

Construction of a State Space Model for an OTEC Plant Using Rankine Cycle with Heat Flow Rate Dynamics^{*}

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Abstract: In this research, a state space model for an ocean thermal energy conversion (OTEC) plant using Rankine cycle is proposed by considering the heat transfer dynamics. The model is constructed by using an existing simple dynamic model. The temperatures and heat flow rates of warm and cold seawater are selected as the state variables. The difficulty of the static calculation in the simple dynamic model on the construction of state space model is also clarified. To cope with this issue, in this research, the relationships between the state variables at steady state and the manipulated variable of warm seawater flow rate are derived. The usefulness and limitation of the proposed model is verified by simulation results.

Keywords: Ocean thermal energy conversion, state space model, Rankine cycle, heat flow rate dynamics, numerical simulation

1. INTRODUCTION

In recent years, renewable energies such as solar energy, wind energy, tidal energy, ocean wave energy and so on have been paid much attention from the environmental point of view, and the significance of their modeling and control is also increased. As one of the renewable energies, ocean thermal energy conversion (OTEC) technology has been developed over a few decades. (e.g., See Khaligh and Onar (2010).) Although the OTEC system has a drawback of low thermal efficiency, some kinds of OTEC systems with higher thermal efficiency have been constructed such as Uehara cycle Uehara et al. (1998), double-stage Rankine cycle Ikegami et al. (2018) and so on.

For the control of OTEC plant using Uehara cycle, in Goto et al. (2011), a plant model for numerical simulation was constructed based on physical laws about mass and energy. By using the model, in Matsuda et al. (2017-1), a power generation control method for OTEC plant using Uehara cycle was proposed based on seawater flow rate regulation, where warm seawater temperature variation was taken into account as a disturbance. The above model and control system for OTEC plant using Uehara cycle were evaluated by simulation results. Furthermore, liquid level control of separator in OTEC plant using Uehara cycle was considered in Matsuda et al. (2016), where the model was derived by using experimental data. The control system was designed based on LQG control theory. In Matsuda

et al. (2017-2), the liquid level model was evaluated by using another experimental data. In Matsuda et al. (2017-3), the control system was improved by resetting the integral action of the controller.

On the other hand, OTEC plant using double-stage Rankine cycle was also modeled in Goto et al. (2017). In the model construction, dynamics on not only temperatures of warm and cold seawater but also heat flow rates (i.e., heat exchange in evaporator and condenser) were considered. By using the model, in Matsuda et al. (2017-4), a power generation control method of OTEC plant using double-stage Rankine cycle with warm seawater temperature variation was proposed. In the control system, either warm seawater flow rate or cold one was adopted as the manipulated variable. In Matsuda et al. (2018), simultaneous regulation of multiple flow rate for the control system in Matsuda et al. (2017-4) was considered, where not only seawater flow rate but also working fluid flow rate was utilized. Furthermore, in Matsuda et al. (2019), control system considered in Matsuda et al. (2018) with target power output changes was investigated. Here, the modeling of OTEC plant using double-stage Rankine cycle with time delay about the movement of fluids was also considered in Aosaki et al. (2019). In the above control system for OTEC plant using double-stage Rankine cycle, control parameters in PI controllers to determine the flow rates were selected by trial and error through many simulations. This problem comes from the complexity of static calculation in Goto et al. (2017). Here, a related work of state space model for OTEC plant using Rankine cycle in Jitsuhara et al. (1994) is explained. In Jitsuhara

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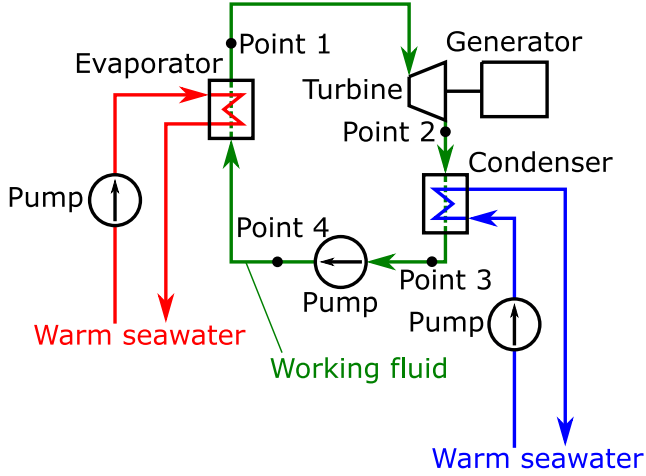


Fig. 1. Principle of power generation

et al. (1994), a state space model was constructed to represent the vapor temperatures, and did not contain the heat transfer dynamics explicitly. This means that the model for overall OTEC plant using Rankine cycle was not considered. In addition, state space model for OTEC plant using Rankine cycle was not proposed as long as the authors know except for Jitsuhara et al. (1994). Therefore, it is important to investigate the construction of state space model for overall OTEC plant using Rankine cycle.

To solve these issues, in this research, a state space model for an OTEC plant is newly derived, where the model construction is realized by using simple dynamic model, and (single) Rankine cycle is considered to verify the essential difficulty.

2. SIMPLE DYNAMIC MODEL OF OTEC PLANT USING RANKINE CYCLE

2.1 Principle of Power Generation

The structure of OTEC plant using Rankine cycle is shown in Fig. 1. In evaporator and condenser, heat between seawater and working fluid with low boiling point is exchanged. The state of working fluid passing through evaporator is changed from liquid to vapor. On the other hand, the state of working fluid passing through condenser is changed from vapor to liquid. The vapor working fluid rotates turbine connected to generator. Then, generator generates electricity. Pumps send seawater and liquid working fluid.

2.2 Simple Dynamic Model

Simple dynamic model has dynamics about temperatures $T_{wso}(t)$ and $T_{cso}(t)$ of outlet warm and cold seawater and heat flow rates $Q_{ws}(t)$ and $Q_{cs}(t)$ of working fluid in evaporator and condenser:

$$\tau_{T_{wso}} \frac{dT_{wso}(t)}{dt} + T_{wso}(t) = T_{wso}^{ss}(t) \quad (1)$$

$$\tau_{T_{cso}} \frac{dT_{cso}(t)}{dt} + T_{cso}(t) = T_{cso}^{ss}(t) \quad (2)$$

$$\tau_{Q_{ws}} \frac{dQ_{ws}(t)}{dt} + Q_{ws}(t) = Q_{ws}^{ss}(t) \quad (3)$$

$$\tau_{Q_{cs}} \frac{dQ_{cs}(t)}{dt} + Q_{cs}(t) = Q_{cs}^{ss}(t), \quad (4)$$

where $\tau_{T_{wso}}$, $\tau_{T_{cso}}$, $\tau_{Q_{ws}}$ and $\tau_{Q_{cs}}$ are time constants. Temperatures $T_{wso}^{ss}(t)$, $T_{cso}^{ss}(t)$, $Q_{ws}^{ss}(t)$ and $Q_{cs}^{ss}(t)$ are calculated by static calculation explained below. Here, the notation $*(t)$ with respect to time t is sometimes omitted for notational simplicity.

Inlet warm and cold seawater temperatures T_{wsi} , T_{csi} , warm and cold seawater flow rates m_{ws} , m_{cs} and working fluid flow rate m_{wf} are assumed to be given. Then, outlet warm and cold seawater temperatures T_{wso}^{ss} , T_{cso}^{ss} and state quantities such as specific enthalpy h_i , temperature T_i , pressure p_i , specific entropy s_i ($i = 1, 2, 3, 4$) in 4 points (Point 1-4 in Fig. 1) are determined so as to satisfy

$$Q_e = Q_{ws}^{ss} \quad (5)$$

$$Q_c = Q_{cs}^{ss}, \quad (6)$$

where Q_e is the heat flow rate of warm seawater in evaporator and Q_c is the heat flow rate of cold seawater in condenser. The heat flow rates in (5) and (6) are represented by

$$Q_e = m_{ws} c_p (T_{wsi} - T_{wso}^{ss}) \quad (7)$$

$$Q_c = m_{cs} c_p (T_{cso}^{ss} - T_{csi}) \quad (8)$$

$$Q_{ws}^{ss} = m_{wf} (h_1 - h_4) \quad (9)$$

$$Q_{cs}^{ss} = m_{wf} (h_2 - h_3), \quad (10)$$

where c_p is the specific heat of seawater and h_i ($i = 1, 2, 3, 4$) is the specific enthalpy at Point i .

In simple dynamic model of previous researches (e.g., Goto et al. (2017) and related works), for T_{wso}^{ss} , T_{cso}^{ss} given as initial values, the outlet warm and cold seawater temperatures T_{wso}^{ss} , T_{cso}^{ss} and state quantities in 4 points were determined by bisection method such that

$$\left| 1 - \frac{Q_e}{Q_{ws}^{ss}} \right| < \varepsilon_e, \quad \left| 1 - \frac{Q_c}{Q_{cs}^{ss}} \right| < \varepsilon_c, \quad (11)$$

hold, where ε_e and ε_c are sufficiently small positive numbers which represent the error bounds. Thus, the static calculation shows the nonlinearity for state quantities. However, in the previous researches, the nonlinearity has never been explicitly expressed. Therefore, in this section, the nonlinearity in static calculation is clarified.

In this research, specific enthalpy h , pressure p , specific entropy s and specific volume v are calculated by 1st order polynomials of evaporation and condensation temperatures T_e , T_c ,

$$h_v = a_{hv0} + a_{hv1} T \quad (\text{for saturated vapor}) \quad (12)$$

$$h_l = a_{hl0} + a_{hl1} T \quad (\text{for saturated liquid}) \quad (13)$$

$$p = a_{p0} + a_{p1} T \quad (14)$$

$$s_v = a_{sv0} + a_{sv1} T \quad (\text{for saturated vapor}) \quad (15)$$

$$s_l = a_{sl0} + a_{sl1} T \quad (\text{for saturated liquid}) \quad (16)$$

$$v_l = a_{vl0} + a_{vl1}T \quad (\text{for saturated liquid}), \quad (17)$$

where $T = T_e$ or T_c , and the coefficients of polynomials were obtained from the approximation of steam table for Ammonia (Haar and Gallagher (1974)). The temperatures T_e , T_c are calculated from logarithmic mean temperature and overall heat transfer coefficient:

$$T_e = -b_{e0} + b_{e1}T_{wso}^{ss} \quad (18)$$

$$T_c = b_{c0} - b_{c1}T_{cso}^{ss}, \quad (19)$$

where

$$b_{e0} = \frac{T_{wsi}}{\exp\{UA_e/(m_{ws}c_p)\} - 1} \quad (20)$$

$$b_{e1} = \frac{\exp\{UA_e/(m_{ws}c_p)\}}{\exp\{UA_e/(m_{ws}c_p)\} - 1} \quad (21)$$

$$b_{c0} = \frac{T_{csi}}{1 - \exp\{UA_c/(m_{cs}c_p)\}} \quad (22)$$

$$b_{c1} = \frac{\exp\{UA_c/(m_{cs}c_p)\}}{1 - \exp\{UA_c/(m_{cs}c_p)\}}, \quad (23)$$

U is the overall heat transfer coefficient, and A_e (A_c) is the heat transfer area of evaporator (condenser). The other relations about static calculation are similar with those in Goto et al. (2017).

For (5) and (6), from (7)-(10), (12)-(23) and the other relations we have

$$k_{e1}T_{wso}^{ss} + k_{e2}T_{wso}^{ss}T_{cso}^{ss} + k_{e3}(T_{cso}^{ss})^2 + k_{e4}T_{cso}^{ss} + k_{e5} = 0 \quad (24)$$

$$k_{c1}(T_{cso}^{ss})^2 + k_{c2}T_{cso}^{ss} - k_{c3}T_{wso}^{ss}T_{cso}^{ss} - k_{c4}T_{wso}^{ss} + k_{c5} = 0, \quad (25)$$

where

$$k_{e1} = a_{hv1}b_{e1} - b_{e1}a_{p1}a_{vl0} - b_{e1}b_{c0}a_{p1}a_{vl1} + \frac{m_{ws}c_p}{m_{wf}}$$

$$k_{e2} = b_{e1}b_{c1}a_{p1}a_{vl1}$$

$$k_{e3} = a_{p1}a_{vl1}b_{c1}^2$$

$$k_{e4} = b_{c1}a_{hl1} - b_{c1}a_{p1}a_{vl0} - 2b_{c0}b_{c1}a_{p1}a_{vl1}$$

$$- b_{e0}b_{c1}a_{p1}a_{vl1}$$

$$k_{e5} = a_{hv0} - a_{hv1}b_{e0} + a_{hl0} - b_{c0}a_{hl1} + b_{e0}a_{p1}a_{vl0}$$

$$+ b_{c0}a_{p1}a_{vl0} + b_{e0}b_{c0}a_{p1}a_{vl1} + b_{c0}^2a_{p1}a_{vl1}$$

$$- \frac{m_{ws}c_pT_{wsi}}{m_{wf}}$$

$$k_{c1} = b_{c1}a_{sl1}(b_{c1}a_{hl1} - b_{c1}a_{hv1})$$

$$- m_{cs}c_p(b_{c1}a_{sv1} + b_{c1}a_{sl1})$$

$$k_{c2} = b_{c1}a_{sl1}(a_{hv0} + a_{hv1}b_{c0} + a_{hl0} - b_{c0}a_{hl1})$$

$$+ (a_{sv0} + b_{e0}a_{sv1} - a_{sl0} - b_{c0}a_{sl1})$$

$$\cdot (b_{c1}a_{hl1} - b_{c1}a_{hv1})$$

$$- m_{cs}c_p(a_{sv0} - b_{c0}a_{sv1} - a_{sl0} - b_{c0}a_{sl1})$$

$$+ m_{cs}c_pT_{csi}(b_{c1}a_{sv1} + b_{c1}a_{sl1})$$

$$k_{c3} = b_{e1}a_{sv1}(b_{c1}a_{hl1} - b_{c1}a_{hv1})$$

$$k_{c4} = b_{e1}a_{sv1}(a_{hv0} + a_{hv1}b_{c0} + a_{hl0} - b_{c0}a_{hl1})$$

$$k_{c5} = (a_{sv0} + b_{e0}a_{sv1} - a_{sl0} - b_{c0}a_{sl1})$$

$$\cdot (a_{hv0} + a_{hv1}b_{c0} + a_{hl0} - b_{c0}a_{hl1})$$

$$+ m_{cs}c_pT_{csi}(a_{sv0} - b_{c0}a_{sv1} - a_{sl0} - b_{c0}a_{sl1}).$$

Since the equations (24) and (25) are severely nonlinear in m_{ws} , m_{cs} and m_{wf} , controllers for the determination of them are difficult to design directly.

Here, in this research, the power output W is defined by

$$W = \eta_t m_{wf}(h_1 - h_2), \quad (26)$$

where η_t is the turbine efficiency. By the similar manner for (5) and (6) explained above, we also have a severely nonlinear expression of $W(t)$:

$$W = g(T_{wso}, T_{cso}, Q_{ws}, Q_{cs}, m_{ws}, m_{cs}, m_{wf}). \quad (27)$$

The explicit expression of g is omitted due to lack of space.

3. CONSTRUCTION OF STATE SPACE MODEL

In this section, a state space model for OTEC plant using double-stage Rankine cycle is constructed, where as the input $u(t)$ and output $y(t)$, warm seawater flow rate $m_{ws}(t)$ and power output $W(t)$ are considered, respectively:

$$u(t) = m_{ws}(t) \quad (28)$$

$$y(t) = W(t). \quad (29)$$

Defining a vector

$$x(t) = [T_{wso}(t) \ T_{cso}(t) \ Q_{ws}(t) \ Q_{cs}(t)]^T, \quad (30)$$

we have

$$\dot{x}(t) = Ax(t) - Ax^{ss}(t) \quad (31)$$

from (1)-(4), where

$$x^{ss}(t) = [T_{wso}^{ss}(t) \ T_{cso}^{ss}(t) \ Q_{ws}^{ss}(t) \ Q_{cs}^{ss}(t)]^T$$

$$A = \text{diag} \left\{ -\frac{1}{\tau_{T_{wso}}}, -\frac{1}{\tau_{T_{cso}}}, -\frac{1}{\tau_{Q_{ws}}}, -\frac{1}{\tau_{Q_{cs}}} \right\}.$$

As mentioned above, the vector $x^{ss}(t)$ is the nonlinear function of $m_{ws}(t)$:

$$x^{ss} = f(m_{ws}). \quad (32)$$

In this research, linear approximation of $f(m_{ws})$ is adopted as one of the simplest expression:

$$f(m_{ws}) \approx \alpha_1 m_{ws} + \alpha_0, \quad (33)$$

where the coefficient vectors α_0 and α_1 are determined by simulations using the conventional simple dynamic model. On the other hand, linear approximation of $g(T_{wso}, T_{cso}, Q_{ws}, Q_{cs}, m_{ws}, m_{cs}, m_{wf})$ with respect to T_{wso} and T_{cso} is considered:

Table 1. Conditions for numerical simulations

Parameter	Value
Warm seawater inlet temperature T_{wsi} (°C)	29.0
Cold seawater inlet temperature T_{csi} (°C)	9.0
Mass flow rate of cold seawater m_{cs} (kg/s)	36.94
Mass flow rate of working fluid m_{wf} (kg/s)	0.35
Overall heat transfer coefficient (kW/(m ² ·K))	2.0
Heat transfer area of evaporator (m ²)	87.4
Heat transfer area of condenser (m ²)	87.4
Specific heat of seawater c_w (J/(s·°C))	4179
Time constant $\tau_{T_{wso}}$ (s)	3.0
Time constant $\tau_{T_{cso}}$ (s)	3.1
Time constant $\tau_{Q_{ws}}$ (s)	4.0
Time constant $\tau_{Q_{cs}}$ (s)	4.0
Turbine efficiency η_t	0.85
Error bounds ε_e and ε_c	0.0001

$$g(T_{wso}, T_{cso}) \approx \beta_{w1}T_{wso} + \beta_{c1}T_{cso} + \beta_0 \quad (34)$$

under the assumption that the behavior of $W(t)$ can be sufficiently captured by T_{wso} and T_{cso} , where the coefficients β_{w1} , β_{c1} and β_0 are determined by simulations using the conventional simple dynamic model.

Thus, by substituting (33) and (34) into (31) and (27), we obtain

$$\dot{x}(t) = Ax(t) + Bu(t) + \zeta_x \quad (35)$$

$$y(t) = Cx(t) + \zeta_y, \quad (36)$$

where

$$B = -A\alpha_1, \quad \zeta_x = -A\alpha_0$$

$$C = [\beta_{w1} \ \beta_{c1} \ 0 \ 0], \quad \zeta_y = \beta_0.$$

4. SIMULATION RESULTS

In order to evaluate the state space model proposed in this research, numerical simulations were conducted. The simulation conditions are listed in Table 1.

4.1 Model Construction

In order to obtain linear approximations (33) and (34), simulation results by static calculation using conventional model for $m_{ws} = 38$ -84 kg/s were used. Then, we obtained

$$\alpha_1 = \begin{bmatrix} 2.951 \times 10^{-2} \\ -1.3216 \times 10^{-4} \\ 4.0246 \\ -20.402 \end{bmatrix}, \quad \alpha_0 = \begin{bmatrix} 25.43 \\ 11.665 \\ 427.64 \times 10^3 \\ 4.114 \times 10^5 \end{bmatrix}$$

$$\beta_{w1} = -0.90775, \quad \beta_{c1} = -314.22, \quad \beta_0 = 3703.$$

The approximated results are depicted in Figs. 2 and 3.

4.2 Step Responses

Figs. 4 and 5 are the step responses for $m_{ws} = 40$ -50 kg/s and $m_{ws} = 20$ -30 kg/s, respectively.

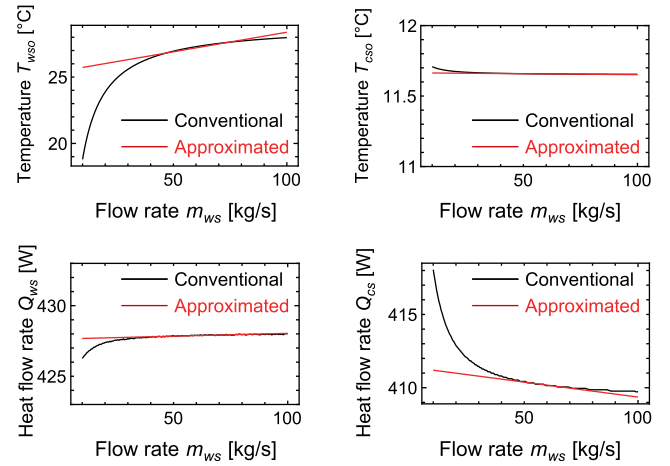


Fig. 2. Approximations of temperatures and heat flow rates

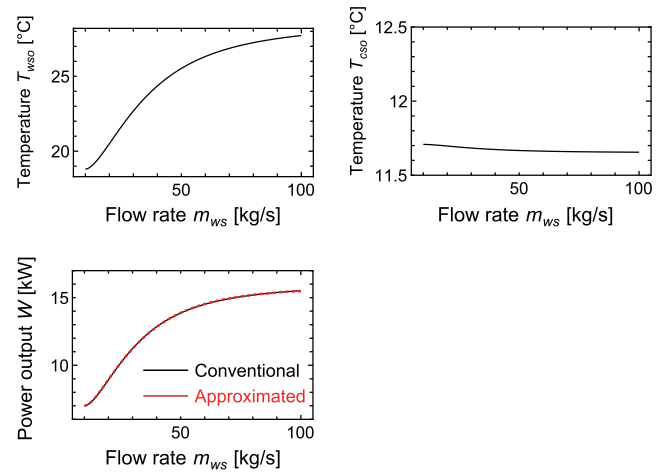


Fig. 3. Approximation of power output

4.3 Control Simulations

Furthermore, control simulations were carried out. To determine the control input $u(t) = m_{ws}(t)$, PI controller was applied:

$$m_{ws}(t) = m_{ws0} + K_p \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau \right), \quad (37)$$

where $e(t) = W_{ref} - W(t)$ is the control error for the target power output W_{ref} , and $m_{ws0} = 39.72$ kg/s is the standard flow rate. In Fig. 6, a simulation result for $W_{ref} = 15.2$ kW is shown, where the parameters K_p and T_i were set as $K_p = 0.2$ (kg/s)/kW and $T_i = 0.05$ s, respectively. In Fig. 7, another simulation result for $W_{ref} = 12$ kW is shown, where the parameters K_p and T_i were set as $K_p = 0.03$ (kg/s)/kW and $T_i = 0.05$ s, respectively. The parameters K_p and T_i were determined through simulations using the conventional model.

5. DISCUSSION

5.1 Model Construction

In this research, the static calculation in the simple dynamic model is explicitly described. Although the approx-

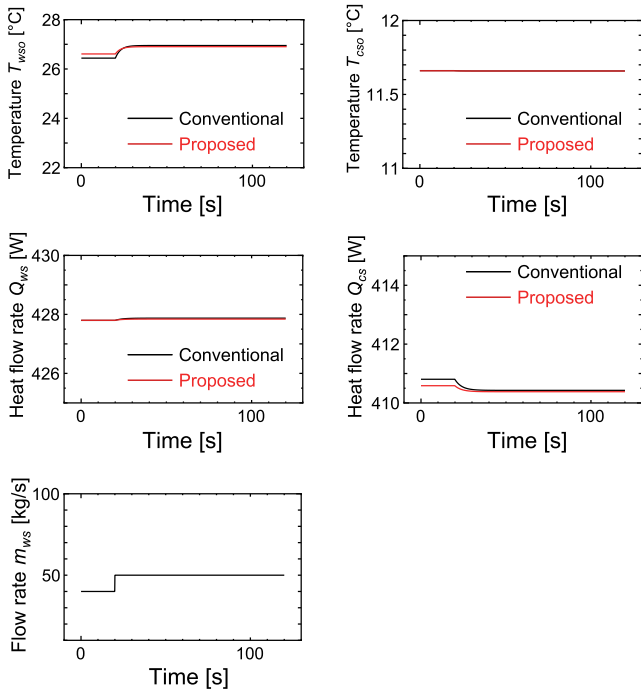


Fig. 4. Simulation result of step response for $m_{ws} = 40-50$ kg/s

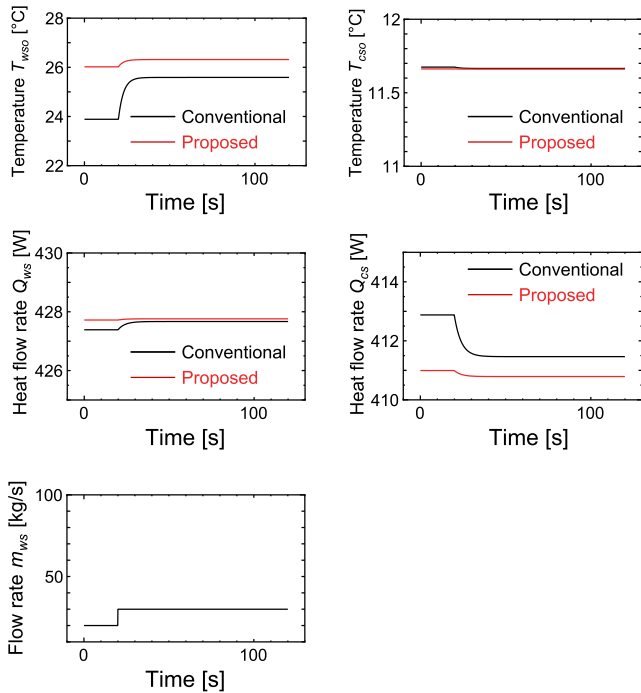
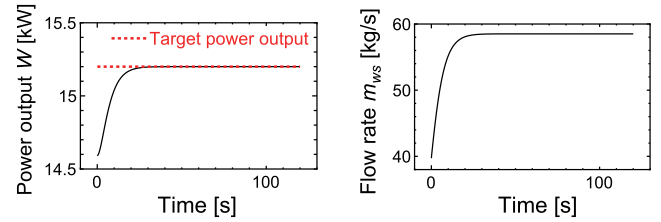
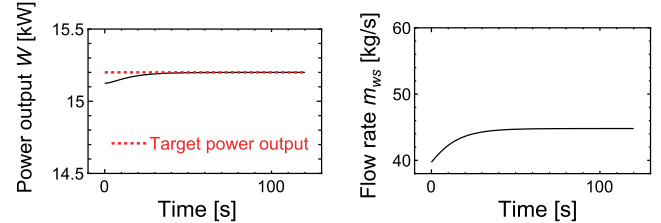


Fig. 5. Simulation result of step response for $m_{ws} = 20-30$ kg/s

imated equations described by 1st order polynomials were used, the resultant relations were severely nonlinear and so complicated. This result clarifies the difficulty in the construction of control mechanisms using flow rates $m_{ws}(t)$, $m_{cs}(t)$ and $m_{wf}(t)$ based on the model. Therefore, to cope with this issue, in this research, linear approximation is considered. From the linear approximation we can derive an linear time-invariant system described by (35) and (36)

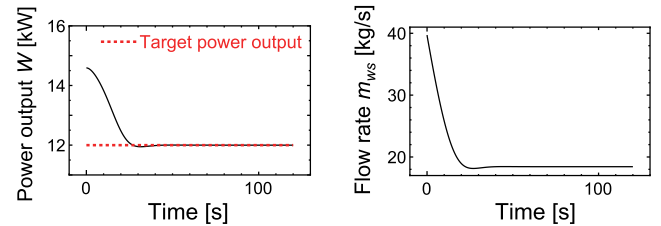


(a) Simulation result by conventional model

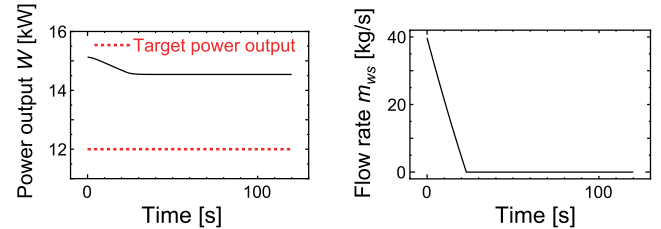


(b) Simulation result by proposed model

Fig. 6. Simulation results of PI control (Target power output $W_{ref} = 15.2$ kW)



(a) Simulation result by conventional model



(b) Simulation result by proposed model

Fig. 7. Simulation results of PI control (Target power output $W_{ref} = 12$ kW)

easily. This system is useful in designing the control system by applying control theories based on state space model. However, the validity (or applicable range) of the linear approximation should be carefully verified corresponding to the purpose.

Here, let us check the similarity and difference of the proposed model with conventional ones (e.g., in Aosaki et al. (2019), Matsuda et al. (2017-4) etc.). In both models, the dynamics on temperatures and heat flow rates are represented by 1st order systems. This is the similarity. However, in the proposed model, approximated equations (12)-(17) in 2.2 are represented by 1st order polynomials. On the other hand, approximated equations in the conventional models have higher order polynomials. This is the difference.

Although the power output $W(t)$ was selected as the output $y(t)$ for the comparison of the proposed model with conventional one, we can adopt any other quantities corresponding to the purpose.

5.2 Simulation Results

In order to check the behavior of the proposed model, 2 kinds of step responses were considered as shown in Figs. 4 and 5. Fig. 4 is the step response for $m_{ws} = 40\text{--}50$ kg/s. This result implies that the simulation result by proposed model was sufficiently close to that by conventional model since the linear approximation was considered for $m_{ws} = 38\text{--}84$ kg/s. On the other hand, Fig. 5 is the step response for $m_{ws} = 20\text{--}30$ kg/s. This figure indicates that the simulation result (especially, for T_{wso}) was not close since the input m_{ws} was out of range of the linear approximation. Therefore, the range of linear approximation should be appropriately chosen.

For the comparison of the control results, simulations using PI control system were performed as shown in Figs. 6 and 7. The results in Fig. 6 clarifies the usefulness of the proposed model since the power output $W(t)$ reached the target one W_{ref} in both cases. However, in Fig. 7, the power output $W(t)$ did not reach the target one W_{ref} when the proposed model was used. This result may be caused by the linear approximation. Therefore, further investigation of the modeling using state space model with linear approximation should be required.

6. CONCLUSION

In this research, a state space model for OTEC plant using Rankine cycle was proposed by applying linear approximation to an existing model of simple dynamic model. The complexity of the static calculation in the simple dynamic model was confirmed analytically. To obtain a model for the application of advanced control theories, a state space model was constructed by linear approximation for the static calculation. The simulation results of step response for the proposed model showed its usefulness and limitation. Furthermore, the simulation results of control by PI controller indicated that the control system using proposed model could be valid. However, the simulation results also exhibited the necessity of further improvement of the proposed model. In future works, systematic control system design procedure will be investigated by using the proposed model. Furthermore, the control system including the proposed model will be evaluated through experiments using an actual experimental plant.

REFERENCES

- Y. Aosaki, Y. Matsuda, T. Sugi, S. Goto, T. Yasunaga and Y. Ikegami. Model Construction of OTEC Plant Using Double-stage Rankine Cycle with Time Delay by Considering Separator and Working Fluid Tank. *Proceedings of 2019 12th Asian Control Conference (ASCC2019)*, 358–363, 2019.
- S. Goto, Y. Matsuda, T. Sugi, T. Morisaki, T. Yasunaga and Y. Ikegami. Web Application for OTEC Simulator Using Double-stage Rankine Cycle. *IFAC PapersOnLine*, 50:121–128, 2017.
- S. Goto, Y. Motoshima, T. Sugi, T. Yasunaga, Y. Ikegami and M. Nakamura. Construction of simulation model for OTEC plant using Uehara cycle. *Electrical Engineering in Japan*, 176:1–13, 2011.
- L. Haar and J.S. Gallagher. Thermodynamic Properties of Ammonia. *J. Phys. Chem.*, 7:635–792, 1974.
- Y. Ikegami, T. Yasunaga and T. Morisaki. Ocean Thermal Energy Conversion Using Double-Stage Rankine Cycle. *Journal of Marine Science and Engineering*, 6:21, 2018.
- S. Jitsuvara, M. Nakamura, Y. Ikegami and H. Uehara. Controller Design for Vapor Temperatures of OTEC Plant Based on Reduced Order Model. *Transactions of the Society of Instrument and Control Engineers*, 30: 1060–1068, 1994 (in Japanese).
- A. Khaligh and O.C. Onar. *Energy Harvesting, Solar, Wind, and Ocean Energy Conversion Systems*. CRC Press, 2010.
- Y. Matsuda, R. Oouchida, T. Sugi, S. Goto, T. Yasunaga and Y. Ikegami. Power Generation Control of OTEC Plant Using Double-stage Rankine Cycle with Target Power Output Variation by Simultaneous Regulation of Multiple Flow Rates. *Proceedings of SICE Annual Conference 2019*, 1412–1417, 2019.
- Y. Matsuda, R. Oouchida, T. Sugi, S. Goto, T. Morisaki, T. Yasunaga and Y. Ikegami. Simultaneous Regulation of Multiple Flow Rates for Power Generation Control of OTEC Plant Using Double-stage Rankine Cycle. *Proceedings of SICE Annual Conference 2018*, 983–988, 2018.
- Y. Matsuda, D. Urayoshi, S. Goto, T. Sugi, T. Morisaki, T. Yasunaga and Y. Ikegami. Seawater Flow Rate Regulation of OTEC Plant Using Uehara Cycle by Considering Warm Seawater Temperature Variation. *International Journal of Innovative Computing, Information and Control*, 13:2123–2131, 2017.
- Y. Matsuda, S. Goto, T. Sugi, T. Morisaki, T. Yasunaga and Y. Ikegami. Evaluation of a Liquid Level Model of Separator in an OTEC Experimental Plant Using Uehara Cycle via Different Experimental Data. *Proceedings of SICE Annual Conference 2017*, 1490–1495, 2017.
- Y. Matsuda, S. Goto, T. Sugi, T. Morisaki, T. Yasunaga and Y. Ikegami. An Improvement on LQG Controller for Liquid Level Control of Separator in an OTEC Experimental Plant Using Uehara Cycle. *Proceedings of SICE Annual Conference 2017*, 1496–1501, 2017.
- Y. Matsuda, S. Goto, T. Sugi, T. Morisaki, T. Yasunaga and Y. Ikegami. Control of OTEC Plant Using Double-stage Rankine Cycle Considering Warm Seawater Temperature Variation. *IFAC PapersOnLine*, 50:135–140, 2017.
- Y. Matsuda, S. Goto, T. Sugi, T. Morisaki, T. Yasunaga and Y. Ikegami. Liquid Level Control of Separator in an OTEC Plant with Uehara Cycle. *Transactions of the Institute of Systems, Control and Information Engineers*, 29:535–543, 2016.
- H. Uehara, Y. Ikegami and T. Nishida. Performance analysis of OTEC system using a cycle with absorption and extraction processes. *Transactions of the Japan Society of Mechanical Engineers B*, 64:2750–2755, 1998 (in Japanese).