Automatic Circulation Control of Working Fluid in Liquid Droplet Radiator

By Tsuyoshi TOTANI¹⁾, Takuhiro TAKEKOSHI²⁾, Masashi WAKITA¹⁾ and Harunori NAGATA¹⁾

¹⁾Faculty of Engineering, Hokkaido University, Sapporo, Japan

²⁾Graduate School of Engineering, Hokkaido University, Sapporo, Japan

(Received June 24th, 2011)

Liquid Droplet Radiator (LDR) is an important candidate for disposing large quantities of waste heat more than 1 MW which will be handled by large space structures such as Space Power Satellite. The working fluid is heated through a heat exchanger by the waste heat generated in a large structure in space. Then, the working fluid is emitted in space through nozzles of the droplet generator toward a droplet collector as multiple streams of droplets. During the flight in space, the droplets lose thermal energy via radiative heat transfer. After the cooled droplets are captured by the droplet collector, the working fluid is recycled to the heat exchanger by a circulating pump. The automatic control system on the circulation of working fluid in a liquid droplet radiator has been built using a programmable logic controller. The proportional control of flow rate with the term of the variation of the counter flow in the gear pump and the relaxation of the change of a target flow rate has succeeded within 5 percent at the automatic circulation control of the working fluid from 100 ml/min to 200 ml/min and from 200 ml/min to 100 ml/min.

Key Words: Radiator, Circulation Control, Liquid Droplet Radiator, Automatic Control

Nomenclature

A : cross-section area of pipe, m
 c : specific value to the shape and the arrangement of the pipe in centrifugal collector, -, (= 0.90 in this study)
 C_a : relaxation coefficient of pressure P_6 , -
 C_l : relaxation coefficient of leak coefficient, -
 C_Q : relaxation coefficient of flow rate, -
 E_l : total loss head of pipe from centrifugal collector to gear pump, m
 f : rotational frequency of centrifugal collector, rpm
 g : acceleration of gravity, m/s²
 K_p : gain of proportional control, -
 M_l : variation of counter flow, m³
 N : number of revolution, rpm
 P_1 : pressure in droplet generator, Pa
 P_2 : pressure at upward of gear pump, Pa
 P_3 : pressure at downward of gear pump, Pa
 P_4 : pressure in vacuum chamber, Pa
 P_5 : pressure of working fluid inside bellows, Pa
 P_6 : pressure of nitrogen gas outside bellows, Pa
 P_k : pressure from spring force of bellows, Pa
 P_{kin} : dynamic pressure of working fluid, Pa
 P_l : pressure loss between bellows pressure regulator and droplet generator, Pa
 P_m : pressure from mass of bottom cover and bellows, Pa
 Q : volumetric flow rate, ml/s
 R : leak coefficient, m³
 r_e : radius of entrance of stationary tube in droplet collector, m
 r_i : radius of inner surface of working fluid in

droplet collector, m
 t_a : control time of under-relaxation, s
 U_{th} : theoretical discharge rate per one rotation of gears, ml/rev, (= 1 ml/rev in this study)
 ζ_i : coefficient of loss at inlet of pipe, -
 η_f : friction coefficient inside pipe, s/m²
 η_i : pressure loss in entrance length of nozzle, s/m²
 η_j : pressure loss at the inlet of nozzle, s²/m⁵
 ρ : density, kg/m³
 μ : viscosity, Pa·s

Subscripts

cal : calculated value
 ex : experimental value
 n : n th cycle of control
 $target$: target of volumetric flow rate

1. Introduction

Disposing of large quantities of waste heat is one of the technical issues that must be resolved in order to realize large space structures, which handle high power (from megawatts to gigawatts), such as Solar Power Satellites. A liquid droplet radiator (LDR) is an important candidate for resolving this issue. Its lightweight structure, high resistance to meteorite impacts, small storage volume at launch and easy deployment in space make it a very attractive heat rejection system¹⁾.

LDR, which consists of a droplet generator, a droplet collector, a circulating pump and a heat exchanger, circulates working fluid as shown in Fig. 1. The working fluid is heated through a heat exchanger by the waste heat generated in a large structure in space. Then, the working fluid is emitted in space through nozzles of the droplet generator toward a

Fig. 1. Schematic diagram of liquid droplet radiator.

Fig. 2. Image of experimental setup.

Fig. 3. Schematic diagram of experimental setup.

droplet collector as multiple streams of droplets. During the flight in space from the droplet generator to the droplet collector, the droplets lose thermal energy by radiative heat transfer. After the cooled droplets are captured by the droplet collector, the working fluid is flowed to the heat exchanger by a circulating pump.

Fig. 4. Schematic diagram of droplet generator.

Fig. 5. Schematic diagram of nozzle.

The minutes-order adjustments of circulating volume of the working fluid are required to correspond to the fluctuation of the quantities of waste heat in a large space structure. The automatic control on the circulation of working fluid is an essential in LDR.

Totani et. al. have clarified the circulation mechanism of the working fluid in LDR, which consists of a droplet generator, a droplet collector, a gear pump and a bellows-type pressure regulator, by numerical analyses and experiments²⁾. They have showed that the circulation mechanism allows to control manually the circulation of working fluid in the liquid droplet radiator. Few studies have been carried out on the automatic control of the circulation of working fluid in the LDR except the group of authors³⁾.

2. Experimental

2.1. Experimental setup

An image of an experimental setup is shown in Fig.2. Figure 3 is a schematic diagram of an experimental setup. The working fluid flows in order of ①②③④⑤⑥⑤① indicated in Fig.3. The volume of the working fluid in droplet collector ② and in bellows-type pressure regulator ⑤ could change. Two flow meters ④⑥ are set between droplet collector ② and bellows-type pressure regulator ⑤, respectively. In the case that the flow rate at flow meter ④ is more than that at flow meter ⑥, the difference volume of the working fluid is supplied from ② and is stored in ⑤. In the case that the flow rate at flow meter ⑥ is more than that at flow meter ④, the difference volume of the working fluid is supplied from bellows pressure regulator ⑤ and is pooled in droplet collector ②. In the case that the flow rate at flow meter ④ are equal to that at flow meter ⑥, the circulation of the working fluid in the experimental setup is achieved. Shin-Etsu Silicone KF-96 10cSt is used as the working fluid in this study.

2.2. Droplet generator

Figure 4 shows a schematic diagram of a droplet generator. The working fluid, which is pressurized by a bellows-type pressure regulator, is subjected to a pressure disturbance using

Fig. 6. Schematic diagram and image of centrifugal collector.

Fig. 7. Schematic diagram of centrifugal collector from top view.

a piezoelectric vibrator in the droplet generator and then is emitted in a vacuum chamber ③ through the nozzle with a single hole, as shown in Fig.5. The pressure disturbance produces radial variation on the surface of a cylindrical jet-shaped working fluid. The amplitude of this radial variation grows under certain conditions⁴⁾. This growth of radial variation causes the working fluid to break up from a jet into tiny droplets.

It is known that the pressure in the droplet generator P_1 required to emit the working fluid with the quantity of flow Q from the nozzle is expressed by the following equation²⁾,

$$P_1 = \rho g \left(\eta_j \left(1 + \frac{1}{2\zeta_i} \right) Q^2 + (\eta_f + \eta_i) Q \right) + P_4. \quad (1)$$

Table 1. Values of constants in Eq.(1).

ζ_i	0.25
η_f	$7.962 \times 10^5 \text{ s/m}^2$
η_i	$4.164 \times 10^5 \text{ s/m}^2$
η_j	$1.610 \times 10^{12} \text{ s}^2/\text{m}^5$

2.3. Droplet collector

Droplet collectors for LDRs must have two functions. One is to capture incident droplets without splashing or separating of the working fluid from a droplet collector because splashing or separating leads to the loss of working fluid in space. The other is to pump working fluid into a circulating pump for establishing fluid circulation because droplet collectors are exposed to space with a high vacuum environment. The centrifugal collector shown in Fig.6 captures incident droplets at the liquid film inside a spinning cone. The liquid film is formed because incident droplets migrate radially outward due to the centrifugal force. The working fluid flows out through

Fig. 8. Image and schematic diagram of gear pump.

the stationary pipe that is immersed in a rotating liquid pool. The working fluid is pushed out by the pressure produced by the centrifugal force and the momentum generated by the rotation of the spinning cone.

The rotational frequency of the centrifugal collector f required in order to pump the working fluid with the quantity of flow Q from the centrifugal collector through the pipe with the total loss head E_l to the gear pump is shown as follows²⁾,

$$f = \frac{60}{c \cdot 2\pi} \sqrt{\frac{2g \left(\frac{1}{2g} \left(\frac{Q}{A} \right)^2 + E_l \right)}{(2r_e^2 - r_i^2)}}. \quad (2)$$

r_i is decided in such a way that the volume of the working fluid pressed against the wall by the rotation of the droplet collector equals to the volume of the working fluid in the droplet collector.

2.4. Gear pump

A gear pump is adopted as the circulating pump in the present work because it is small and can push out the working fluid under large pressure difference between upstream and downstream of the gear pump. A schematic diagram of a gear pump is shown in Fig.8. The working fluid is pushed out by the revolution of gears. Gear pump SK1-213 (Shimadzu Corporation) has been used in this study.

The number of revolution N [rpm] enough to pump the working fluid with the volumetric flow rate Q [ml/s] against the pressure difference between upstream and downstream of the gear pump ($=P_3-P_2$) is expressed by,

$$N = \frac{60}{U_{th}} \left(Q + R \frac{P_3 - P_2}{\mu} \right). \quad (3)$$

As shown in Fig.8, there is the clearance between the gear and the outside housing case of a gear pump because of self-lubricating and the rotation of a gear. The second term in the right-hand side in Eq.(3) indicates the flow rate reversing from downstream to upstream of the gear pump through the clearance. The leak coefficient R depends on the viscosity of the working fluid, the pressure difference between upstream and downstream of a gear pump and the revolution speed of the gear pump.

2.5. Bellows pressure regulator

The bellows pressure regulator has two functions of pressurizing the working fluid and flow equalization. The structure of bellows pressure regulator ⑤ is shown in Fig.9. The bellows pressure regulator has a bellows structure that

Fig. 9. Schematic diagram of bellows pressure regulator.

contains the working fluid inside. The working fluid is pressurized using nitrogen gas from outside of the bellows structure. The bellows structure contributes to preventing the working fluid from absorbing the pressurized nitrogen gas.

The pressure outside the bellows P_6 is balanced to the sum of the pressure from the spring force of the bellows P_k , the pressure from the weight of the working fluid in the bellows and bellows itself, and the pressure inside bellows P_5 . Taking account of the pressure of the droplet generator P_1 , pressure loss between the bellows pressure regulator and the droplet generator P_l , and dynamic pressure P_{kin} , the pressure outside the bellows P_6 is expressed by the following equation.

$$P_6 = P_1 + P_m + P_k + P_l - P_{kin} \quad (4)$$

2.6. Equipments of automatic control on circulation

Figure 10 shows a flow chart of signals. Target flow rate is inputted from the terminal. The data of sensors, two thermocouples, two flow meters, an optical displacement meter, and eight pressure gauges, are transferred to a programmable logic controller (PLC, Omron Corporation, CJ-1). The PLC calculates the pressure outside the bellows and the revolution speeds of the centrifugal collector and the gear pump from Eqs.(1)-(4) in such a way that a flow rate set from a terminal is satisfied. The data computed by PLC are sent to actuators, the electropneumatic regulator (ASCO Japan Co., Ltd., Sentronic D) controlling bellows pressure regulator, the droplet collector, and the gear pump. The data of sensors are monitored on the terminal. The flow rate of working fluid is controlled once per 50 ms.

The pressure loss at Filter ⑮ and strainers of Flow meter ④⑥ shown in Fig.3 increases with the operation time in order to clog. The data of these pressure loss are obtained by pressure gauges during operation and are used to calculate the pressure outside the bellows and the revolution speeds of the centrifugal collector and the gear pump.

2.7. Automatic control method on circulation

The pressure P_6 outside the bellows in the bellows-type pressure regulator is controlled by the relaxation control method using the following equation,

$$P_{6,n} = P_{6,n-1} + C_a (P_{6,n} - P_{6,n-1}) \quad (5)$$

C_a is set to a smaller value than 1 for t_a seconds after a target flow rate changes in order to prevent the pressure P_6 from

Fig. 10. Flow chart of signals.

severely fluctuating immediately after a target flow rate changes. C_a is set to a larger value than 1 in order to increase amount of the pressure change because the resolution of the electropneumatic regulator is low and the electropneumatic regulator does not adjust the pressure in the case that the amount of the pressure change is small.

The leak coefficient R of the gear pump depends on the viscosity of the working fluid, the pressure difference between upstream and downstream of the gear pump and the revolution speed of the gear. In the case that a target flow rate changes, the downstream pressure of the gear pump and the revolution speed of the gear pump change. Although the leak coefficient R could be identified by preliminary experiments under all of the envisioned conditions, it takes numerous time and considerable effort to do that. In this study, the feed back control method and the proportional control method have been introduced to control flow rate of working fluid automatically.

In the feed back control method, the leak coefficient R is calculated from the following equation,

$$R_{cal} = \frac{\mu}{P_3 - P_2} \left(N \frac{U_{th}}{60} - Q_{ex} \right) \quad (6)$$

The leak coefficient R is controlled by the relaxation control method using the following equation,

$$R_n = R_{n-1} + C_l (R_{cal} - R_{n-1}) \quad (7)$$

C_l is set to a smaller value than 1 in order to prevent the leak volume of working fluid from severely fluctuating immediately after a target flow rate changes. Substituting R_n into Eq.(3), the number of revolution N is calculated.

In the proportional control method, the number of revolution N is calculated as follows,

$$N_n = N_{n-1} + K_p (Q_{target} - Q_{ex}) \frac{60}{U_{th}} \quad (8)$$

This method has the advantage that a leak coefficient, which is difficult to know the correct value, is not used. The goal of the development of automatic control method is to control flow rate less than the relative error of 5 %.

Fig. 11. History of flow rate in the case that the feed back control method is applied to the control of leak coefficient R of the gear pump.

Fig. 12. History of leak coefficient in the case of Fig. 11.

3. Results and Discussion

3.1. Feed back control of leak coefficient R

The history of flow rate under the experimental condition of Table 2 is shown in Fig. 11. The overshoot phenomenon of the flow rate between the gear pump and the bellows pressure regulator occurs immediately after the target flow rate changes from 100 ml/min. to 200 ml/min. This overshoot phenomenon is undesirable because it causes the failure of a gear in the gear pump. Figure 12 shows the history of the leak coefficient calculated from Eq. (7). The overshoot phenomenon of the leak coefficient also occurs. When target flow rate changes from 100 ml/min. to 200 ml/min., the number of revolution of the gear pump required to flow working fluid of 200 ml/min. is calculated by Eq. (3) and then is substituted into Eq. (6) to calculate the leak coefficient. The calculated leak coefficient undergoes the relaxation process using Eq. (7) and then is fed back in Eq. (3). Although the number of revolution of the gear pump N in Eq. (6) changes immediately after target flow rate changes from 100 ml/min. to 200 ml/min., the experimental value of flow rate Q_{ex} does not change. The larger value of the leak coefficient than the real value of the leak coefficient in the gear pump is calculated. This is the reason why the overshoot phenomenon of flow rate occurs immediately after target flow rate changes from 100 ml/min. to 200 ml/min.

Table 2. Experimental condition in the case that the feed back control method is applied to the control of leak coefficient R of the gear pump.

Target flow rate [ml/min.]	100 → 200 → 100 (for 2 minutes, respectively)	
Temperature of working fluid	26 degree Celsius	
C_l	0.02	
C_a	before t_a	0.2
	after t_a	1.5
t_a	5 seconds	

Table 3. Relative error of flow rate.

Target flow rate [ml/min.]	Relative error [%]	
	Droplet generator	Gear pump
100	1.3	-0.04
200	Immediate after change	-4.5
	Other	-3.1
100	Immediate after change	2.3
	Other	3.1

To reduce the overshoot phenomenon, the following way is possible.

1. Quit the feed back control of leak coefficient R and use a contact value only for several seconds after a target flow rate changes.
2. Use a smaller relaxation coefficient of leak coefficient C_l .
3. Use the experimental value for the number of revolution of the gear pump N in Eq. (6).
4. Relax the change of a target flow rate.

Way 1 needs many preliminary experiments to identify the leak coefficient R under all of envisioned conditions. Way 2 has a weak point that it takes a longer time for the flow rate in gear pump to reach a target flow rate, while the flow rate of the droplet generator reach a target flow rate for a shorter time. This means that the amount of working fluid in bellows-type pressure regulator changes. Way 3 needs a motor with a function of outputting the number of revolution. Way 3 is one of realistic solutions to overcome the overshoot phenomenon if a target flow rate must change without the relaxation of target flow rate. In way 4, it takes time for both flow rates of a gear pump and a droplet generator to reach a target flow rate. If the amount of time is several tens of seconds, there is no concern because spacecrafts normally need thermal control of minutes order.

Figure 13 shows the history of flow rate in the case that a target flow rate is relaxed using the following equation under the experimental condition of Table 2 and $C_Q = 0.01$,

$$Q_n = Q_{n-1} + C_Q(Q_{\text{target}} - Q_{n-1}). \quad (9)$$

The relative error in the period of stable flow rate and the amount of time taken to reach stable flow rate are shown in Table 4. The overshoot phenomenon of the flow rate as shown in Fig. 11 does not occur in Fig. 13. The overshoot of the leak coefficient is shown in Fig. 14. The overshoot of leak coefficient is smaller than that of Fig. 12. It is clear that the

Fig. 13. History of flow rate in the case that the feed back control method is applied to the control of leak coefficient R of the gear pump and a target flow rate is relaxed.

Fig. 14. History of leak coefficient in the case of Fig. 13.

relaxation of a target flow rate is effective to reduce the overshoots of flow rate and leak coefficient. On the other hand, the overshoot of leak coefficient does not disappear and the flow rate from the gear pump is larger than that of the target flow rate during the relaxation of the target flow rate. It can not be denied that the overshoot phenomenon of flow rate occurs under the other conditions.

Table 4. Relative error in period of stable flow rate and time taken to reach stable flow rate.

Target flow rate [ml/min.]	Average relative error [%]		Time taken to reach stable flow rate [sec.]	
	Droplet generator	Gear pump	Droplet generator	Gear pump
100	-1.9	0.0730		
200	-4.3	-0.0026	11	13
100	-1.8	-0.0086	13	8

3.2. Proportional control of flow rate from the gear pump

The history of flow rate under the experimental condition of Table 5 is shown in Fig. 15. The region where the flow rate from the gear pump is severely different from a target flow

Fig. 15. History of flow rate in the case that the proportional control method is applied to the control of flow rate from the gear pump.

rate is enclosed by a circle. In Region 1 and 2, the flow rate from the gear pump vibrates severely after a target flow rate changes. The flow rate from the gear pump in Region 2 oscillates for about a minute. Although the target flow rate increases in Region 3, the flow rate from the gear pump decreases and then increases. Although the target flow rate decreases in Region 3', the flow rate from the gear pump increases and then decreases.

Table 5. Experimental condition in the case that the proportional control method is applied to the control of flow rate from the gear pump.

Target flow rate [ml/min.]	100 → 200 → 100 (for 2 minutes, respectively)		
Temperature of working fluid	21 degree Celsius		
K_p	0.09		
C_a	before t_a	0.2	
	after t_a	1.5	
t_a	5 seconds		

It is known that the vibration of the flow rate from the gear pump in Region 1 and 2 is caused by too large gain K_p in the proportional control method. In Region 3, the flow rate to the droplet generator increases immediately after the target flow rate changes. The increase of the flow rate to the droplet generator is caused by the increase of Pressure P_6 , the pressure outside the bellows in the bellows-type pressure regulator. The increase of P_6 causes not only the increase of P_1 , the pressure in the droplet generator, but also the increase of P_3 , the pressure of downstream of gear pump. The increase of P_3 leads to the increase of the pressure difference between downstream and upstream of gear pump because the droplet collector can not generate the large pump head and P_2 is small in comparison with P_3 . The volume of counter flow from downstream to upstream in the gear pump increases by the increase of the pressure difference between downstream and upstream of gear pump. The number of revolution of gear pump is calculated from Eq.(8). Immediately after a target flow rate changes, the increase of counter flow in the gear pump does not be reflected in Eq.(8). This is the reason why the flow rate from the gear pump decreases immediately after an target flow rate increases. To prevent the flow rate from the

Fig. 16. History of flow rate in the case that the proportional control method with the term of the variation of the counter flow in the gear pump is applied to the control of flow rate from the gear pump.

gear pump from decreasing immediately after a target flow rate changes, a large gain in the proportional control K_p is required. As previously explained, a large gain of proportional control causes the vibration of flow rate. It is difficult to switch the value of gain of proportional control because the vibration of the flow rate from the gear pump happens just after the decrease of the flow rate.

The term of the variation of the counter flow in the gear pump is introduced in Eq.(8) to overcome the opposite change of flow rate from the gear pump against the change of a target flow rate as follows.

$$N_n = N_{n-1} + K_p (Q_{target} - Q_{ex}) \frac{60}{U_{th}} + M_l. \quad (10)$$

$$M_l = \left(R \frac{(P_3 - P_2)_n}{\mu} - R \frac{(P_3 - P_2)_{n-1}}{\mu} \right) \times \frac{60}{U_{th}}. \quad (11)$$

This method has the advantage that the correct values of leak coefficients are not required because the error between the real variation and the calculated variation of the counter flow is absorbed by the second term in Eq.(10). The term means the proportional control of flow rate.

Figure 16 shows the history of flow rate in the case of controlling the working fluid using Eq.(10) and Eq.(11) under the experimental condition of Table 6. The leak coefficient R of $1.5 \times 10^{-13} \text{ m}^3$ is the recommended value by the manufacturer of gear pump. The vibration of flow rate and the opposite change of flow rate against the change of a target flow rate as shown in Fig.15 does not appear in Fig.16. The gain of proportional control K_p in Fig.16 is smaller than that in Fig.15. It is clear that the small gain of proportional control is effective in order to prevent the vibration of flow rate. It is clarified that the control method using Eq.(10) and Eq.(11) is effective in order to prevent the opposite change of flow rate against the change of a target flow rate.

Table 7 shows the relative errors of flow rate immediately after a target flow rate changes and in the period of stable flow rate. The relative errors of flow rate to the droplet generator and of flow rate from the gear pump exceeds 5 % immediately

Table 6. Experimental condition in the case that the proportional control method with the term of the variation of the counter flow in the gear pump is applied to the control of flow rate from the gear pump.

Target flow rate [ml/min.]	100 → 200 → 100 (for 2 minutes, respectively)	
Temperature of working fluid	26 degree Celsius	
K_p	0.03	
R	$1.5 \times 10^{-13} \text{ m}^3$	
C_a	before t_a	0.17
	after t_a	1.5
t_a	5 seconds	

Table 7. Relative error immediately after change of target flow rate and in period of stable flow rate and time taken to reach stable flow rate.

Target flow rate [ml/min.]		Relative error [%]		Time taken to reach stable flow rate [sec.]	
		Droplet generator	Gear pump	Droplet generator	Gear pump
100		1.3	0.019		
200	Immediate after change	-4.6	4.5	3.6	7.2
	Other	-5.0	-0.064		
100	Immediate after change	-9.8	-11.0	9.6	9.6
	Other	-4.9	-0.049		

after a target flow rate changes from 200 ml/min to 100 ml/min. The value of the leak coefficient R does not cause this large relative error because the absolute value of the decrement of the revolution of gear pump calculated by Eq. (11) is smaller than the decrement of the revolution of gear pump corresponding to the decrement of real counter flow as the leak coefficient R of $1.5 \times 10^{-13} \text{ m}^3$ is smaller than those of Fig.12 and Fig.14. The decrease of flow rate occurs not only at the gear pump but also at the droplet generator. This suggests that the pressure outside the bellows in the bellows-type pressure regulator decreases too much. The cause can presume that the resolution of the electropneumatic regulator is low.

Figure 17 indicates the history of flow rate in the case that a target flow rate is relaxed using Eq.(9) and in the case of controlling the working fluid using Eq.(10) and Eq.(11) under the experimental condition of Table 8. The overshoot and undershoot of flow rate as shown in Fig.16 does not appear. Table 9 shows the relative error of flow rate and the amount of time taken to reach stable flow rate. The relative error is smaller than 5 %. It is clarified that the proportional control of flow rate with the term of the variation of the counter flow in the gear pump and the relaxation of the change of a target flow rate is effective to control flow rate automatically in a liquid droplet radiator.

Fig. 17. History of volume flow rate in the case that the proportional control method with the term of the variation of the counter flow in the gear pump is applied to the control of flow rate from the gear pump and a target flow rate is relaxed.

4. Conclusion

In this study, the feed back control method and the proportional control method have been introduced to control flow rate of working fluid automatically in a liquid droplet radiator (LDR). The proportional control of flow rate with the term of the variation of the counter flow in the gear pump and the relaxation of the change of an target flow rate has succeeded within 5 percent at the automatic circulation control of the working fluid from 100 ml/min to 200 ml/min and from 200 ml/min to 100 ml/min. It is clarified that this method is effective to control flow rate automatically in a liquid droplet radiator.

Acknowledgments

This work was supported by Grant-in-Aid for Young Scientists (A) (18686068) of the Ministry of Education, Culture, Sports, Science and Technology in Japan.

Table 8. Experimental condition in the case that the proportional control method with the term of the variation of the counter flow in the gear pump is applied to the control of flow rate from the gear pump and a target flow rate is relaxed.

Target flow rate [ml/min.]	100 → 200 → 100 (for 2 minutes, respectively)	
Temperature of working fluid	26 degree Celsius	
C_o	0.01	
K_p	0.03	
R	$1.6 \times 10^{-13} \text{ m}^3$	
C_a	before t_a	0.17
	after t_a	1.5
t_a	5 seconds	

Table 9. Relative error in period of stable flow rate and time taken to reach stable flow rate.

Target flow rate [ml/min.]	Average relative error [%]		Time taken to reach stable flow rate [sec.]	
	Droplet generator	Gear pump	Droplet generator	Gear pump
100	-3.3	0.014		
200	-5.0	-0.034	10.8	10.8
100	-2.3	-0.070	13.2	16.8

References

- 1) Taussig, R. T. and Mattick A. T.: Droplet Radiator Systems for Spacecraft Thermal Control, *Journal of Spacecraft and Rockets*, **23**, 1 (1986), pp.10-17.
- 2) Totani, T., Kodama, T., Watanabe, K., Nanbu, K., Nagata, H., Kudo, I.: Numerical and Experimental Studies on Circulation of Working Fluid in Liquid Droplet Radiator, *Acta Astronautica*, **59**(2006), pp.192-199.
- 3) Totani, T., Takekoshi, T., Wakita, M. and Nagata H.: Automatic Control on Circulation of Working Fluid in Liquid Droplet Radiator, Proceedings of the 13th Asian Congress of Fluid Mechanics, 2010, pp.586-589.
- 4) Chandrasekhar, S.: *Hydrodynamic and Hydromagnetic Stability*, Dover Publications Inc, New York, 1981, pp.515-576.