Simultaneous Regulation of Multiple Flow Rates for Power Generation Control of OTEC Plant Using Double-stage Rankine Cycle

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Abstract: This research investigates the power generation control of ocean thermal energy conversion (OTEC) plant using double-stage Rankine cycle whose warm seawater temperature varies. As the plant model, a simple dynamic model is used. For the construction of control system, not only warm and cold seawater mass flow rates but also working fluid ones are manipulated, where each mass flow rate is determined by proportional integral (PI) control law. In this research, the concept of simultaneous regulation of mass flow rates in OTEC plant using double-stage Rankine cycle is proposed. In order to verify the behavior of the proposed control system, simulations were conducted.

Keywords: Ocean thermal energy conversion (OTEC), double-stage Rankine cycle, flow rate regulation, power generation control

1. INTRODUCTION

Ocean thermal energy conversion (OTEC) [1] is an important technology to generate electricity by using temperature difference in seawater (warm seawater (25-30 [°C]) at surface and cold seawater (5-19 [°C]) in depth). Since OTEC plants utilize only warm seawater and cold seawater as the heat source, generated energy is clean. However, the thermal efficiency of OTEC plants is not so high because of the low temperature difference. Indeed, the thermal efficiency of OTEC plant using Rankine cycle is about 3.5%.

To improve the thermal efficiency, some kinds of cycles have been investigated. In particular, an OTEC plant using Uehara cycle [2] was developed by improving Kalina cycle [3]. In [4], a model for numerical simulation of OTEC plant using Uehara cycle was developed based on conservation laws about mass and energy. In [5], by using the model in [4], a method for seawater flow rate regulation of OTEC plant using Uehara cycle with warm seawater temperature variation was proposed to control the power output. Although Uehara cycle brings higher thermal efficiency theoretically, the behavior as the thermal system is so complicated due to its structure.

On the other hand, OTEC plant using double-stage Rankine cycle [6] has been studied in recent years, where double-stage Rankine cycle is constructed by joining two Rankine cycles to reduce the irreversible loss in the heat exchange on Rankine cycles. In [7], a web application of OTEC plant using double-stage Rankine cycle was developed to simulate the remote monitoring/operation. In [8], the power output control of OTEC plant using double-stage Rankine cycle with warm seawater temperature variation was considered by manipulating either warm or cold seawater flow rate appropriately. Furthermore, in [9], the control of OTEC plant using double-stage Rankine cycle was investigated by considering the target power output variation. However, in both [8] and [9], only single seawater flow rate regulation was dealt with.

In this research, a method of simultaneous regulation of multiple flow rates to apply to the power generation control of OTEC plant using double-stage Rankine cycle is newly proposed.

2. OTEC PLANT USING DOUBLE-STAGE RANKINE CYCLE

2.1. Principle of Power Generation

The structure of an OTEC plant using double-stage Rankine cycle is depicted in Fig. 1. In this OTEC plant, electricity is generated by two generators in both Rankine cycles (Unit A and Unit B), where the power generation is conducted by rotating the turbines connected to generators. The turbines are rotated by vapor working fluid generated in the evaporators. As the working fluid, fluid with low boiling point such as ammonia is used since the warm heat source of OTEC plants is seawater at surface. The vapor working fluid is generated by vaporizing liq-
uid one through heat exchange in the evaporator between warm seawater and working fluid. The liquid working fluid to be vaporized is supplied from condenser by the pump. In the condenser, vapor working fluid from turbine is completely condensed through heat exchange between cold seawater and working fluid. The warm seawater is sent to the evaporator in Unit B after that in Unit A by the pump. On the other hand, the cold seawater is sent to the condenser in Unit A after that in Unit B by the pump.

2.2. Plant Model

In this research, as the plant model, a simple dynamic model [7] is employed. The details are included in [7].

The outline of the model is explained below: The simple dynamic model consists of three calculations:

(i) the nonlinear steady state calculation of state quantities such as temperature, specific volume, specific entropy and specific enthalpy in Points 1-8 shown in Fig. 1,

(ii) the dynamics calculations about temperature and heat flow rate, and

(iii) the performance index calculations of OTEC.

In (i), nonlinear algebraic equations about the heat balance in evaporators and condensers are solved by the bisection method. The detailed description for (i) is included in [7].

In (ii), the dynamics is described by

\[
\tau_{T_{wsA}} \frac{dT_{wsA}(t)}{dt} + T_{wsA}(t) = T_{ssA}(t) \quad (1)
\]

\[
\tau_{Q_{wsA}} \frac{dQ_{wsA}(t)}{dt} + Q_{wsA}(t) = Q_{ssA}(t) \quad (2)
\]

\[
\tau_{T_{csA}} \frac{dT_{csA}(t)}{dt} + T_{csA}(t) = T_{ssA}(t) \quad (3)
\]

\[
\tau_{Q_{csA}} \frac{dQ_{csA}(t)}{dt} + Q_{csA}(t) = Q_{ssA}(t) \quad (4)
\]

\[
\tau_{T_{wsB}} \frac{dT_{wsB}(t)}{dt} + T_{wsB}(t) = T_{ssB}(t) \quad (5)
\]

\[
\tau_{Q_{wsB}} \frac{dQ_{wsB}(t)}{dt} + Q_{wsB}(t) = Q_{ssB}(t) \quad (6)
\]

\[
\tau_{T_{csB}} \frac{dT_{csB}(t)}{dt} + T_{csB}(t) = T_{ssB}(t) \quad (7)
\]

\[
\tau_{Q_{csB}} \frac{dQ_{csB}(t)}{dt} + Q_{csB}(t) = Q_{ssB}(t) \quad (8)
\]

where \( T_{ws}(t) \) is the outlet warm seawater temperature of evaporator in Unit *, \( Q_{ws}(t) \) is the heat flow rate in evaporator of Unit *, \( T_{cs}(t) \) is the outlet cold seawater temperature of condenser in Unit *, \( Q_{cs}(t) \) is the heat flow rate in condenser of Unit *, \( \tau_{*} \) is the time constant, \( T_{ss}^{*} \) or \( Q_{ss}^{*} \) is the steady state quantity for * calculated by the corresponding steady state calculation.
In (iii), the power outputs $W_A(t)$ in Unit A and $W_B(t)$ in Unit B are calculated by

$$W_A(t) = \eta_A m_{wfA}(t) [h_1(t) - h_2(t)]$$  \hspace{1cm} (9)$$
$$W_B(t) = \eta_B m_{wfB}(t) [h_3(t) - h_6(t)]$$  \hspace{1cm} (10)$$

respectively, where $\eta_A$ is the turbine efficiency of Unit A, $m_{wf}(t)$ is the working fluid mass flow rate of Unit A, and $h_i(t)$ is the specific enthalpy of working fluid in Point $i$. The specific enthalpy $h_1(t)$ (or $h_3(t)$) is calculated from the temperature $T_1(t)$ (or $T_3(t)$) of the working fluid in Point 1 (or Point 5) based on the thermophysical property. The enthalpy $h_2(t)$ (or $h_6(t)$) is calculated from the temperature $T_2(t)$ (or $T_6(t)$) and the entropy $s_2(t)$ (or $s_6(t)$) of the working fluid in Point 2 (or Point 6) based on the thermophysical property. The enthalpies are a sort of internal state variables which cannot be directly measured.

Therefore, the total power output $W(t)$ is given by

$$W(t) = W_A(t) + W_B(t).$$  \hspace{1cm} (11)$$

The control objective is to approach the power output $W(t)$ in OTEC plant using double-stage Rankine cycle with the variation of warm seawater temperature $T_{wsiA}(t)$ to the target power output $W_{ref}$.

### 3. CONTROL SYSTEM

In this section, a control strategy for OTEC plant using double-stage Rankine cycle with the variation of warm seawater temperature $T_{wsiA}(t)$ is proposed based on the simultaneous regulation of multiple flow rates, where in this research, as one of the most simple control laws for the determination of flow rates from the application point of view, PI control law is adopted.

As verified in [8], under the assumption that both warm and cold seawater mass flow rates $m_{ws}(t)$ and $m_{cs}(t)$ are constant, the power output $W(t)$ varies if the warm seawater temperature $T_{wsiA}(t)$ varies. It was also verified in [8] that the power output $W(t)$ modeled by a simple dynamic model can be successfully controlled by regulating either $m_{ws}(t)$ or $m_{cs}(t)$ appropriately based on PI control law:

$$m_{ws}(t) = K_{Pws} e(t) + \frac{1}{T_{Iws}} \int_0^t e(\tau) d\tau$$ \hspace{1cm} (12)$$
$$m_{cs}(t) = K_{Pcs} e(t) + \frac{1}{T_{Ics}} \int_0^t e(\tau) d\tau,$$  \hspace{1cm} (13)$$

where the error $e(t)$ is defined by

$$e(t) = W_{ref} - W(t).$$  \hspace{1cm} (14)$$

On the other hand, since we can see from Eqs. (9) and (10) that the working fluid mass flow rates $m_{wfA}(t)$ and $m_{wfB}(t)$ also affect the power output $W(t) (= W_A(t) + W_B(t))$, the power output $W(t)$ may be controlled by regulating the working fluid mass flow rates $m_{wfA}(t)$ and $m_{wfB}(t)$ appropriately.

From this point of view, in this research, PI control law

$$m_{wfA}(t) = K_{PwfA} e_A(t)$$
$$+ \frac{1}{T_{IwfA}} \int_0^t e_A(\tau) d\tau$$ \hspace{1cm} (15)$$
$$m_{wfB}(t) = K_{PwfB} e_b(t)$$
$$+ \frac{1}{T_{IwfB}} \int_0^t e_B(\tau) d\tau,$$  \hspace{1cm} (16)$$

for working fluid mass flow rate regulation is proposed, where

$$e_A(t) = W_{refA} - W_A(t)$$  \hspace{1cm} (17)$$
$$e_B(t) = W_{refB} - W_B(t).$$  \hspace{1cm} (18)$$

In this research, simultaneous regulation of multiple flow rates is investigated. The block diagram of control system is illustrated in Fig. 2.

### 4. SIMULATION RESULTS

In this section, the effect of simultaneous regulation of multiple flow rates is verified by four kinds of simulations:

(A) Regulation of warm seawater mass flow rate $m_{ws}(t)$ and cold one $m_{cs}(t)$,

(B) Regulation of warm seawater mass flow rate $m_{ws}(t)$ and working fluid ones $m_{wfA}(t), m_{wfB}(t)$,

(C) Regulation of cold seawater mass flow rate $m_{cs}(t)$ and working fluid ones $m_{wfA}(t), m_{wfB}(t)$, and

(D) Regulation of warm and cold seawater mass flow rates $m_{ws}(t), m_{cs}(t)$ and working fluid ones $m_{wfA}(t), m_{wfB}(t)$.
Table 1 Parameters for control laws

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<td>$KP_{ws}$</td>
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<td>$TI_{ws}$</td>
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Simulation (B)

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Simulation (C)

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<td>$KP_{cs}$</td>
<td>= 0.01 [kg/s]/kW, $T_{wsiB} = 150$ [s]</td>
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<tr>
<td>$W_{ref}$</td>
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Simulation (D)

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<tr>
<td>$W_{ref}$</td>
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As the variation of the warm seawater temperature $T_{wsA}(t)$, increasing temperature and decreasing one depicted in Fig. 3 are considered. The parameters for control laws were given as in Table 1, where the parameters were determined through simulations conducted by changing them. The other simulation conditions were set as the same ones in [8].

The simulation results are shown in Figs. 4-11.

5. DISCUSSION

Fig. 4 and Fig. 5 are the simulation results for simulation (A) with increasing and decreasing temperature $T_{wsA}(t)$, respectively. In both cases, the power output $W(t)$ reached the target power output $W_{ref} = 24$ [kW] successfully with reasonable settling time. In these figures, the simulation results by conventional methods in [8] are also depicted. These results indicate that, by selecting the PI parameters appropriately, rapid changes of seawater mass flow rates $m_{ws}(t)$ and $m_{cs}(t)$ can be avoided. Furthermore, the amplitudes of $m_{ws}(t)$ and $m_{cs}(t)$ can be reduced compared with the conventional results, especially in Fig. 5. This is just the merit to introduce the simultaneous regulation proposed in this research.

Fig. 6 and Fig. 7 are the simulation results for simulation (B) with increasing and decreasing temperature $T_{wsA}(t)$, respectively. In both results, the power output $W(t)$ finally reached the target power output $W_{ref} = 24$ [kW]. However, the transient responses are not seemed to be so good. Indeed, the working fluid flow rates $m_{wfA}(t)$ and $m_{wfB}(t)$ are suffered from the saturation by their upper limit 0.52 [kg/s]. In the simulations of this research, the upper limit compatible with the specification of an existing OTEC experimental plant at the Institute of Ocean Energy, Saga University (IOES) [10] was selected. By applying anti-windup compensation techniques [11] or improving the specification of the working fluid pump, we may obtain better responses.

Fig. 8 and Fig. 9 are the simulation results for sim-
ulation (C) with increasing and decreasing temperature $T_{wsiA}(t)$, respectively. In both cases, the power output $W(t)$ approached the target power output $W_{ref} = 21$ [kW]. However, the working fluid flow rates $m_{wfA}(t)$ and $m_{wfB}(t)$ are also affected by the saturation which comes from their upper limit 0.52 [kg/s]. Here, the difference of transient responses between Fig. 8 and Fig. 9 may be caused by the integral time $T_{Ics}$.

Fig. 10 and Fig. 11 are the simulation results for simulation (D) with increasing and decreasing temperature $T_{wsiA}(t)$, respectively. In both results, the power output $W(t)$ finally approached the target power output $W_{ref} = 21$ [kW]. The transient responses were similar to those of simulation results in Figs. 6-8 from the viewpoint of saturation in working fluid mass flow rates. This fact shows that the seawater mass flow rates and the working fluid ones are mutually affected, and therefore, the concept of simultaneous regulation proposed in this research is essentially important for the control of OTEC plant using double-stage Rankine cycle.

6. CONCLUSIONS

In this research, the power generation control of OTEC plant using double-stage Rankine cycle with the variation of warm seawater temperature was investigated by regulating the multiple flow rates. As the flow rates, warm and cold seawater mass flow rates were considered, where the individual regulation of these flow rates were proposed in [8]. In addition, in this research, working fluid mass flow rates in Unit A and Unit B were also taken into account. In order to verify the behavior of the control system by applying the proposed method of simultaneous regulation, four kinds of simulations were carried out. The simulation results of regulating warm and cold seawater flow rates clarified that the amplitudes of both flow rates could be reduced compared with the conventional ones. The simulation results of regulating seawater flow rate and working fluid flow rate showed that the characteris-
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