Liquid Level Control of Separator in an OTEC Plant with Uehara Cycle*

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In this paper, the liquid level control of separator in an ocean thermal energy conversion (OTEC) experimental plant with Uehara cycle is considered. A liquid level model of separator is constructed based on not only experimental data about the characteristics between the liquid level and the valve opening but also simulations using a stochastic model. The control system for the liquid level control of separator is designed by employing the LQG control theory. The usefulness of both the liquid level model and the control system is confirmed through simulations.

1. Introduction

Ocean thermal energy conversion (OTEC) plant yields electricity by heat energy from the temperature difference between warm seawater at surface and cold seawater in depth. Although there are many researches on OTEC systems with Rankine cycle [1–5] and related works such as desalination system [6], potential evaluation [7], controller design [8,9] and so on, in general, the thermal efficiency of the OTEC plants with Rankine cycle is not so high (about 3-4 [%]) due to the small temperature difference.

In order to improve the efficiency, an OTEC plant with Uehara cycle has been developed [10–16]. In particular, in [12], a model for the numerical simulation of the OTEC plant with Uehara cycle was constructed based on some physical laws such as the mass balance, the heat balance and so on. Although the model in [12] is intended for the plant design and the controller design of general class of OTEC plants with Uehara cycle, the model has some difficulties such as the limited convergence of the optimization with respect to the heat balance, the heavy calculation time and so forth due to the complicated structure of the plant.

Furthermore, the liquid level control of separator in an OTEC experimental plant with Uehara cycle at Institute of Ocean Energy, Saga University (IOES) [17] has been investigated [13–16] since it is indispensable to safety and steady operation of the OTEC plant with Uehara cycle due to the use of an ammonia-water mixture as the working fluid, where the detailed mechanism of the plant is explained in Section 2. In order to cope with a problem that the model in [12] does not contain the liquid level of separator, in [13], a model of evaporator and separator in the OTEC plant with Uehara cycle for liquid level control was constructed by using some physical laws and experimental data, where, in the model construction, physical laws were mainly used to apply to general class of OTEC plants with Uehara cycle. However, as pointed out in [14], the model in [13] did not reflect the experimental behavior at all, and the reason has never been clarified because of the complicated structure of OTEC plant with Uehara cycle.

To establish a constructive and practical methodology to solve this problem, in this paper, a liquid level model of separator in the OTEC experimental plant with Uehara cycle based on experimental data is proposed by extending the methodology for model construction via weighted least squares in [15]. Indeed, it is shown that better liquid level model can be obtained without the trial-and-error selection of the weights in [15] by using a method with a stochastic process in this paper. Furthermore, based on the liquid level model in this paper, a control system for the liquid level control of separator is designed by improving the state space representation of the liquid level model, which was considered in the conference paper [16].

The rest of this paper is organized as follows: the structure and the principle of the OTEC plant with Uehara cycle are explained in Section 2. The structure of separator and the control objective are also
stated. In Section 3., a liquid level model of separator in the OTEC experimental plant with Uehara cycle is proposed by integrating the relationship obtained from experimental data with simulations using a stochastic model. The proposed model is also evaluated through simulations. A control system for the liquid level control of separator in the OTEC experimental plant with Uehara cycle is designed by using the LQG (Linear Quadratic Gaussian) control theory [18] in Section 4. The effectiveness of the designed control system is verified through simulation result. Section 5. is devoted to the discussion about the liquid level model of separator and the liquid level control system considered in this paper. Finally, Section 6. summarizes this paper.

2. OTEC Plant with Uehara Cycle

The structure of the OTEC experimental plant with Uehara cycle at IOES is illustrated in Fig. 1. The OTEC plant with Uehara cycle mainly consists of evaporator, separator, turbines, generator, absorber, condenser, heater, regenerator, diffuser, working fluid pumps and tanks, where they are connected by pipes as shown in Fig. 1.

The procedure for the power generation by the OTEC plant with Uehara cycle is as follows: the working fluid, which is an ammonia-water mixture, is partly changed from liquid to wet vapor in the evaporator by the heat exchange to the warm water after passing through the heater and the regenerator by the working fluid pump 1. The wet vapor is separated into vapor and liquid in the separator. The vapor is sent to the turbine 1 to do the work. Then, part of vapor is extracted and sent to the heater. The rest of the vapor is sent to the absorber after sending to the turbine 2 to do the work. The power generation is conducted by the generator connected to the turbines. The liquid working fluid in the separator is sent to the regenerator to heat the working fluid to be sent to the evaporator. The liquid working fluid is sent from the regenerator to the absorber through the diffuser. In the absorber, the vapor working fluid is absorbed by the liquid working fluid. The working fluid with vapor is completely condensed to the liquid after sending to the condenser. The part of the vapor working fluid which is extracted from the turbine 1 heats the working fluid sent from the working fluid pump 1 to the evaporator, and meets it before reaching the regenerator.

The structure of the separator in the OTEC experimental plant with Uehara cycle is shown in Fig. 2. As explained above, the working fluid through the evaporator consists of vapor and liquid. In the separator, the vapor and the liquid of the working fluid are separated. The vapor is finally sent to turbines connected to the generator for power generation. The liquid is stored in the tank of separator.

The liquid level $H(t)$ should maintain an appropriate level $H_{\text{ref}}$ from the viewpoints of safety and steady operation of OTEC plant with Uehara cycle, where in the following arguments, the description of time $t$ (e.g., $(t)$ in $H(t)$) is sometimes omitted for notational simplicity. Indeed, if the liquid overflows the tank of separator into the turbine by rising above a level, the turbine may be broken. This means that the safety of the OTEC plant with Uehara cycle cannot be retained. On the other hand, if the tank of separator is entirely empty by falling the liquid level, the vapor is sent from the bottom of tank to another components and the turbine output may eventually decrease. This implies that the steady operation of the OTEC plant with Uehara cycle cannot be realized. Therefore, the liquid level $H(t)$ of separator in OTEC plant with Uehara cycle is important. Although the liquid working fluid in the tank of separator is sent to the regenerator, the flow rate of liquid working fluid can be changed by adjusting the valve opening $u(t)$ of the diffuser, where as the valve, a single seated globe valve is used in the OTEC experimental plant with Uehara cycle at IOES. This means that we can control the liquid level $H(t)$ of separator by changing the valve opening $u(t)$ appropriately.
3. Construction of Liquid Level Model of Separator

In this paper, a liquid level model of separator in an OTEC experimental plant with Uehara cycle is constructed based on the experimental data obtained from the actual experimental equipment in IOES since the model construction of the OTEC plant with Uehara cycle based on some physical laws is not easy due to its complexity.

3.1 Experiment for Model Construction

In this paper, a liquid level model is derived by considering the relationship between the valve opening $u(t)$ and the variations of the liquid level $H(t)$. In order to grasp the characteristics of the liquid level of separator, experiments were conducted by using the actual OTEC experimental plant at IOES, where the experimental conditions are listed in Table 1.

| Parameter          | Value  |
|--------------------|--------|
| Temperature of warm water | 30 $^\circ$C |
| Temperature of cold water   | 9 $^\circ$C |
| Mass flow rate of warm water  | 400 [t/h] |
| Mass flow rate of cold water    | 400 [t/h] |
| Mass flow rate of working fluid  | 8 [t/h]   |
| Sampling interval            | 1 [s]    |

In the experiments, the variation of the liquid level $H(t)$ was measured under the condition that the valve opening $u(t)$ was kept constant, where five values of the valve opening were adopted since they are usually used during manual operation of the actual OTEC experimental plant. The experimental results are shown in Fig. 3, where (a)-(e) in Fig. 3 are the results by measuring the liquid level $H(t)$ for constant valve openings corresponding to $u(t) = 35 \%$, 40 \%, 45 \%, 50 \%, 55 \%, respectively, the solid circles are the experimental data obtained by the experiments and the solid lines are the fitted lines via least squares.

Thus, we obtain the relationship between the valve opening and the slope as depicted in Fig. 4.

3.2 Construction of Liquid Level Model

By regarding the slope of liquid level $H(t)$ in the above experimental results as its time variation $\frac{dH}{dt}$, we have a relationship:

$$\frac{dH}{dt} = f(u),$$

where $f(u)$ is the polynomial

$$f(u) = a_0 + a_1 u + \cdots + a_m u^m$$
whose coefficients \( \{a_0, a_1, \cdots, a_m\} \) are determined via least squares as shown in Fig.4. The coefficients \( \{a_0, a_1, \cdots, a_m\} \) for \( m = 1, 2 \) and 3 are listed in Table 2.

In order to verify the behavior of the relationship eq. (1), simulations were carried out by using MATLAB/simulink. The simulation results for given valve opening are depicted in Fig.5. This figure implies that, in any cases, the difference \( e_H(t) = H_{\text{exp}}(t) - H(t) \) between the simulation result \( H(t) \) and the experimental one \( H_{\text{exp}}(t) \) becomes larger as time goes by.

Since the error \( e_H(t) \) satisfies
\[
\frac{dH_{\text{exp}}}{dt} = f(u) + \frac{de_H}{dt},
\] (3)
we can regard \( \frac{de_H}{dt} \) as the unmodeled part for the liquid level of separator by comparing eq. (3) and eq. (1). Therefore, in this paper, instead of eq. (1), we adopt
\[
\frac{dH}{dt} = f(u) + w(t)
\] (4)
as the liquid level model of separator, where \( w(t) \) is assumed to be white Gaussian noise with mean \( \mu_w \) and variance \( \sigma_w^2 \).

As listed in Table 3, the mean \( \mu_w \) and the standard deviation \( \sigma_w \) (or the variance \( \sigma_w^2 \)) are identified by calculating the mean and the standard deviation of data \( \frac{de_H}{dt} \) obtained from the simulation in Fig.5 (c).

### 3.3 Evaluation of Liquid Level Model

In order to evaluate the proposed liquid level model eq. (4) of separator, 20 simulations with different seeds for the numerical generation of the random process \( w(t) \) were conducted by using MATLAB/Simulink, where the valve opening \( u(t) \) in Fig.5 (b) was used as the input. The simulation results are evaluated by IAE (integral of absolute value of error) \( \int_{t_s}^{t_f} |e_H(t)| \, dt \) with \( t_s = 1 \) [s] and \( t_f = 329 \) [s]. The results are listed in Table 4.

Two simulation results for minimal IAE (best case in this paper) and maximal IAE (worst case in this paper) are shown in Fig.6.

Simulation results state that, in any cases, the influence of the order \( m \) of the polynomial eq. (2) is negligibly small. Furthermore, any IAEs for simulations by the proposed model eq. (4) with \( m = 1 \) are smaller than that for the simulation by eq. (1) (or eq. (4) without \( w(t) \)) with \( m = 1 \). Therefore, in this paper, as the liquid level model, we adopt eq. (4) with \( m = 1 \).

### 4. Design of Liquid Level Control System

In order to verify the applicability of the proposed liquid level model eq. (4) to the liquid level control of separator in an OTEC experimental plant with Uehara cycle, a control system is designed. Since the liquid level model eq. (4) contains the stochastic process \( w(t) \) expressed by the white Gaussian noise, in this paper, LQG control theory is employed.

#### 4.1 Design of Control System

By defining
\[
x(t) = \left[ e(t) \int_0^t e(\tau) \, d\tau \right]^T
\] (5)
Table 4  IAE on simulation results for model evaluation

| Seed | $m = 1$ | $m = 2$ | $m = 3$ |
|------|--------|--------|--------|
| 0    | 46.218 | 49.106 | 48.019 |
| 1    | 78.638 | 82.615 | 80.430 |
| 2    | 49.399 | 53.202 | 51.835 |
| 3    | 80.683 | 85.088 | 82.549 |
| 4    | 185.63 | 193.80 | 189.07 |
| 5    | 101.23 | 106.97 | 106.30 |
| 6    | 61.672 | 65.185 | 63.745 |
| 7    | 45.401 | 48.156 | 47.597 |
| 8    | 51.023 | 54.024 | 52.531 |
| 9    | 82.045 | 85.501 | 82.645 |
| 10   | 108.21 | 113.03 | 109.68 |
| 11   | 69.371 | 73.717 | 72.382 |
| 12   | 167.99 | 175.24 | 170.93 |
| 13   | 108.11 | 114.92 | 113.33 |
| 14   | 46.846 | 49.951 | 48.694 |
| 15   | 67.973 | 70.979 | 69.136 |
| 16   | 49.975 | 52.931 | 51.367 |
| 17   | 60.762 | 65.153 | 64.568 |
| 18   | 91.354 | 95.439 | 92.989 |
| 19   | 80.543 | 83.872 | 81.064 |
| Mean | 81.654 | 85.999 | 83.943 |
| Standard Deviation | 38.455 | 39.852 | 38.946 |
| Min. | 45.401 | 48.156 | 47.597 |
| Max. | 185.63 | 193.80 | 189.07 |
| without $w(t)$ | 241.50 | 86.429 | 107.02 |

\[
e(t) = H_{\text{ref}} - H(t)
\]

\[
\xi_u(t) = -\alpha_0 - \alpha_1 u(t) - \mu_w,
\]

\[
w_0(t) = w(t) - \mu_w,
\]

we have from eq. (4) the following state space representation:

\[
\dot{x}(t) = Ax(t) + B\xi_u(t) + Gw_0(t),
\]

where

\[
A = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad G = \begin{bmatrix} -1 \\ 0 \end{bmatrix}
\]

and the target level $H_{\text{ref}}$ is assumed to be constant from the control purpose. In the OTEC experimental plant at IOES, the liquid level of separator can be measured directly. In this paper, the observation data $y(t)$ is assumed to be represented by

\[
y(t) = H(t) + v_0(t),
\]

where $v_0(t)$ is assumed to be white Gaussian noise with zero mean and variance $\sigma_v^2$. The standard deviation $\sigma_v$ is given by $3\sigma_v = 1.5 \times 10^{-2} [\text{m}]$ or $\sigma_v = 5.0 \times 10^{-3} [\text{m}]$ from the accuracy $(H(t) \pm 1.5 \times 10^{-2} [\text{m}])$ of the measurement equipment.

Furthermore, by defining

\[
y_H(t) = y(t) - H_{\text{ref}}
\]

and its integral

\[
\zeta_v(t) = \int_0^t y_H(\tau) \, d\tau,
\]

we have the representation of the observation mechanism:

\[
\zeta_v(t) = Cx(t) + \eta_0(t),
\]

where $C = [0 \ 1]$.

Although the process $\eta_0(t)$ is defined by

\[
\eta_0(t) = \int_0^t v_0(\tau) \, d\tau,
\]

in the design of estimation mechanism below, $\eta_0(t)$ is regarded as the white Gaussian noise with zero mean and variance $\alpha \sigma_v^2$, where the parameter $\alpha (> 0)$ is determined appropriately.

For the system represented by eq. (9) and eq. (14), we construct a feedback control law

\[
\xi_u(t) = -F \dot{x}(t).
\]

The feedback gain $F$ is determined so as to minimize

\[
\left. J_e = \lim_{T \to \infty} \frac{1}{T} \mathcal{E} \left\{ \int_0^T [x^T(t)Qx(t) + \xi_u^T(t)R\xi_u(t)] \, dt \right\} \right|_{(17)}
\]

with given positive semidefinite matrix $Q$ and positive
The estimate $\hat{x}(t)$ of $x(t)$ is obtained from the stationary Kalman filter:

$$\dot{\hat{x}}(t) = A\hat{x}(t) + B\xi(t) + K\{\xi(t) - C\hat{x}(t)\}. \quad (18)$$

It is well-known (cf. e.g., [18]) that both $F$ and $K$ can be calculated by solving the corresponding algebraic Riccati equations numerically.

Indeed, for given $Q = 1.0 \times 10^3 I$, $R = 1.0 \times 10^7$, $\alpha = 1.0 \times 10^2$, the following matrices were obtained by using MATLAB:

$$F = \begin{bmatrix} 1.4177 \times 10^{-1} & 1.0000 \times 10^{-2} \\ \end{bmatrix}$$

$$K = \begin{bmatrix} -4.1164 \times 10^{-1} & -9.0734 \times 10^{-1} \end{bmatrix}^T, \quad (19)$$

where the matrices $Q$, $R$ and the parameter $\alpha$ were selected by trial and error, and $I$ stands for the identity matrix with appropriate dimension.

4.2 Control Simulation

To confirm the usefulness of the designed control system, a control simulation was carried out by using MATLAB/Simulink. In the simulation, as the liquid level model, eq. (4) with $m = 1$ and the seed No. 7 for best case in this paper was adopted. Furthermore, the process $\eta_0(t)$ in eq. (15) was used for the observation mechanism eq. (14). The target level $H_{\text{ref}}$ was set as $H_{\text{ref}} = 2.0$ [m]. The initial states of $x(t)$ and $\hat{x}(t)$ were given by $x(0) = [-0.5 \ 0]^T$ (i.e., $H(0) = 2.5$ [m]) and $\hat{x}(0) = [0 \ 0]^T$, respectively. The sampling interval was $1$ [s]. In Fig. 7, a simulation result is shown, where (a), (b), (c) and (f) are the time evolution of the liquid level $H(t)$, the valve opening $u(t)$, the noise $\eta_0(t)$ and the observation noise $v_0(t)$, respectively; and (c) and (d) are the error $e(t)$ and the integral $\int_0^t e(\tau)d\tau$ with their estimates, respectively. This figure reveals that the successful liquid level control of separator in OTEC experimental plant with Uehara cycle could be achieved.

5. Discussion

5.1 Liquid Level Model of Separator

The proposed liquid level model of separator requires some experimental data, and can be applied to existing OTEC plants with Uehara cycle only. Therefore, it is, in general, difficult to directly utilize the proposed model for the design of OTEC plant with Uehara cycle itself. However, since there is only one OTEC plant with Uehara cycle at IOES and even the specifications of each components are now under investigation, the proposed liquid level model of separator could be helpful to the meaningful development of OTEC plant with Uehara cycle from the viewpoint of its safely steady operation. Furthermore, if we can integrate the proposed liquid level model of separator into the existing model as in [12], the unknown influence of the liquid level of separator on the behavior of the OTEC plant with Uehara cycle may be clarified.

Although the experiment to acquire the data for model construction of liquid level is not so complicated, the simulation results of this paper show that suitable model can be constructed by only introducing a white Gaussian noise as a stochastic process. Further simulations with different seeds may bring better liquid level model in the sense of IAE. How-

![Fig. 7 A control simulation result](image-url)
5.2 Liquid Level Control System

The result of control simulation shows that the liquid level control can be achieved by using one of the most fundamental control mechanism from the stochastic control theory. This is an important fact for the application to the control of the actual OTEC plant with Uehara cycle in the future, where the current OTEC plant with Uehara cycle (or the other ones) at IOES does not have the environment for such control mechanisms sufficiently since the investigations of OTEC plants have mainly focused on their steady state properties. Therefore, the control mechanism in this paper may give a significant insight into the control of OTEC plant with Uehara cycle.

Here, let us verify the results of the control simulation in Fig. 7 in detail. Although the liquid level $H(t)$ seems to fluctuate around the target level $H_{\text{ref}} = 2.0$ [m] by the process $u(t)$ in the proposed model eq. (4), the simulation result implies that the sufficient control effect on the steady operation of the OTEC experimental plant with Uehara cycle could be achieved since the range was about $2.0 \pm 0.15$ [m]. The valve opening $u(t)$ could also be successfully regulated since it finally fluctuated around $\mathcal{E}(u) = -\frac{a_0 + \mu_w}{a_1} = 43.88$ [%] for steady state (or formally, $\frac{dH}{dt} = 0$). The estimation of the error $e(t)$ was appropriately done. On the other hand, we see from Fig. 7 (d) that as time goes by, the estimation error of the integral $\int_0^t e(\tau) d\tau$ tends to be larger. The enlargement of this estimation error may be caused by regarding the process $\eta(t)$ as the white Gaussian noise in the design of estimation mechanism. However, since the control result is not so heavily influenced by the estimation errors, it follows that there is no fatal problem, and therefore, the evaluation of the process $\eta(t)$ by the white Gaussian noise in the estimation mechanism design is effective in the liquid level control of separator considered in this paper.

6. Conclusions

In this paper, the liquid level control of separator in an OTEC experimental plant with Uehara cycle was considered. A liquid level model of separator was constructed by combining the experimental data with simulations using a stochastic model. The simulation results revealed that the introduction of stochastic process to the relationship obtained from experimental data enhanced the accuracy of the model in the sense of IAE. The introduced stochastic process also provided the linearity of the liquid level model, which led to the applicability of the LQG control theory to the liquid level control of separator. The control simulation result demonstrated the practical usefulness of the designed control system for the liquid level control of separator. By introducing the mathematically rigorous description such as stochastic differential equations into the equations considered in this paper, we may also enjoy the mathematical beauty.

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