

Article

Automatic Actuation of the Anti-Freezing System Using SMA Coil Springs

Daehwan Cho ¹, Joonhong Park ^{1,*} and Jaeil Kim ²

¹ Department of Mechanical Engineering, Dong-A University, 37, Nakdong-daero 550beon-gil, Saha-gu, Busan 49315, Korea; 1327276@donga.ac.kr

² Department of Advanced Materials Engineering, Dong-A University, 37, Nakdong-daero 550beon-gil, Saha-gu, Busan 49315, Korea; kimchi@dau.ac.kr

* Correspondence: acttom@dau.ac.kr; Tel.: +82-51-200-7645

Abstract: Studies have been actively conducted on systems that prevent the breakage of water pipes from freezing in winter. Shape memory alloy (SMA) coil springs have been used as the key components of actuators that can operate automatically by detecting the real-time outside temperature changes, but research on its use as an actuator that can operate at sub-zero temperatures is insufficient. This study proposes the anti-freezing system using Ni-44.08Ti-1.46Co (wt.%) SMA coil springs that operate near sub-zero temperatures to prevent the freezing accident of water pipes. After fabricating the SMA coil springs, the test for performance evaluation of the springs applied static load conditions was conducted on the specific outside temperature. To examine the operation of anti-freezing systems applied the SMA coil spring as an actuator, the water discharge test (WDT) was also conducted along with the computational fluid simulation. The results of water discharge measurement obtained by WDT, simulations, and theoretical equations applied to the fluid resupply system constructed were compared with each other to verify the reliability. Consequently, it was confirmed that water discharge can be automatically controlled in real time according to temperature changes of SMA coil springs in the anti-freezing system.



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Keywords: anti-freezing system; fluid resupply system (FRSS); shape memory alloy (SMA); shape memory effect (SME); spring loading test (SLT); water discharge test (WDT)

1. Introduction

SMA called “smart materials” is attracting attention as a key component material of actuators owing to its excellent mechanical properties such as high resilience and suitable weight-to-power ratio until a recent date. In particular, SMA coil springs have been most frequently used as an actuator because of their low production cost relatively. Actuators powered by conventional energy sources such as electricity, hydraulic, and air pressure have also been proposed in various fields; however, they have low energy efficiency and difficulty in mass production, which made that their application range is limited to the operation of small and lightweight components.

To overcome the limitations of these conventional operation methods, we considered the SMA based on Ni-Ti-X systems, which are potential candidates for further progress [1]. The mechanical properties and operational conditions containing the temperature and load at which phase transformation first occurs in the system are different according to the X element content. Thus, it has been applied in various fields depending on the forming method such as welding and casting [2,3]. We previously performed the DSC and confirmed that the temperature at which phase transformation occurs for the first time could be controlled to near sub-zero temperatures depending on the elemental content of cobalt and suggested the use of Ni-Ti-Co SMA coil spring as a small actuator in that study. SMA is also differentiated from other materials because its mechanical properties do not change despite exposure to the water environment and can be used semi-permanently without

the supply of additional energy [4]. The components that used SMA subjected to plastic deformation caused by specific external factors can be restored to the initial shape before the occurrence of the deformation by controlling the temperature, the strength of the load, and the current applied to the alloy. The shape memory effect (SME) related to the recovery property of SMA is a phenomenon in which the alloy returns to the geometry before plastic deformation owing to the occurrence of bidirectional transformation of the austenite and martensitic phases in the alloy when the SMA subjected to plastic deformation is heated to a temperature above the critical point. Pseudoelasticity, which is another property of SMA, refers to a characteristic in which recovery deformation occurs as a load is applied or removed while a constant temperature is maintained for SMA, and it occurs above the austenite finish temperature (A_f). However, because pseudoelasticity occurs only when a specific temperature is maintained, it is not suitable for actuators that enable automatic operation by detecting outside temperature. SME, however, is an essential element for the real-time automatic operation of actuators, as mechanical properties and the crystal arrangement of SMA applying the constant load would be changed according to the outside temperature. That is, if the shape memory effect is utilized to SMA coil springs, it means that the occurrence of spring deflection can be iteratively generated depending on changes in the outside temperature.

Jani et al. [5] explained that actuators using SME have been widely used in various fields and conducted research on the method of applying SMA to vehicles. Fumagalli et al. [6] conducted research on the actuation of Ni-Ti SMA wires and demonstrated that actuators using SMA wire in μm units could operate through fatigue tests with static load according to temperature change. Tiboni et al. [7] designed a pneumatic mini-valve using an SMA spring based on Ni-Ti wires and showed that its operation can be controlled through current. Abhinaba et al. [8] conducted research on the effects of high-tension current and voltage on surface processing geometry in the wire electrical discharge machining (WEDM) process using Ni-Ti-Cu SMA.

As described, it is believed that the initial actuation conditions of actuators can be controlled by using the SMA composed of different chemical compositions. Thus, it is necessary to gradually extend the application range of actuators in each field by continuously devising and developing new actuators to maximize versatility and efficiency.

In recent years, the “Polar Vortex” phenomenon in which the jet stream weakens, and the cold vortex of the North Pole descends south has occurred owing to the reduction in temperature difference between the North Pole and mid-latitudes caused by global warming, thereby increasing the intensity of the cold wave annually. As the minimum outside temperature in winter decreases under the influence of the intensified cold wave, the freezing of industrial and household piping systems is also increasing each year, causing enormous economic losses. Water freezes and its volume expands when the temperature drops below $0\text{ }^{\circ}\text{C}$. Solid water, composed of hexagonal molecular structures joined by hydrogen bonds, expands the volume by approximately 9% to 10% by increasing the distance between molecules during freezing. When the pressure generated by the increase in volume temperatures exceeds the maximum inner pressure of the water pipe, a crack in the inner wall of pipes propagates and results in breakage of the pipe, as shown in Figure 1.

Currently, commercial products for preventing water pipe breakage from freezing are available, including insulation materials, heating devices, and pressure-absorbing members installed in water meters, but they still cannot perfectly prevent freezing. The insulation method, which blocks heat transfer from the outside temperature by wrapping the outer wall of water pipes with insulation materials, contributes to a reduction in freezing rate to some extent, but it is difficult to install insulation materials for all water pipes with a considerable length. The heating wire tracing method, which prevents freezing by installing heating wires on the outside of water pipes exposed to the outside air, can determine the amounts and locations of heating wires for parts vulnerable to freezing [9]. However, heating wires require high power consumption and frequent operation over an extended period of time, which might cause fire accidents. This method might be also less practical

because thorough maintenance is required to achieve the maximum heating wire lifespan of five years, and it is necessary to provide a power source for manual control [10,11].

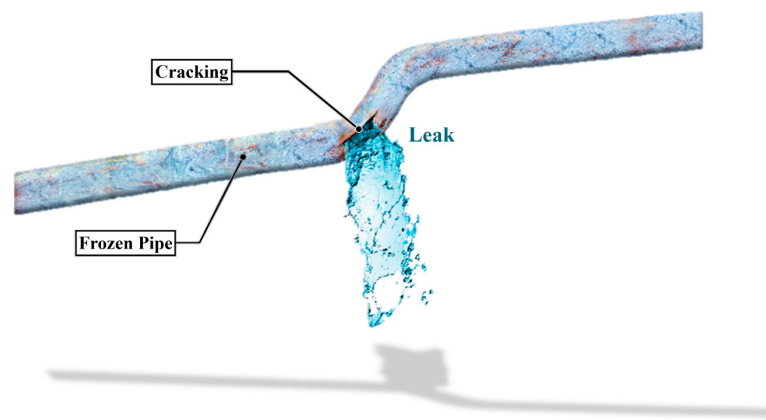


Figure 1. Cracking in pipes caused by volume expansion of water.

Water meters used to measure the amount of water flowing in water pipes cause freezing as the internal pressure increases since water in the meter undergoes a phase transition from liquid to solid at sub-zero temperatures. In response to this problem, recently, a pressure-absorbing member acting as an airbag has been installed inside the meter to prevent freezing of water meters [12]. Other studies have continuously been conducted on actuators using new materials for preventing pipe freezing such as phase-change materials; however, such actuators have difficulty controlling the amount of water discharge in a stable manner and have high manufacturing costs [13]. To address these problems, a new anti-freezing system that is safe and durable with high energy efficiency is required.

Therefore, this study proposes a new anti-freezing system that can automatically prevent the freezing of a pipe in real time using the springs made of Ni-Ti-Co SMA coil springs. SME characteristics of SMA coil springs installed inside the new actuator model were utilized for automatic actuation, and a new anti-freezing system called the “fluid resupply system (FRSS)” was constructed in Figure 2, in which the circulation and discharge of water occurred by installing an anti-freezing valve in the water pipes.

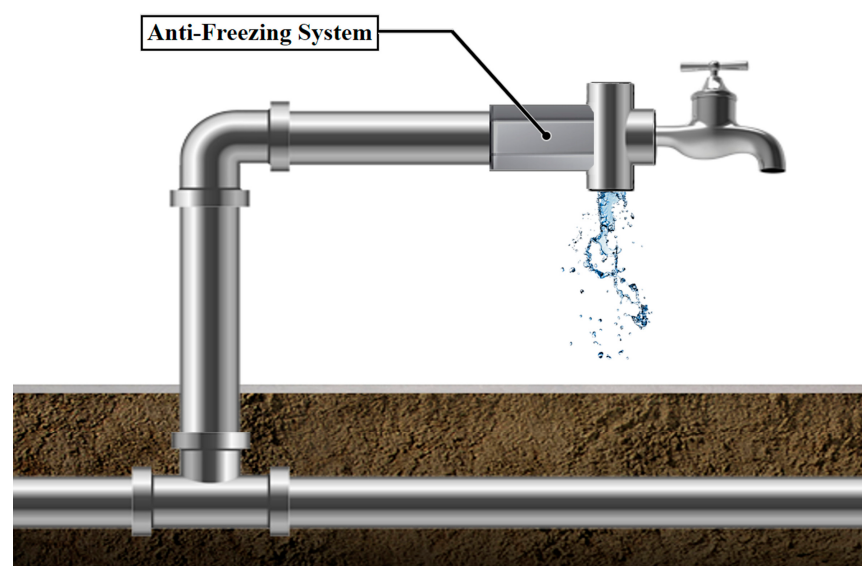


Figure 2. FRSS applied anti-freezing valves using the SMA coil spring.

FRSS is a circulation system that continuously refills the pipes with the amount of fluid discharged through the anti-freezing valves. The new fluid resupply system can

prevent the freezing of water pipes by making water inside the pipe maintain a higher temperature than sub-zero temperatures [14].

Representative cases in which a resupply system using SMA coil springs was constructed include sprinklers for fire prevention. Ras Mathew et al. [15] conducted research on the automatic water discharge control system of a fire prevention sprinkler that used SMA coil springs operation, which starts over 88 °C. Matsui et al. [16] proposed a thermostatic mixing valve capable of automatic water discharge control using SMA coil springs. Reddy et al. [17] conducted research on the method of generating water discharge in real time using solar energy as a power source for the automatic operation of the SMA coil spring actuator. However, it appears that there has been no study on the new anti-freezing system that utilized the SME characteristics of Ni-44.08Ti-1.46Co (wt.%) SMA coil springs to construct the FRSS.

In this paper, the mechanical properties and structural safety of coil springs fabricated using Ni-Ti-Co SMA wires were examined through the spring loading test (SLT) and a non-linear static structural analysis method by evaluating the performance of spring actuation. In addition, the water discharge test (WDT) and computational fluid simulation were conducted to determine the feasibility of controlling the amount of water discharge according to temperatures of the SMA coil springs and were compared with the values calculated through the theoretical equations.

2. Design and Fabrication of SMA Springs

2.1. SMA Alloys

The existence of SMA was first revealed when Olander Arne of the University of California conducted research on the electrochemical reaction of an alloy composed of cadmium and gold. Later, the Naval Ordnance Laboratory produced the alloys with nickel as the main element and named it “Nitinol” and then specified the SME characteristics of Ni-Ti SMA. Research on the pseudoelasticity and SME characteristics of Ni-Ti-Co SMA has been actively conducted along with its application in various industries. Recently, it was found that Ni-Ti-Co alloys have a relatively higher yield strength at a low temperature, and the phase transition also occurs at lower temperatures than Ni-Ti alloys [18,19]. Therefore, it was determined to use the SMA considering the transformation initiation temperature, which means the shape or crystal structure of a metal changes from one state to another without changing the chemical composition; the materials for actuators and the chemical composition of the fabricated SMA wire are shown in Table 1.

Table 1. Chemical composition of the fabricated SMA wires.

Composition	Ni	Ti	Co
wt.%	54.46	44.08	1.46

2.2. Design and Fabrication

Experiments and simulations are essentially required to identify the mechanical properties of the Ni-Ti-Co SMA coil springs since there is no metal standard available for the alloy used. By this token, the SMA coil springs were designed prior to experiments and simulation in accordance with Korean Industrial Standard (KS) [20–22]. After the drawings and design parameters of the SMA coil springs shown in Figure 3 and Table 2 were determined, the prototypes of SMA coil springs were fabricated for the SLT to obtain the spring constant values and evaluate the performance of the SMA coil springs. The Ni-Ti-Co SMA wire, which was the raw material, was used to create the spring shape through a spring forming machine, shown in Figure 4, and it was subjected to natural aging after annealing in a furnace at 490 °C for 30 min. The heat treatment temperature was designated in view of the precipitation of nickel for hardening-related transformation temperature so that the transformation initiation temperature could be between 0 °C and 5 °C.

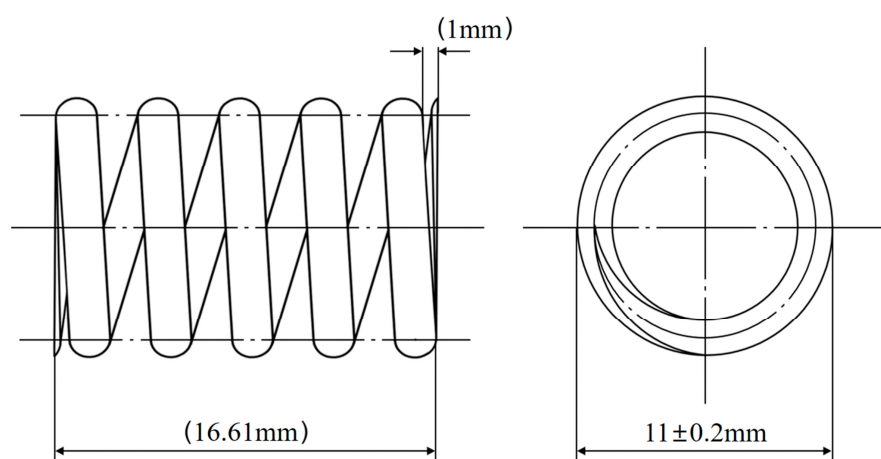


Figure 3. Geometry of SMA coil springs.

Table 2. Design parameters of SMA coil springs.

Parameters	Symbols	Values	Units
Total No. of coils	N_t	6	turns
No. of active coils	N_a	4	turns
No. of turns on the left edge	N_l	1	turns
No. of turns on the right edge	N_r	1	turns
Wire diameter	d	1.5	mm
Inside diameter	D_i	8	mm
Outside diameter	D_o	11	mm
Mean diameter of coil	D	9.5	mm
Height	H_t	16.61	mm
Pitch	p	3	mm
Pitch angle	α	5.08	degree
Spring index	C	6.33	-
Poisson's ratio	ν	0.33	-



Figure 4. Fabrication process of Ni-Ti-Co SMA coil springs.

3. Experimental Measurement of SMA Springs

3.1. Spring Loading Test

When the outside temperature changes from room temperature to sub-zero temperatures, the spring constant value varies as a phase transition occurs inside the SMA coil spring. This means that the spring deflection would also vary according to the temperature changes when a certain level of water pressure acts on the SMA coil spring in a pipe. Therefore, the changed spring constant values related to temperature changes of SMA

coil spring were judged to be the main factor for water discharge control. Thus, SLT was conducted to measure the SMA coil spring constant.

An SLT machine and a cooling chamber (MTDI Inc. Daejeong, Korea) shown in Figure 5 were used to obtain the spring constant data of SMA coil springs. A cooling chamber that included control devices such as a temperature display window and control levers was used to vary the temperature of the SMA coil spring. On the temperature display window, the temperature value of SMA coil springs was displayed over time. Four control levers inside the cooling chamber ensure that different functions such as lighting, cooling, heating, and power could be controlled individually.

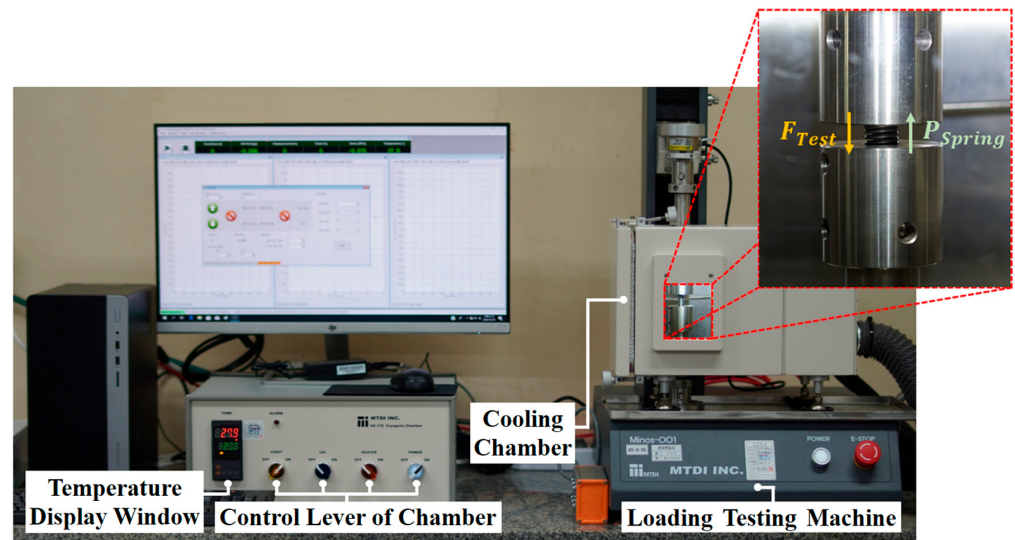


Figure 5. Experimentation setup for SMA coil spring characterization.

As for the test method to measure the SMA coil spring constant, the load tester and cooling chamber equipment were turned on and then stabilized for 30 min. After that, the SMA coil spring was set on the guide shaft, and zero-point adjustment was performed so that the spring could move to the point of contact with the jig. Test conditions, including the load, temperature, time, and data storage path, were entered into the program before starting the SLT. The static load of 1.6 kgf was continuously applied in the spring compression direction, and the spring constant was measured while the temperature of the SMA coil spring varied from $-10\text{ }^{\circ}\text{C}$ to $20\text{ }^{\circ}\text{C}$. The SMA coil spring, which was fabricated based on the design parameters in Table 2, was used in the SLT. During the SLT, the spring constant was measured using Hooke's law in real time by detecting the spring deflection based on the initial set point of 0 mm and the static load value of 1.6 kgf.

3.2. Results of Spring Loading Test

The spring constant and deflection values of the SMA coil spring measured through the SLT according to temperature changes are shown in Figure 6 and Table 3. It was found that the spring constant measured is averagely proportional to the temperature and inversely proportional to the deflection value. Therefore, when the temperature of the SMA coil spring is slowly reduced by the outside temperature, and constant water pressure is consistently applied in the pipe, it seems to decrease numerically due to the recovery properties of SMA coil springs, although spring constant values do not change in reality. It can be predicted that the spring constant later calculated will continue to decrease with the increase in the spring deflection. The modulus of elasticity according to temperatures values shown in Figure 6 could be calculated using spring constant values on SMA coil springs fabricated in accordance with KS using Equations (1) and (2) [20]. The obtained modulus of elasticity values on the SMA coil spring were used when the structural analysis

was conducted, to calculate the spring deflection in the y-axis direction and von Mises stress distribution.

$$k = \frac{F}{\delta} = \frac{Gd^4}{8N_a D^3} \quad (1)$$

$$G = \frac{E}{2(1 + \nu)} \quad (2)$$

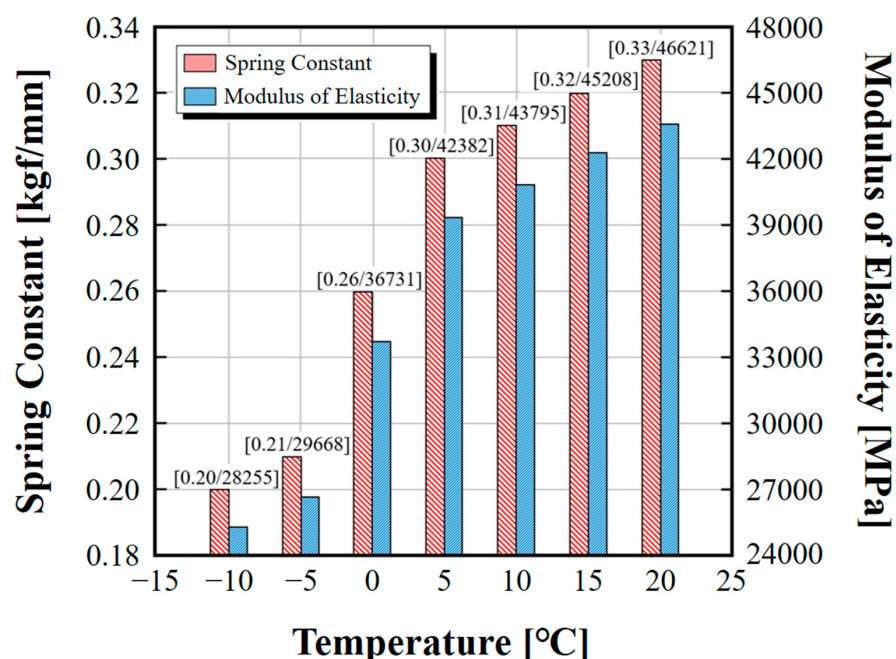


Figure 6. Results of spring loading test.

Table 3. Deflection of SMA coil springs according to temperatures.

Temperature [°C]		−10	−5	0	5	10	15	20
Deflection [mm]	Experiment	7.98	7.24	6.18	5.43	5.0	4.78	4.7
	Theoretical	8.00	7.62	6.15	5.33	5.16	4.99	4.85

Here, k is the spring constant, G is the stiffness coefficient, E is the modulus of elasticity, N_a is the number of active coils, D is the mean diameter of the coil, d is the diameter of the wire, ν is Poisson's ratio, F is the static load applied on the spring, and δ is the spring deflection in the y-axis direction. When the spring constant is determined for each temperature, the deflection of the SMA coil spring according to the static load applied on the spring can be theoretically calculated using Equation (1).

The maximum deflection value of the SMA coil spring according to the temperature changes was measured to be 3.28 mm by the SLT and calculated as 8.00 mm using the theoretical equations. In the spring deflection values, the difference between the SLT test value and the calculated values obtained by the theoretical equations was about 4.81 mm on average. This is expected due to not adding the recovery force of the Ni-Ti-Co SMA coil spring according to temperatures in the calculated theoretical equations, and for accurate prediction, a new equation is derived to obtain the recovery force of the Ni-44.08Ti-1.46Co (wt.%) SMA coil spring. Regarding the experimental value for the spring y-axis deflection, it can be calculated that the maximum recovery force in the y-axis direction of the spring occurs for a static load of 1.6 kgf, with a maximum value of 1.6 kgf at 20 °C and a minimum value of 0.94 kgf at −10 °C. As the temperature dropped from 20 °C to −10 °C, the recovery force of springs decreased.

4. Actuation Evaluation of SMA Springs Using Structural Analysis

4.1. Model and Boundary Conditions of Structural Analysis

A non-linear static structural analysis was conducted to evaluate the structural stability and to calculate the spring deflection values in the y-axis direction according to the temperatures of the previously designed and fabricated SMA coil springs. To achieve these, the calculated elastic modulus values were input as the initial mechanical property condition of the SMA coil spring in the structural analysis program of ANSYS, Inc. (Canonsburg, PA, USA) called the static structural module V20. Except for the elastic modulus values of the SMA coil spring, the entire model used for the analysis was input based on the mechanical properties of STS304.

The prototype of anti-freezing valves combined the disc, cap, and SMA coil spring with the models for structural analysis, which are shown schematically in Figure 7. Disc and cap were set the same outer radius of 9 mm, which coincides with the inner diameter of anti-freezing valves. The total heights of the disc and cap are 10 mm and 7 mm, respectively. The height and angle of the protruding part on the disc for controlling the amount of water discharge are 5 mm and 63.4 degrees. For stable coupling with SMA coil springs, the inner and outer diameters of the joints with a depth of 3 mm were set to 7.9 mm and 11.10 mm on the disc and cap. These are the values designed after setting the dimensional tolerance to 0.1 mm, considering the inner and outer diameters of the SMA coil spring when combining parts. The radius of holes on the disc and cap was set to 1 mm for efficient discharging. The number and radius of disc holes, the height, and angle of the disc protrusion, and the height of the inner joint were expected to affect the structural analysis results. In order to minimize the analysis time, the shape of the analytical models was simplified.

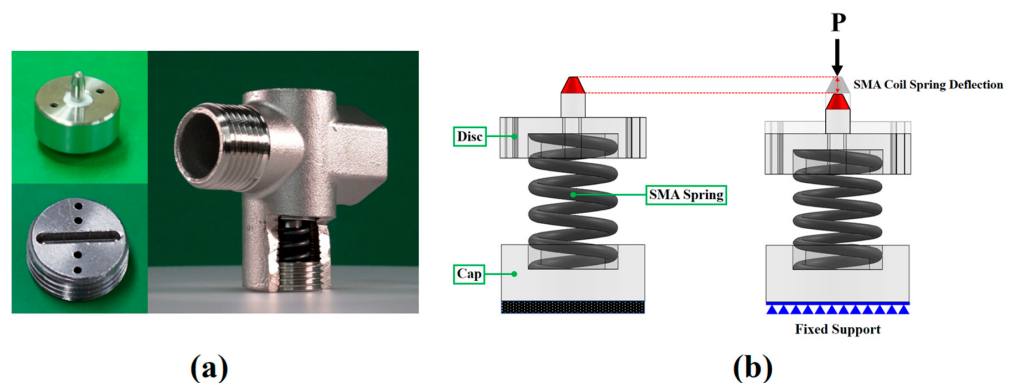


Figure 7. Application of fabricated SMA coil springs for anti-freezing system: (a) anti-freezing valves combined SMA coil springs; (b) schematics of the model and boundary conditions in structural analysis.

As regards the boundary conditions for structural analysis, specific water pressure values of 3 bars, 4 bars, and 5 bars due to the internal flow in the water pipe were applied to the protrusion parts of the disc. As the purpose of this study is to precisely control the amount of water discharge through the generation of deflection in the y-axis direction on SMA coil springs, the minimum pressure condition was set as 0.306 kgf/mm^2 .

The fixed support condition was applied at the lower end of the cap considering that the cap itself was fixed with anti-freezing valves by means of a screw thread. In the structural analysis to obtain the deflection of SMA coil springs, the data were input differently considering that the values of the elastic modulus, a major variable among the mechanical properties of the spring, would be changed according to temperatures, and the mechanical property data of the remaining parts were entered based on STS304.

Thus, a finite element model composed of elements and nodes was constructed, and non-linear static structural analysis was performed. As a result, we could obtain the values for spring deflection and von Mises stress distribution of the SMA coil spring to evaluate the structural stability and operability.

4.2. Results of Structural Analysis

Through structural analysis, the deflection in the y-axis direction and von Mises stress occurring in the SMA coil springs were calculated and are shown in Figures 8 and 9. The results of the graph in Figure 8 are regarding the deflection in the y-axis direction that occurred in the SMA coil spring when a pressure of 3 bars was completely transferred, and the values tend to be inversely proportional to the temperature. The minimum deflection values of SMA coil springs were calculated to be 0.53 mm at 3 bars, 0.7 mm at 4 bars, and 0.88 mm at 5 bars, respectively. These are the results obtained by increasing the deflection of SMA coil springs by adding the weight of the disc. Assuming the weight of the disc is removed, the deflection values derived from the theoretical formula would be 0.09 mm at 3 bars, 0.12 mm at 4 bars, and 0.15 mm at 5 bars.

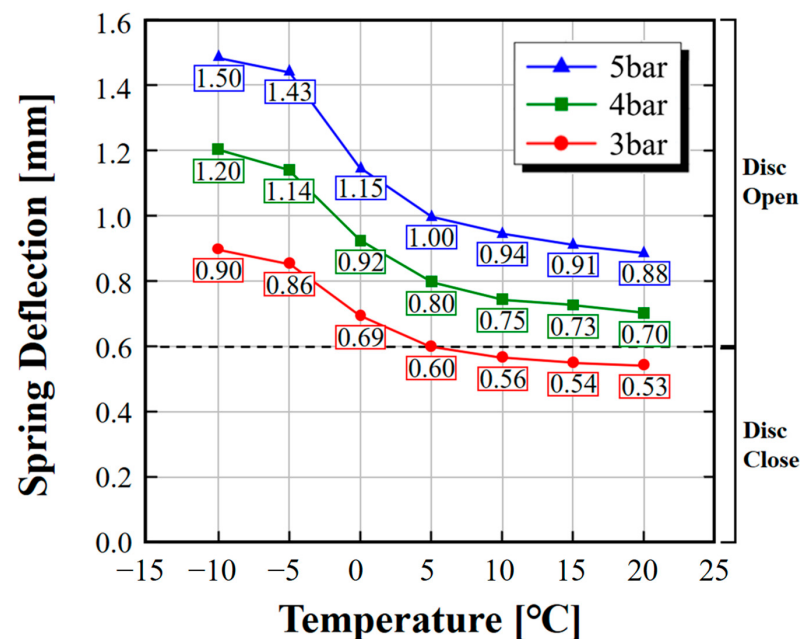


Figure 8. Spring deflection values according to temperature changes and water pressure levels.

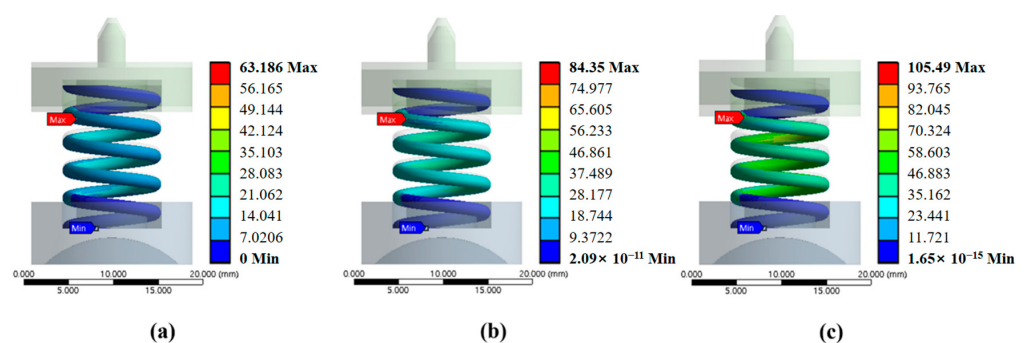


Figure 9. Von-Mises stress distribution of SMA coil springs applied the specific water pressure conditions to the top part of disc protrusion: (a) 3 bars; (b) 4 bars; (c) 5 bars.

The maximum von Mises stress values were calculated to be 63.168 MPa at 3 bars, 84.35 MPa at 4 bars, and 105.49 MPa at 5 bars on the point near the joints with the disc of SMA coil springs according to the pressure conditions, which are shown in Figure 9. In the SLT using the SMA coil spring, yielding did not occur up to the uniformly distributed load of 1.6 kgf, so it seems unlikely yielding will occur under the pressure condition from 3 bars to 5 bars.

The actual deflection values of SMA coil springs caused by water pressure inside the pipe are expected to be lower than analytical and theoretical values because the load is

distributed by the angle of disc protrusion. This means that the load distribution of SMA coil springs can be controlled by adjusting the angle of disc protrusion.

As a result, it is found that the SMA coil springs proposed in this study are suitable for stable actuation even at water pressure between 3 bars and 5 bars or less. Based on the fact that the minimum deflection of SMA coil springs occurred with the pressure level of 3 bars, FRSS was established and WDT was conducted to investigate the possibility of precise control in water discharge and freeze prevention through the anti-freezing system combined with SMA coil springs. In addition, the height of the disc is increased more by 0.2 mm at 4 bars and by 0.4 mm at 5 bars from original models, indicating that the model could be a solution to controlling the amount of water discharge according to water pressure applied to the disc.

5. Application of Anti-Freezing Systems to Water Pipeline

5.1. Actuation Evaluation of Anti-Freezing Systems

In this study, computational fluid simulation was performed under the same conditions as those for the model used in the WDT to secure the reliability of the measured results. Furthermore, the amount of water discharge calculated for each temperature in the fluid analysis was compared with the experimental data to secure reliability through additional verification.

5.1.1. Theoretical Method

The mass flow rate value of 0.1903 kg/s was derived from the mass flow rate at a flow velocity of 1.308 m/s using Equation (4), called the Darcy-Weisbach Equation, and Equation (5), called the law of mass conservation; it was applied to the inlet of pipes [23,24].

$$\dot{m} = \rho VA = \dot{m}_{in} = \dot{m}_{out} \quad (3)$$

$$\Delta P = \frac{\lambda \rho LV^2}{2D} \quad (4)$$

$$\dot{m}_w = \sqrt{\frac{2\rho_w \Delta P A^2 D}{\lambda L_p}} \quad (5)$$

To consider the friction loss according to the entire length of pipes, the friction coefficient of pipes was calculated for each using Equation (4). Through the application of Equation (3) to (4), Equation (5) that represents the relationship between the pressure difference of inlet–outlet and the mass flow rate was derived. The flow velocity at the outlet was obtained by applying Equation (5) to the mass flow rate according to temperatures measured in the WDT. If the values of ΔP are assumed to be constant at 3 bars, the unreliable results that would be obtained owing to the friction coefficient of pipes could also vary depending on the mass flow rate.

Therefore, the flow velocity at the outlet was calculated based on water discharge measured at 5 °C in WDT. In this instance, the friction coefficient values of the pipe were calculated by designating the water pressure difference between the inlet and outlet as 1 Pa. The actual flow velocity at the outlet, V_o , which corresponds to the mass flow rate measured in the WDT, was also calculated using Equation (4). Based on the calculated values of flow velocity, the pressure P_o that acts on the top of the disc as it opens and subsequent theoretical values of the amount of water discharge were also obtained using Equations (4) and (5).

5.1.2. Calculation of Water Discharge Using Fluid Analysis

The analytical FRSS model for the fluid analysis was designed with the same geometry, as shown in Figure 10. The finite element modeling was created of the 32,238,420 nodes and 23,504,482 elements considering that the outlet of anti-freezing systems is narrow for water discharge.

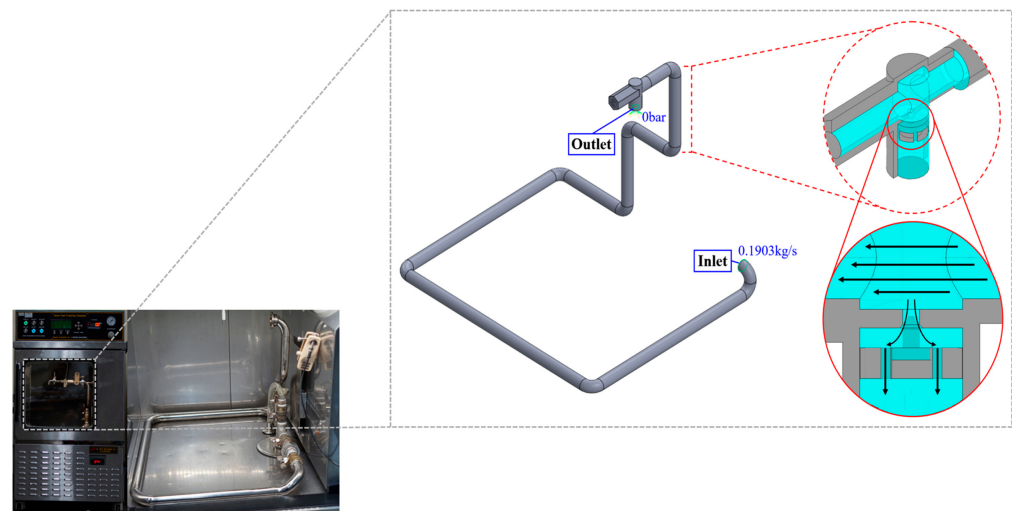


Figure 10. Schematics of the model and boundary conditions for fluid analysis.

As for boundary conditions for the fluid analysis, water pressure of 3 bars was applied to the entire inside of pipes, and the fluid was assumed to be turbulent flow. A static pressure condition of 0 bar was assigned to the outlet of anti-freezing systems. In the fluid analysis program of ANSYS, Inc. (Canonsburg, PA, USA) called the CFX module, a relatively accurate and stable fluid analysis is possible when the boundary conditions such as mass flow rate or flow velocity, rather than pressure conditions, are applied to the inlet of a pipe [25,26].

To verify the accurate values of the mass flow rate obtained through the theoretical equation, the fluid analysis was first performed for water pipes without the anti-freezing system, and the error rate between the theoretical and analytical values for the mass flow rate was calculated to be less than 1% when a pressure of 3 bars was applied as the boundary condition on the inlet of pipes.

Then, a computational fluid simulation was performed again based on the models using the setting shown in Figure 11 to compare the values of mass flow rate calculated on the outlet, using the theoretical equation, with the results of water discharge measured through the WDT, which installed the FRSS used SMA coil spring for the actuation of anti-freezing systems.

5.2. Water Discharge Experiments

In order to verify the functionality and practicality of SMA coil springs as an actuator for freeze protection, the prototype of anti-freezing systems was applied to an actual pipe, and the WDT was conducted. The pipe used for the WDT had an inner diameter of 13.31 mm and a total length of 1850 mm.

The built FRSS was put into the chamber during the WDT, and the temperature was changed to measure the amount of water discharge. After the target temperature was set at 5 °C, the time taken for the temperature to decrease from 20 °C to 5 °C was set to 30 min and cooled slowly. The cooling time was set to 10 min, and the experiment was performed again after changing the target temperature to 0 °C. It was confirmed that the start of water discharge occurred while the temperature in the chamber decreased from 5 °C to 0 °C. For accurate water discharge measurement, water discharge per minute was measured through the anti-freezing system immediately when the temperature in the chamber reached the set target temperature, with the flow rate stabilization time for 30 min. The target temperature interval in the chamber was set at 5 °C. Additionally, the temperature was gradually decreased from 20 °C to −10 °C. In addition, the amount of water discharge according to the temperature was measured 7 times each through the 10 repeated experiments.

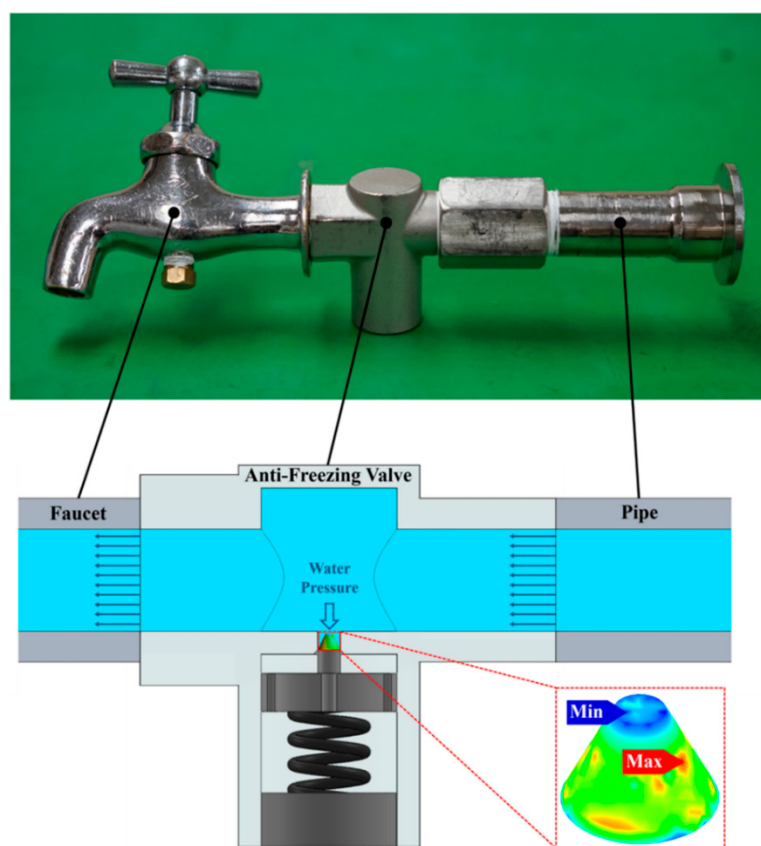


Figure 11. Application of anti-freezing systems to water pipeline.

The results confirmed that the anti-freezing system did not operate above 5 °C, and the amount of water discharge per minute measured tended to decrease in proportion to the temperature of the chamber. By analyzing the data of WDT results shown in Table 4, it was also found that it is possible to prevent freezing of water pipe by using the constructed FRSS. Although it was confirmed that water discharge occurs at the sub-zero temperature without freezing, it is necessary to accurately verify the amount of discharged water according to temperatures. Consequently, the flow analysis was performed with the aim of comparing the calculated simulation and theoretical values with the measured amount of water discharge through WDT.

Table 4. Fluid characteristic values through the anti-freezing system.

Symbol	T_0	$\dot{m}_0$	V_0	P_0
Units	°C	mL/min	m/s	bar
Theoretical Values	5	1	0.0011	2.999
	0	18	0.0203	2.982
	−5	30	0.0567	2.951
	−10	53	0.0614	2.946
Simulation Values	5	1.7	0.0019	2.999
	0	17.5	0.0202	2.989
	−5	49	0.0568	2.917
	−10	54	0.0625	2.899
Experiments	5	1	0.0016	2.999
	0	17	0.0197	2.971
	−5	30	0.0347	2.901
	−10	53	0.0613	2.719

6. Results

The reliability of the fluid analysis was then secured by comparing the simulation results with the values of mass flow rate shown in Figure 12 obtained through the theoretical equations and WDT. When the temperature of the SMA coil spring was higher than 5 °C, the mass flow rate of the outlet of the anti-freezing system converged to 0 mL/min. This is because the mass flow rate of the outlet was calculated to be 0 mL/min at the temperature of SMA coil springs higher than 5 °C, as the value of ΔP was 0 bar.

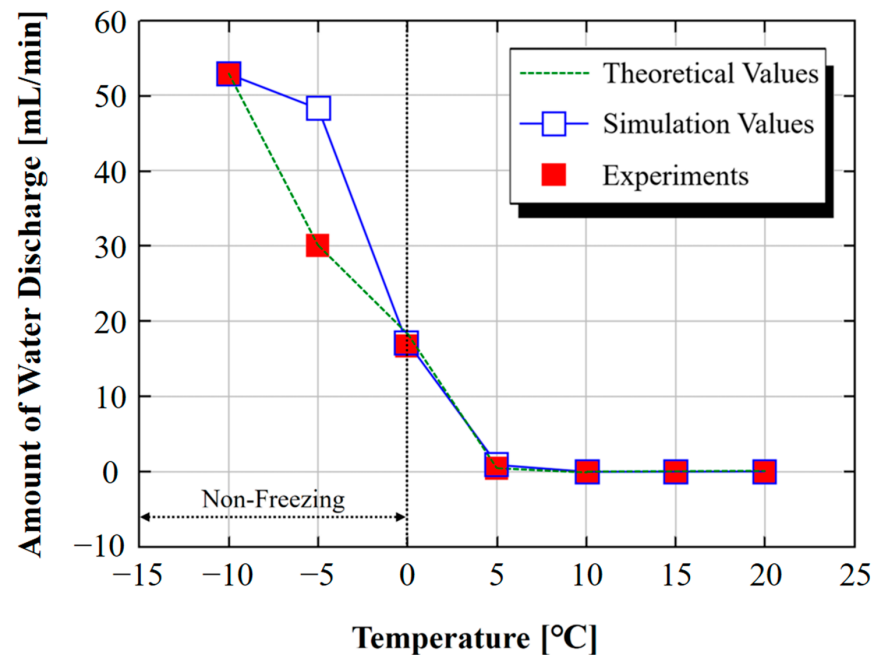


Figure 12. Comparison of the result data according to water discharge measurement methods.

In addition, a spring deflection of 0.6 mm or more occurs when the temperature of SMA coil springs is 5 °C or less, and it can be also confirmed that water is discharged through anti-freezing systems. Therefore, it has been proven, through the WDT, that the FRSS constructed using anti-freezing systems can prevent the freezing of a pipe below sub-zero temperatures. As the temperature of SMA coil springs decreased, water discharge through anti-freezing systems showed a tendency to increase, and the maximum amount of water discharge occurred at 10 °C. The result of WDT performed earlier showed a similar tendency regarding the amount of water discharge calculated using theoretical equations and computational fluid simulation performed later. The computational fluid simulation and the experimental values calculated for the amount of water discharge differ by about 20 mL/min at −5 °C. Both the theoretical equation and the computational fluid simulation in the water discharge calculation were measured based on the experimentally derived spring constant k and water discharge. The reason for the difference between the simulation and the experimental values is that the y -axis deflection of springs was calculated based on the spring constant k , which changes according to the temperature when the simulation was performed, while the water discharge was calculated based on the flow rate measured in the experiment when calculating the theoretical equation. This problem can be solved by applying new equations for the measurement of the amount of water discharge due to the recovery force changes in SMA coil springs that act conversely to the static load applied.

7. Discussion

To examine the hypothesis that the initial actuation temperature condition can be controlled using SMA coil springs composed of different chemical compositions, actual experiments and simulations were conducted to measure the results of water discharge.

As a result, anti-freezing systems using SMA coil springs actuated below the 5 °C, and it was also found the pipe was not frozen through the constructed FRSS [14].

It can be predicted that the starting temperature of phase transformation in the inner SMA coil springs at 3 bars, fabricated with the chemical composition ratio of Ni-44.08Ti-1.46Co used in this study, is about 4 °C. It is assessed that the operable temperature range of the SMA coil spring as actuators can be extended by analyzing the effect of the cobalt composition change on the transformation initiation temperature and mechanical properties of the SMA. The possibility of setting transformation initiation temperatures by controlling the chemical composition ratio of nickel called “austenite stabilization element” while maintaining the chemical composition of cobalt in SMA can also be a method for controlling actuation according to the temperatures. Regarding the bidirectional phase transformation of SMA, it is believed that the recovery force is determined by the ratio of austenite and martensite in the SMA alloy according to the temperature, and the directionality during phase transformation can also be a major factor.

When the entire phase in the SMA is converted to martensite, and recovery force is applied relatively weaker than before, the spring deflection is expected to remain constant. Thus, a study with additional spring deflection experiments on constant water discharge is essential.

Design variables that directly affect the control of water discharge in the anti-freezing system include the upper angle of the disc, the number of holes in direct contact with water, the structural shape of the cap considering insulation, the additional parts blocking the contact between water and SMA coil springs, etc. could be considered. In particular, it should be considered that the contact between water and SMA coil springs must be avoided for stable control of water discharge. Except for the very small amount of water discharge as the spring deflection occurs, the weight of water filling up on the upper part of the disc in the anti-freezing system can also be a major variable.

8. Conclusions

In this study, the reviews related to the actuation control possibility of anti-freezing systems below sub-zero temperatures were performed to prevent the cracking of a pipe caused by the volume expansion during freezing of water. The results of the study should be summarized as follows:

- (1) It was confirmed that anti-freezing systems proposed using Ni-44.08Ti-1.46Co (wt.%) SMA coil spring actuates near the sub-zero temperature to prevent freezing of water. The results of WDT and fluid analysis showed that water discharge started at 5 °C and increased as the temperature of SMA coil springs decreased. The freezing phenomenon of a pipe did not occur even with water discharge of 18 mL/min at 0 °C. Consequently, the design of optimal anti-freezing systems is possible based on minimum water discharge that can prevent freezing of water.
- (2) The results of SLT showed that the different recovery forces according to changes in temperature work due to the SME of springs. When a static load of 1.6 kgf was applied to the SMA coil spring, a maximum deflection of 3.28 mm at −10 °C occurred. The deflection measurement value at −5 °C differed from the value predicted using the theoretical equations by 5.08 mm, and the reason for this difference is that the change in static load due to the recovery force of the SMA coil spring could not be considered when using the theoretical equations for the measurement of spring deflection. It can be seen that the recovery force is more than 1.56 kgf at 5 °C and 0.94 kgf at −10 °C, resulting from theoretical equations that consider the recovery force.
- (3) Water discharge was suddenly stopped due to the contact between water and SMA coil springs when water discharge occurred in the anti-freezing system at the temperature of 5 °C or less. Based on the results of this experiment, it is assessed that there should be a structural change in the anti-freezing system that can block the contact between the SMA coil spring and discharged water. The structural shape and

chemical composition ratio of automatically actuated anti-freezing systems can be optimized in further research.

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