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SEAWATER FLOW RATE REGULATION OF OTEC PLANT USING UEHARA CYCLE BY CONSIDERING WARM SEAWATER TEMPERATURE VARIATION

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Abstract. *In ocean thermal energy conversion (OTEC) plant, electricity is generated by heat energy come from temperature difference between warm seawater at surface and cold seawater in depth. Therefore, the power generation is influenced by the temperature change of seawater. In this paper, a method for the regulation of seawater flow rate to control the power generation under the variation of warm seawater temperature of an OTEC plant using Uehara cycle is proposed. The flow rate of warm seawater is regulated by keeping the heat quantity constant and taking account of the variation of warm seawater temperature. Furthermore, the flow rate of cold seawater is also regulated by constructing a PI controller. The effectiveness of the proposed method is confirmed through simulation.*

Keywords: Ocean thermal energy conversion, Uehara cycle, Heat quantity, Seawater temperature, PI control

1. Introduction.

Recently, in order to cope with the exhaustion of fossil fuel and environmental problems, the promotion of the effective utilization of renewable energy such as wind power, wave power, solar power and so on has been required. Ocean thermal energy conversion (OTEC) plant is a system to generate electricity by utilizing the heat energy via the temperature difference between warm seawater obtained from sea surface and cold seawater from deep sea [1]. Since OTEC plants use the warm seawater (25-30 [°C]) and cold seawater (4-10 [°C]) as the heat source, they hardly emit CO_2 in operation. Furthermore, OTEC plants enable to multi-purpose application such as desalination of seawater [2, 3, 4]. The thermal efficiency of OTEC is not so high compared with that of commercial thermal power generation or nuclear power generation since the available temperature difference in OTEC system is about 20 [°C]. In order to improve the thermal efficiency, researches on the thermal cycle and heat exchanger have been conducted [5, 6, 7, 8, 9, 10].

In particular, an OTEC plant using Uehara cycle was proposed [8, 9] to obtain higher thermal efficiency, where in the Uehara cycle, an ammonia-water mixture is used as the working fluid and two turbines for absorption and extraction of vaporized working fluid are equipped. As one of the related works, a model for OTEC plant using Uehara cycle was developed [11] to apply to the controller design and simulator construction, where some physical laws and a program package PROPATH [12] were used for the model construction. In [13], the liquid level control of separator in OTEC experimental plant using Uehara cycle was considered by LQG control theory, where the influence of seawater was not taken into account.

On the other hand, the power generation is affected by external circumstances such as meteorological conditions since the temperature difference of seawater is utilized as the heat source. For this problem, digital control of working fluid flow rate of an OTEC plant using Rankine cycle to keep the power generation constant was considered [14]. In [15], a simple dynamic model for an OTEC plant using Rankine cycle was constructed. In [16], based on the model of [15], a web application of remote monitoring for OTEC plant was developed. However, the control problem on OTEC plant using Uehara cycle has never been investigated, and therefore, there is no methodology for the control of OTEC plant using Uehara cycle to cope with the influence of external circumstances.

The aim of this paper is to establish a methodology for the regulation of seawater flow rates to control the power generation of OTEC plant using Uehara cycle under the variation of seawater temperature. In this paper, the method for the regulation of not only the warm seawater flow rate but also the cold one is considered. The effectiveness of the proposed methods is evaluated through numerical simulations.

The rest of this paper is organized as follows. In Section 2, OTEC plant using Uehara cycle is described with the principle of power generation and a mathematical model. The influence of the variation of warm seawater inlet temperature on the power output is also mentioned. In Section 3, two kinds of methodologies for the control of the power output are proposed. In order to evaluate the proposed methods, numerical simulations were conducted as shown in Section 4. Section 5 concludes this paper.

2. OTEC Plant Using Uehara Cycle.

The structure of an experimental OTEC plant using Uehara cycle at Institute of Ocean Energy, Saga University, Japan (IOES) [17] is shown in Figure 1.

2.1. Principle of power generation.

The principal components of OTEC plant using Uehara cycle are a condenser, an evaporator, two turbines, a generator, two working fluid pumps, a heater, a regenerator, a separator, a diffuser, an absorber and two tanks.

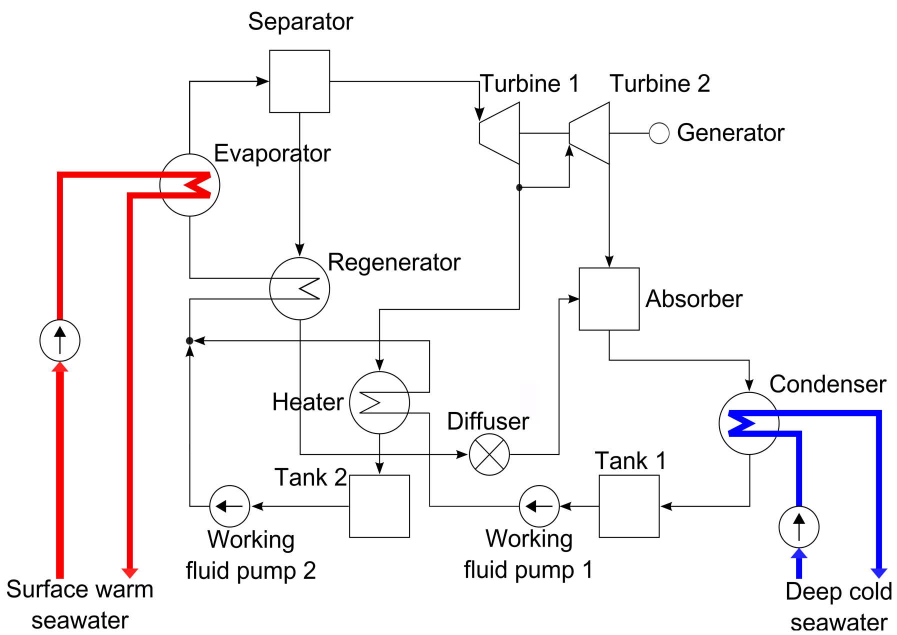


FIGURE 1. Overview of OTEC plant using Uehara cycle

The working fluid sent to the evaporator is partly vaporized by the heat exchange between the working fluid and the warm seawater. After the partly vaporized working fluid is sent to the separator, it is separated into vapor and liquid in the separator. The vapor working fluid is sent to the turbine 1, and the liquid one is sent to the regenerator. The vapor working fluid does the work of rotating the turbine 1, and it is partly condensed and sent to tank 2 through the heater. The rest of the vapor working fluid does the work of rotating the turbine 2, and is sent to the absorber. On the other hand, the liquid working fluid sent from the separator to the regenerator gives the heat the working fluid sent to the evaporator by the heat exchange. After that, the liquid working fluid is sent to the absorber through the diffuser. The working fluid in the absorber is sent to the condenser, and is condensed by the heat exchange for the cold seawater. The working fluid condensed in the condenser is sent to the tank 1. The working fluid in tank 1 and tank 2 meets before sending to the regenerator by working fluid pumps 1 and 2, and is sent to the evaporator through the regenerator.

2.2. **Mathematical model of OTEC plant using Uehara cycle.**

2.2.1. *Overview of model.* In this paper, a mathematical model of Uehara cycle constructed in [11] is used. The model is constructed based on the mass balance and heat balance, where the inlet and outlet state quantities of each component in OTEC plant using Uehara cycle are calculated by a program package PROPATH for the thermophysical properties calculation of ammonia-water mixture.

In the following subsection, the evaporator part of the model is described. Any other parts of the model are explained in [11] in detail.

2.2.2. *Evaporator part.* The schematic diagram of evaporator in OTEC plant using Uehara cycle is shown in Figure 2, where T_{WSI} is the warm seawater temperature of evaporator inlet, T_{WSO} is the warm seawater temperature of evaporator outlet, T_{LI} is the working fluid temperature of evaporator inlet, T_{LO} is the working fluid temperature of evaporator

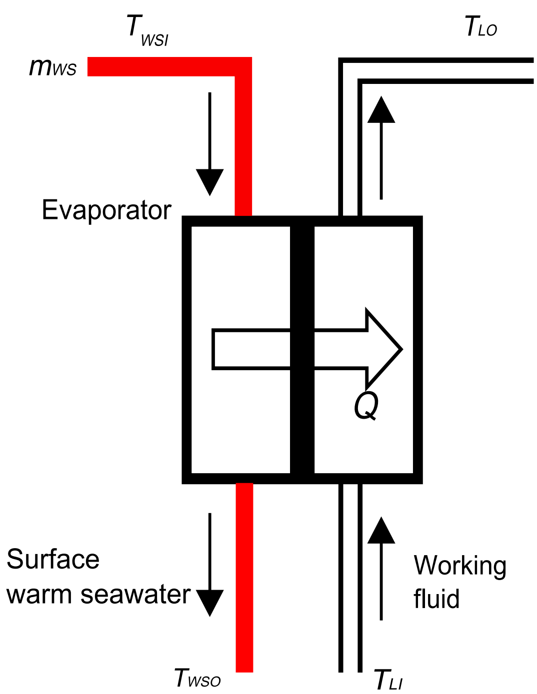


FIGURE 2. Heat exchange in evaporator

outlet, and m_{WS} is the mass flow rate of warm seawater. In the evaporator, the working fluid is partly vaporized by the heat exchange between the working fluid and the warm seawater, and is sent to the separator.

In the mathematical model of OTEC plant using Uehara cycle, the overall heat transfer coefficient U, the logarithmic mean temperature difference ΔT and the heat flow rate Q are given by

$$U = U^* \sqrt{\frac{m_{WS}}{m_{WS}^*}} \tag{1}$$

$$\Delta T = \frac{(T_{WSI} - T_{LO}) - (T_{WSO} - T_{LI})}{\ln \dfrac{(T_{WSI} - T_{LO})}{(T_{WSO} - T_{LI})}} \tag{2}$$

$$Q = UA\Delta T, \tag{3}$$

respectively, where U^* is the standard overall heat transfer coefficient, m_{WS}^* is the standard warm seawater flow rate, and A is the heat transfer area of evaporator. It follows from (2) and (3) that, if the temperature T_{WSI} varies, then the temperature difference ΔT and the heat flow rate Q vary. Furthermore, the enthalpy in the seawater varies by the change of the heat flow rate Q. In the mathematical model of OTEC plant using Uehara cycle, the power output W of the turbine is calculated by

$$W = m_{WF} \left(h_{IN} - h_{OUT} \right), \tag{4}$$

where m_{WF} is the mass flow rate of working fluid, and h_{IN}, h_{OUT} are the inlet and outlet turbine enthalpies, respectively. If the enthalpy in the separator varies, then the enthalpies h_{IN} and h_{OUT} also vary. Thus, the power output W is finally affected by the change of the warm seawater inlet temperature T_{WSI}.

3. Regulation of Seawater Flow Rate.

3.1. **Regulation of warm seawater flow rate.** As mentioned in the last section, if the warm seawater inlet temperature T_{WSI} varies, then the heat flow rate Q varies, and therefore, the power output W also does. In this paper, a method to suppress the variation of the power output by regulating the warm seawater mass flow rate m_{WS} appropriately so as to keep the heat flow rate Q constant under the condition that the warm seawater inlet temperature T_{WSI} is changed.

Here, it is noted from (1) and (3) that the warm seawater flow rate m_{WS} is represented by

$$m_{WS} = m_{WS}^* \left(\frac{Q}{U^* A \Delta T} \right)^2. \tag{5}$$

Then, for a given target heat flow rate Q_{ref}, the warm seawater flow rate m_{WS} is selected as

$$m_{WS} = m_{WS}^* \left(\frac{Q_{ref}}{U^* A \Delta T} \right)^2. \tag{6}$$

From (6) and (2), the warm seawater flow rate m_{WS} is determined by considering the variation of the warm seawater inlet temperature T_{WSI}. The target heat flow rate Q_{ref} is chosen such that the heat flow rate Q is equal to the target heat flow rate Q_{ref} in steady state. The block diagram of the proposed warm seawater flow rate regulation method is depicted in Figure 3.

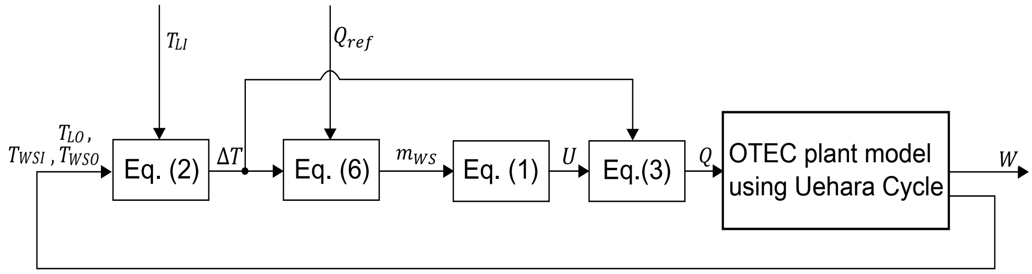


FIGURE 3. Block diagram of warm seawater flow rate regulation

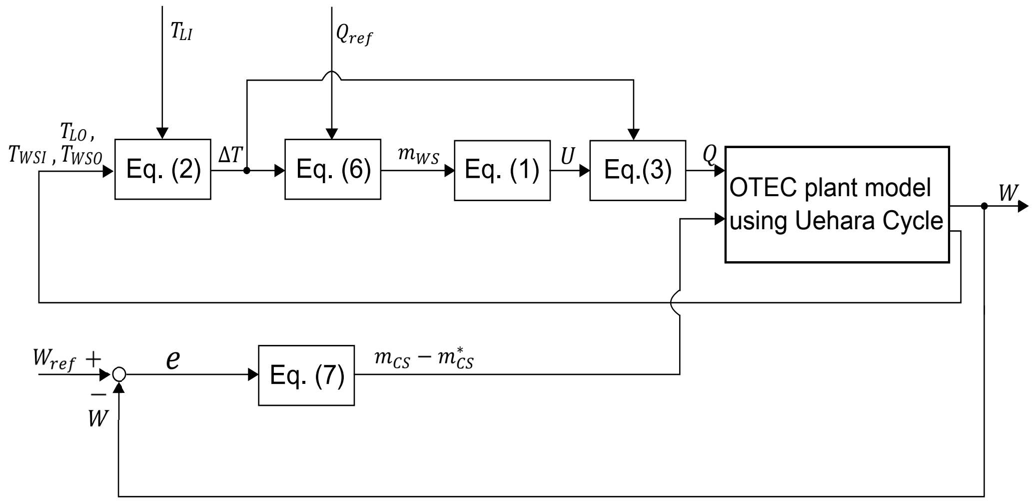


FIGURE 4. Block diagram of warm and cold seawater flow rate regulation

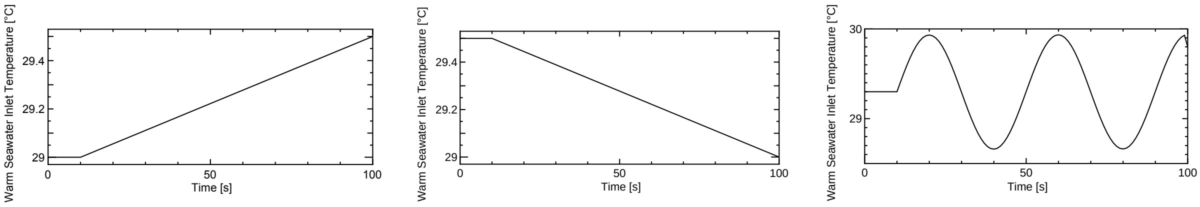
3.2. **Regulation of both warm and cold seawater flow rates.** In the last subsection, a method to regulate the warm seawater flow rate by considering the variation of the warm seawater inlet temperature T_{WSI} to keep the heat flow rate Q constant based on (6) is proposed. However, the transient behavior of the power output (i.e., rise time, etc.) cannot be controlled. To cope with this issue, another method to regulate the transient behavior of the power output under the variation of the warm seawater inlet temperature T_{WSI} by regulating not only the warm seawater mass flow rate m_{WS} via (6) but also the cold seawater mass flow rate m_{CS} is also proposed.

In this paper, the cold seawater flow rate m_{CS} is determined by the following PI control law:

$$m_{CS} - m_{CS}^* = K_P \left(e(t) + \frac{1}{T_I} \int_0^t e(\tau) d\tau \right), \tag{7}$$

where m_{CS}^* is the standard cold seawater flow rate, and $e(t)$ is the error between the target power output W_{ref} and the power output $W(t)$ defined by $e(t) = W_{ref} - W(t)$. The block diagram of the proposed cold seawater flow rate regulation combined with the warm seawater flow rate regulation is shown in Figure 4.

4. **Verification by Numerical Simulation.** In order to verify the usefulness of the proposed seawater flow rate regulation methods, numerical simulations by using the mathematical model of Uehara cycle [11] were conducted. As the warm seawater inlet temperature T_{WSI}, three kinds of inputs ((a) increasing input, (b) decreasing input, and (c) sinusoidal input in Figure 5) were given. For each parameter of OTEC plant,



(a) Increasing input (b) Decreasing input (c) Sinusoidal input

FIGURE 5. Variation of warm seawater inlet temperature T_{WSI}

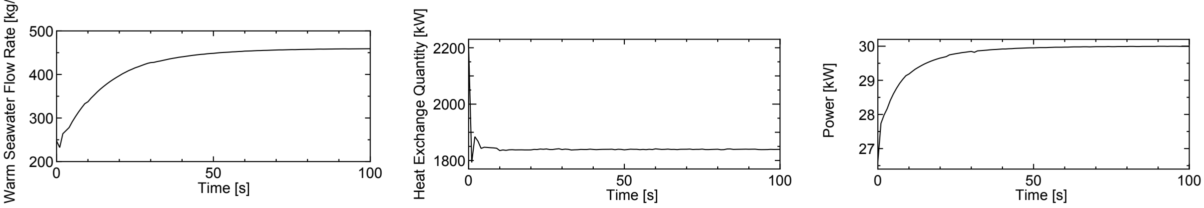


FIGURE 6. Simulation result (m_{WS} is regulated by PI controller for $T_{WSI} =$ 29 [°C] (constant))

$U^* = 690$ [J/(m^{2}s °C)], $m^*_{WS} = 194.17$ [kg/s], $A = 560$ [m^2] and $m^*_{CS} = 110.56$ [kg/s] were used, where these values are compatible with the specification of an OTEC experimental plant using Uehara cycle at IOES (rated output 30 [kW]) as in the simulation of [11].

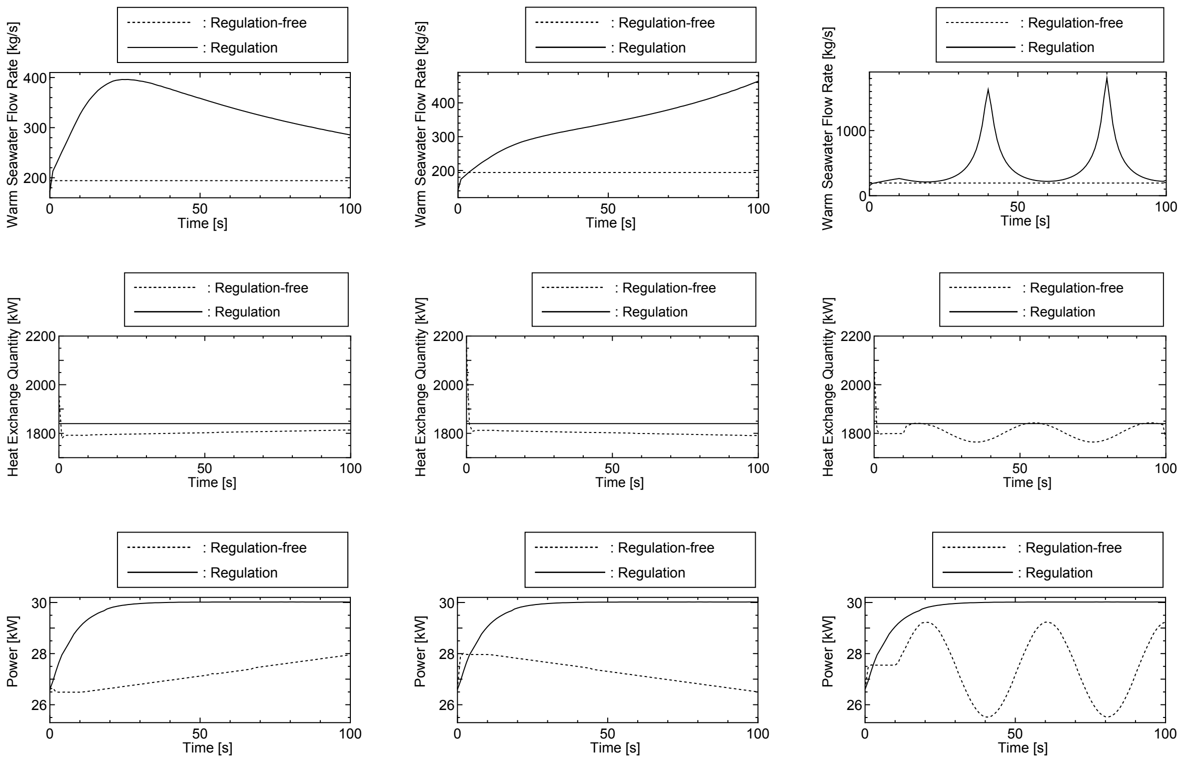
4.1. **Regulation of warm seawater flow rate.** First, simulations of regulating the warm seawater flow rate m_{WS} by using (6) under the variations of the warm seawater inlet temperature T_{WSI} in Figure 5 were conducted. The target power output W_{ref} was set as $W_{ref} = 30$ [kW], which is the rated output of the OTEC experimental plant. As the target heat flow rate Q_{ref}, the heat flow rate in steady state for the power output $W(t) = 30$ [kW] was adopted, where it was identified from the numerical simulation result using the mathematical model of Uehara cycle. Indeed, the heat flow rate $Q(t)$ was verified when the power output $W(t)$ reached 30 [kW] by regulating m_{WS} based on a PI control law for a fixed temperature $T_{WSI} = 29$ [°C], where Ziegler-Nichols tuning rule based on critical gain $K_u = 0.157$ and critical period $P_u = 5$ [s] [18] was utilized for the PI parameters. Thus, PI parameters in the PI control law

$$m_{WS} = K_{WSP}\left(e(t) + \frac{1}{T_{WSI}}\int_0^t e(\tau)d\tau\right) \tag{8}$$

were given by $K_{WSP} = 0.45K_u = 0.07065$ and $T_{WSI} = 0.83P_u = 4.15$ [s]. The simulation result is depicted in Figure 6. From this result, the target heat flow rate Q_{ref} was selected as $Q_{ref} = 1840$ [kW].

The simulation results for inputs in Figures 5(a)-5(c) by regulating m_{WS} based on (6) are shown in Figure 7. In Figure 7, the broken line indicates the simulation results without regulation of the warm seawater flow rate. These results clarified that, in any cases, the power output $W(t)$ was severely affected by the variation of T_{WSI}. On the other hand, in any cases, the heat flow rate $Q(t)$ was identically equal to $Q_{ref} = 1840$ [kW] when the warm seawater flow rate was regulated by (6) even if the warm seawater inlet temperature T_{WSI} varied. Furthermore, the power output $W(t)$ reached the target power output $W_{ref} = 30$ [kW] about 35 [s] in any cases.

4.2. **Regulation of both warm and cold seawater flow rates.** Secondly, simulations of regulating both the warm seawater flow rate m_{WS} by (6) and the cold seawater flow



(a) Responses for increasing input (b) Responses for decreasing input (c) Responses for sinusoidal input

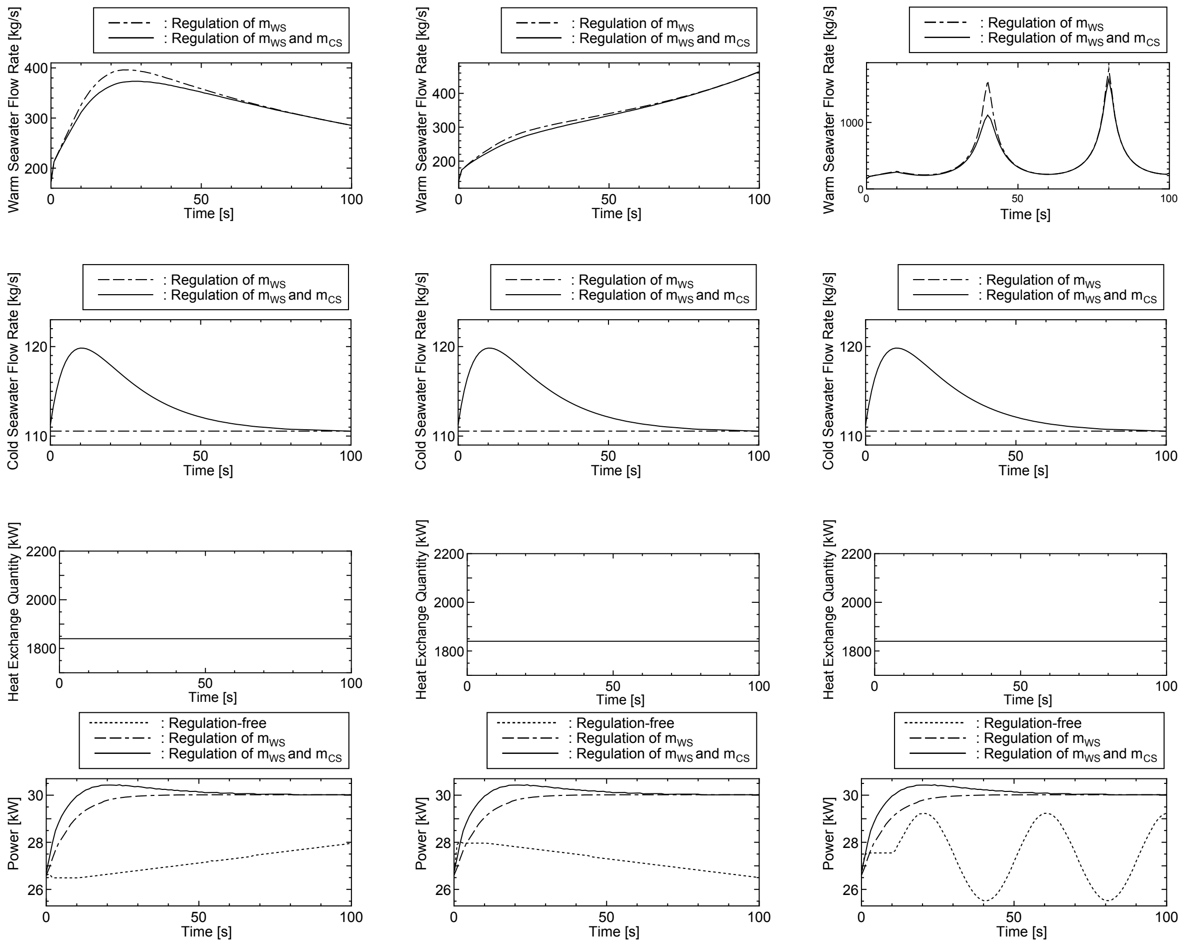
FIGURE 7. Simulation results (regulation of m_{WS})

rate m_{CS} by the PI control law (7) were carried out under the variations of the warm seawater inlet temperature in Figure 5. The target power output and the target heat flow rate were given by $W_{ref} = 30$ [kW] and $Q_{ref} = 1840$ [kW], respectively.

The PI parameters K_P and T_I were determined by the numerical simulations using the mathematical model of Uehara cycle. To determine the parameters, 100 simulations were conducted by changing K_P and T_I from $(K_P, T_I) = (0.0001, 0.1)$ to $(K_P, T_I) = (0.001, 1.0)$, where the warm seawater flow rate m_{WS} was regulated by (6), and the target power output W_{ref} and the target heat flow rate Q_{ref} were set as $W_{ref} = 30$ [kW] and $Q_{ref} = 1840$ [kW], respectively. Then, in this paper, a parameter $(K_P, T_I) = (0.0002, 0.3)$ which achieves the minimal overshoot of the power output was adopted, where the parameters by which the power output $W(t)$ did not reach the target power output W_{ref} were not taken into consideration in determining the parameters (K_P, T_I) to be adopted.

Simulation results for the variations in Figures 5(a)-5(c) are shown in Figure 8. The dotted line in Figure 8 indicates the simulation results without regulation of both warm and cold seawater flow rates, and the results show that the power output is heavily affected by the influence of the warm seawater inlet temperature. The dash-dotted line in Figure 8 indicates the simulation results with regulation of warm seawater flow rate. The simulation results clarify that, in any cases, the rise time of the power output $W(t)$ was reduced about 10 [s] by introducing the proposed method of warm and cold seawater flow rates regulation. Although the power output $W(t)$ had the overshoot, there is no fatal problem from the practical point of view since it was sufficiently small (i.e., about 0.44 [kW] for the target power output $W_{ref} = 30$ [kW]).

5. **Conclusion.** In this paper, methods for the regulation of seawater flow rates to cope with the variations of the warm seawater temperature of an OTEC plant using Uehara cycle were proposed. It was verified that the power output reached the target power



(a) Responses for increasing input (b) Responses for decreasing input (c) Responses for sinusoidal input

FIGURE 8. Simulation results (regulation of m_{WS} and m_{CS})

output by keeping the heat flow rate constant under the variation of warm seawater temperature. Furthermore, it was clarified that by combining the warm seawater flow rate regulation with the cold seawater flow rate regulation using PI control law, the rise time of the power output was improved. If the proposed control methods can be applied to actual OTEC plant using Uehara cycle, their effectiveness may be demonstrated.

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