30°C and **(B)** 120°C.

has slow response time. Therefore, in this work, control target is selected as the displacement of the spool instead of the flow rate to accommodate high excitation frequency. It is remarked that the response time of the displacement sensor is sufficiently fast to acquire the signal occurred at the excitation frequency of 200 Hz.

As mentioned earlier, in this work, a simple PID feedback controller is adopted to achieve tracking control response of the spool displacement. As well known, the PID control input is calculated as flows:

$$u(t) = k_p e(t) + k_i \int e(t) + k_d \frac{d}{dt} e(t) \quad (6)$$

where $e(t)$ is the error of displacement of the spool between desired and actual signals. k_p, k_i, and k_d are the proportional, integral, and derivative gain of PID controller, respectively. The k_p, k_i, and k_d are determined using Ziegler–Nichols tuning method with each temperature condition. **Figure 9** shows the tracking control results of the spool displacement at 1 Hz. At low temperature with 0.12, 80, and 0.0001 of k_p, k_i, and k_d gains, the maximum input voltage is 80 V to reach the 0.3 mm with a small error. The maximum voltage is 119 V at 150°C with 0.2, 80, and 0.0001, and tracking error is almost the same as room temperature. The maximum flow rate is 9.077 LPM and 11.734 LPM at low temperature and 150°C. However, the minimum flow rate has a big error because the flow meter has 3.78–37.8 LPM measurement range. In high temperature, the maximum flow rate increases since the viscosity of the hydraulic oil decreases. **Figure 10** shows the experimental results, which are operated at 200 Hz with room temperature and 150°C. The PID gains are changed from 0.12 and 620 to 0.25 and 420 at room temperature and high temperature, respectively. The phase (time) delay is occurred as expected, and the delay is more serious at 200 Hz frequency. The phase delay of 75.6° is occurred at room temperature, while it is 79.2° at 150°C. Because the value of the phase delay is less than 180°, the system is still stable with a certain margin. The tracking error caused by time delay is observed, and the delay is identified by 1 ms in both cases. The dominant reason makes the time delay that the stiffness of the return spring

FIGURE 7 | **Photograph of the piezostack actuator with the heat insulation**.

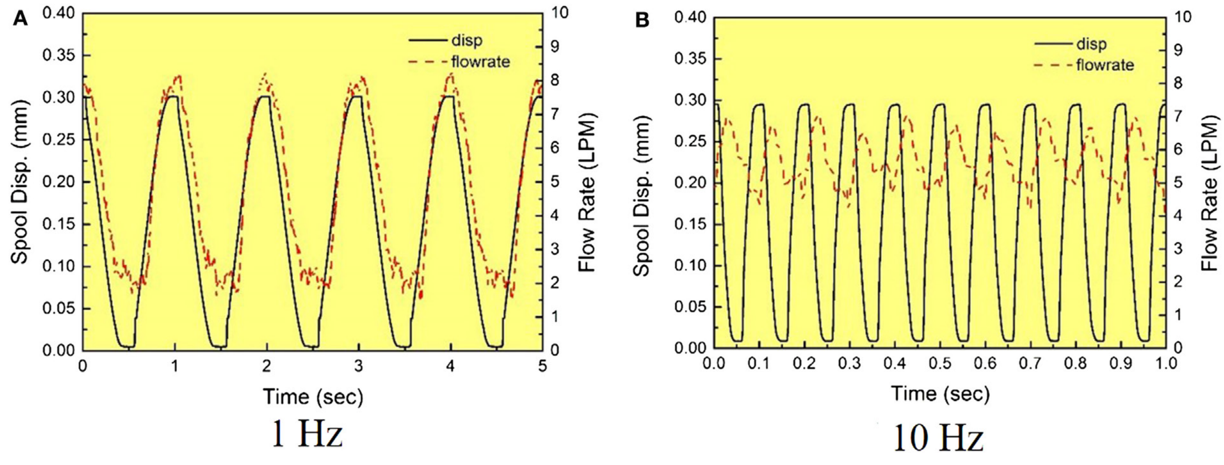

FIGURE 8 | **Flow rate measured by the flow meter**. **(A)** 1 Hz and **(B)** 10 Hz.

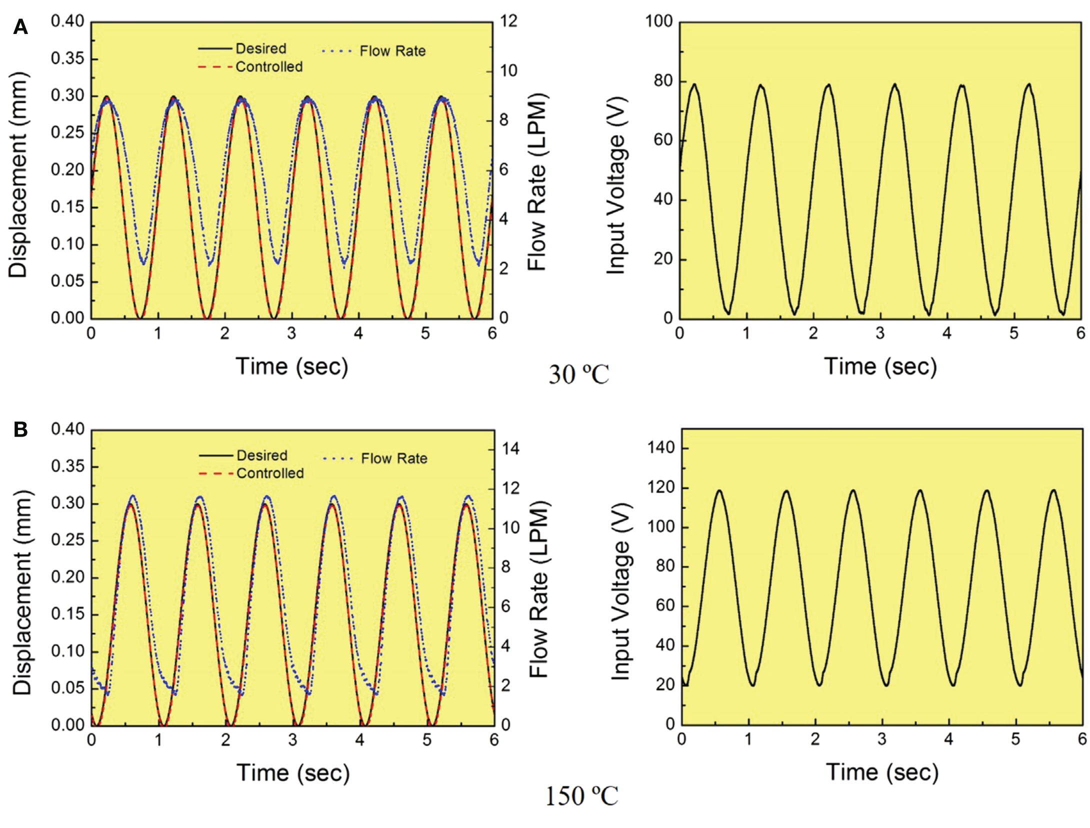

FIGURE 9 | **Tracking control results at 1 Hz**. **(A)** 30°C and **(B)** 150°C.

is not enough to operate up to 200 Hz without delay. Therefore, the stiffness will be designed much higher for the valve system in the next study. However, the time delay is not directly related to the operating temperature. The used simple PID controller has good performance with fixed conditions such as 150°C and 200 Hz, but the control performance loses when the operating condition is changed from the initial condition to different conditions, such as operating temperature and frequency. Therefore, a fuzzy algorithm is applied for tuning the gain of k_i because the k_i is changed frequently with temperature and operating frequency. The fuzzy

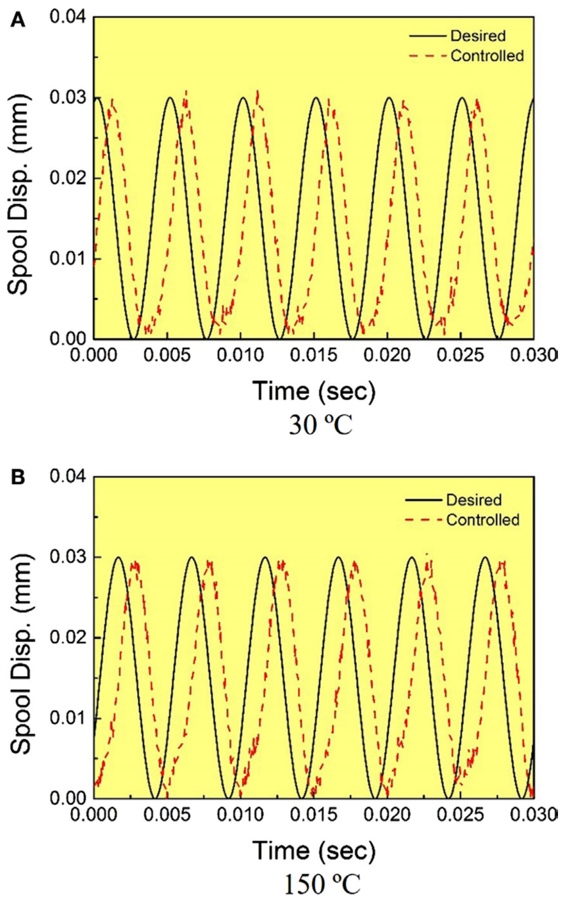

FIGURE 10 | Tracking control results at 200 Hz. **(A)** 30°C and **(B)** 150°C.

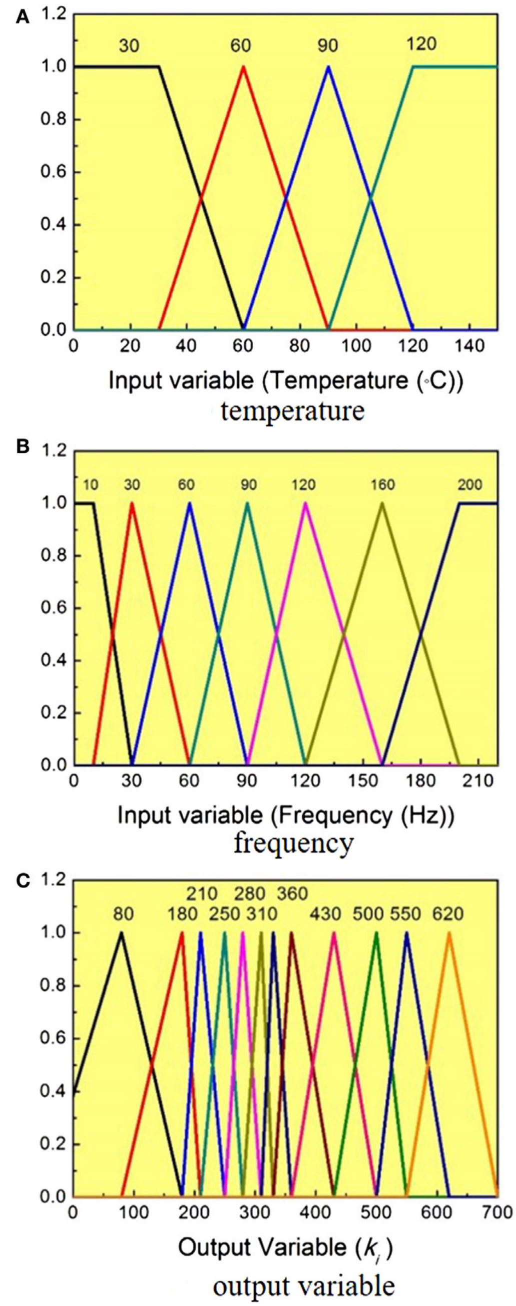

FIGURE 11 | Membership functions. **(A)** Temperature, **(B)** frequency, and **(C)** output variable.

rule is based on the acquired gains by the experiment. **Figure 11** shows the membership function of temperature input variable, frequency input variable, and output variable of k_i. The membership function of output variable is constructed based on k_i from the results of Ziegler–Nichols tuning method. **Table 3** shows the rule base table of two input and one output variables. The center of gravity defuzzification method is used to define output value (Lilly, 2011). **Figure 12** presents the tracking result obtained from the fuzzy associated with PID controller. In this experimental, the operating temperature is regulated by 110°C. **Figures 12A,B** show the tracking result at the excitation frequency of 50 and 200 Hz, respectively. It is clearly observed from the figure that the tracking control results have the time delay as that occurred with the PID controller. However, the spool displacement flows well with the time delay. It is noted that the shape of the spool displacement is distorted because the PID gain is not optimized from the fuzzy algorithm. The choice of the optimized control gains using the fuzzy algorithm will be undertaken in the future.

CONCLUSION

In this work, the piezostack direct drive valve (PDDV) system was designed for flow rate control, and control performances were

TABLE 3 | Rule base table.

	30°	60°	90°	120°
10	80	80	80	80
30	180	180	180	180
60	280	280	210	210
90	310	310	250	230
120	420	360	320	280
160	550	440	360	330
200	620	500	430	420

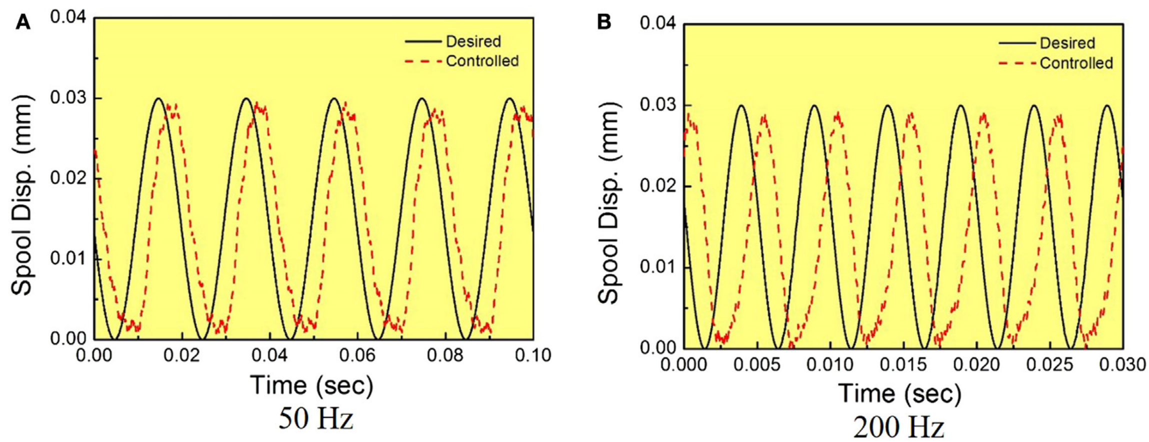

FIGURE 12 | **Tracking control results with the fuzzy algorithm at 110°C**. **(A)** 50 Hz and **(B)** 200 Hz.

experimentally evaluated at various temperatures. As the first step, the valve system was devised, and operating principle was explained in details. The valve system had been installed into the large heat chamber, which has the electric circuits and various sensors. To change air pressure to the hydraulic pressure, the pneumatic-hydraulic cylinder was used with air pressure vessel. Second, the performance of the valve system was tested without thermal insulation in high temperature. Finally, the performance of tracking control of the spool displacement was evaluated by implementing PID controller, and the fuzzy algorithm integrated PID controller. The tests were undertaken by changing both the operating temperature and excitation frequency. It had been shown that the proposed valve system exhibited good tracking control performances at both 30 and 150°C. However, the time delay was occurred over 50 Hz frequency independently of the operating temperature since the return spring had low stiffness. The results presented in this work are self-explanatory, justifying that the piezostack actuator can be effectively employed for active servo valve system to control fast flow rate at high temperatures. It is finally remarked that the thermal insulation is required to operate the piezoactuator-driven valve system at high temperature up to 150°C, and control durability of the servo valve system should be undertaken at high temperatures for practical utilization.

AUTHOR CONTRIBUTIONS

S-BC developed the concept of the proposed valve system and CH and Y-HH did experimental testing.

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