Dynamic Characteristics and Modeling of a Directly Combined Binary Turbine System Consisting of a 40 kW Steam and a 30 kW R 11 Turbine*

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The dynamic behavior of a directly combined binary turbine system is investigated experimentally and theoretically in this work. In the theoretical investigation, the dynamic behavior of the system is discussed from the viewpoint of the network theory. In this case, the components of the system are represented as two- or three-port elements of the network and the vapor flow rate and shaft torque are appropriated for the through variable, and the vapor pressure and rotational speed for the across variable. As a result, a very simple network model is derived. The validity of the model is proven by comparison with the experimental results, which are the frequency responses examined with respect to the generator load changes. In addition, it is shown that the present model is very effective in predicting the dynamic behavior and the mechanism of power generation in the directly combined binary turbine systems.

Key Words: Power Plant, Combined Cycle, Steam Turbine, R 11 Turbine, Heat Exchanger, Process Dynamics, Binary Turbine System

1. Introduction

There are many methods that improve the cycle efficiency of conventional power systems⁽¹⁾⁻⁽⁵⁾. Some of them are particularly effective for low-temperature heat sources of approximately 100°C. One is an LBM (low-boiling-temperature medium compared with water) turbine system, e.g. an organic Rankine cycle⁽⁶⁾. If an LBM turbine system is employed in a conventional steam turbine system, the effectiveness of the power system will increase depending on the system conditions^{(7),(8)}. The authors call one of such systems a directly combined binary turbine system (Fig. 1). It consists of two turbine systems with different working fluids. In this system two turbines

are combined by using two components, one of which is an LBM vapor generator and the other a rotational shaft. In the LBM vapor generator, the LBM liquid is heated and vaporized by the steam turbine exhaust. The LBM vapor generator joins two turbines in thermal series. On the other hand, the rotational shaft joins two turbines directly in mechanical parallel. The rotational speed is controlled only by an electrohydraulic governor that is located at the inlet of the steam turbine. Therefore, the dynamic behavior of the directly combined binary turbine system is very complicated.

The effectiveness of the system is greatly influenced by the working fluids and operating points⁽⁹⁾. The refrigerant R 11 taken up in this study is not the best adaptable second medium for the system. It is employed on account of its thermodynamic properties and experimental convenience. In actual systems, the second medium should be selected taking into account environmental protection. It is of great urgency to develop new media to be used in place of CFCs. Considering that new media, the thermodynamic properties of which are similar to refrigerant R 11, will be developed, it is clear that this

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study is applicable to actual power systems even now.

Nomenclature

- A : Heat transfer area m^2
 D : Rotational conductance Nms
 G : Flow rate kg/s
 G^* : Apparent flow rate kg/s
 h : Specific enthalpy J/kg
 J : Rotational inertia kgm^2
 K : Heat transfer coefficient $\text{W}/(\text{m}^2 \cdot \text{K})$
 L : Generator load W
 m : Condensing ratio
 n : Rotational speed rad/s
 P : Pressure Pa
 r : Specific latent heat J/kg
 T : Admittance element between two media $(\text{kg/s})/\text{Pa}$
 t : Time s
 u : Specific internal energy J/kg
 V : Volume m^3
 v : Specific volume m^3/kg
 W : Mass kg
 Y : Thermal admittance $(\text{kg/s})/\text{Pa}$
 Y_R : Rotational admittance $\text{Nm}/(\text{rad/s})$
 Δ : Minute change
 η : Internal efficiency
 τ : Torque Nm
 τ^* : Generating torque Nm

Subscripts

- ad : Adiabatic change
 C : Condenser
 E : Evaporator
 F : R 11
 G : Generator
 L : Liquid phase
 m : Arithmetic mean
 S : Steam
 U : Upper stream
 V : Vapor phase
 W : Cooling water
 0 : Initial steady-state operating point
 1 : Inlet
 2 : Outlet

2. Description of Test System

In this system, as shown in Fig. 1, the steam generated in a steam boiler is accumulated in a steam header, its flow is controlled by a hydraulic regulating valve, and it is supplied to a steam turbine. The steam turbine exhaust flows into an R 11 vapor generator and condenses. The R 11 vapor generated in the R 11 vapor generator flows into an R 11 condenser through an R 11 turbine, and condenses into the liquid that is sent to the R 11 vapor generator. The condensing

Table 1 Specifications of the test system

Item	Condition
Steam supplied pressure flow rate quality	3.5 [MPa] (max.) 1300[kg/h] dry saturated
Steam (R11 evaporator inlet) pressure flow rate quality	0.3 [MPa] (max.) 1300[kg/h] dry satu. (almost)
R11 vapor (turbine inlet) pressure flow rate	1.1 [MPa] (max.) 8000[kg/h]
R11 liquid (R11 pump inlet) pressure temperature	0.1 [MPa] 20 [°C]

Fig. 1 Rough sketch of the binary turbine system

Fig. 2 Heat transfer in the R 11 vapor generator

pressure in the R 11 condenser is kept roughly constant because the R 11 condenser has a large condensing capacity. The two turbines are coupled directly to the A.C. generator of which all the output power is consumed at a load resistor. The rotational speed is controlled only by the steam-regulating valve that has a hydraulic actuator instead of a diaphragm motor. The R 11 vapor generator exhibits three modes of heat transfer between the steam and R 11. In this case, three different heat exchangers are applied to those heat transfer modes, as shown in Fig. 2⁽¹⁰⁾.

Specifications of the test system and main components at the rating are shown in Tables 1 and 2. Figure 3 shows the sectional view of the R 11

evaporator that is the most important component in the R11 vapor generator.

3. Outline and Method of Experimental Investigation

Figure 4 shows the flow sheet of the test system indicating the measuring points. In the steady-state tests, the characteristics of the system and components are investigated from the viewpoint of the

network theory. That is, each component is regarded as a two-port element, and the input and output port characteristics are investigated, in addition to the investigation of the overall characteristic of the system. In the dynamic characteristic tests, the frequency response of the system and main components to the changes of the generator load are examined.

A data recorder (TEAC: XR-7000) compatible with the FFT analyzer (HP: 3562 A) is used to record the following state variables: flow rate (orifice and electro-differential pressure transmitter), pressure (electro-pressure transmitter), temperature (thermocouple, Type T), rotational speed (electromagnetic speed detector and F/V converter), and torque (rotary transformer strain torque meter). The dryness fractions at the steam turbine inlet and outlet are measured using dryness meters made by us. During each test, the turbine speed, the liquid level in the R11 evaporator, and the output voltage of the A.C. generator are controlled well against various fluctuations.

Table 2 Specifications of the components

Item	Specification
Steam boiler	3.5 [MPa] (max.) 1550[kg/h] (equivalent)
Steam turbine	40[kW] / 3600[rpm] 1000[kg/h] / 3.0[MPa] (inlet)
R11 turbine	30[kW] / 3600[rpm] 7000[kg/h] / 1.0[MPa] (inlet)
R11 preheater I	Type : Shell and tube, One-pass Size : $\phi 165 \times 1340$ [mm] Steam : 800[kg/h] (condensed) 133[°C] (inlet) / 96[°C] (outlet) R11 : 8000[kg/h] (liquid) 20[°C] (inlet) / 38[°C] (outlet)
R11 preheater II	Type : Shell and tube, One-pass Size : $\phi 165 \times 1530$ [mm] Steam : 800[kg/h] / 0.3[MPa] R11 : 8000[kg/h] (liquid) 38[°C] (inlet) / 114[°C] (outlet)
R11 evaporator	Type : Shell and tube, One-pass Size : $\phi 356 \times 2940$ [mm] Steam : 800[kg/h] / 0.3[MPa] R11 : 8000[kg/h] / 1.1[MPa]
R11 condenser	Type : Shell and tube, Two-pass Size : $\phi 460 \times 4200$ [mm] R11 : 7000[kg/h] / 0.2[MPa] Water : 75[m ³ /h]
A.C. generator	85[kVA] / 200[V] / 3600[rpm]

Fig. 3 Sectional view of the R11 evaporator

Fig. 4 Flow sheet of the 80 kW directly combined binary turbine system

4. Experimental Results of Steady-State Characteristics

The steady-state characteristics of the main components of the system are shown in Figs. 5 to 8. In Figs. 6 to 8, the input port characteristic is shown in the third quadrant, and the output port characteristic in the first quadrant. Figure 5 shows the steady-state characteristics of both the turbines. As the mechanical output characteristic, the braking torques of turbines are shown in relation to the rotational speed and working fluid flow rate. Because the efficiency of the R 11 turbine is higher than expected, the output power ratio is about 1 : 1, though the power rating of the steam turbine is larger than that of the R 11 turbine. At the same time, the thermal output port characteristic of the steam turbine is shown in the third quadrant and the thermal input port characteristic of the R 11 turbine in the fourth quadrant in relation to the working fluid flow rate. They are almost the same as the input and output characteristics of the R 11 evaporator shown in Fig. 7. Figure 6 shows the steady-state thermal characteristic of the steam turbine, Fig. 7 that of the R 11 evaporator, and Fig. 8 that of the R 11

Fig. 5 Steady-state characteristics of the system

Fig. 6 Steady-state characteristics of the steam turbine

turbine. The input port characteristic of the R 11 evaporator influences the output port characteristic of the steam turbine. On the other hand, the output port characteristic of the R 11 evaporator is dependent on the input port characteristic of the R 11 turbine. In the same way, the output port characteristic of the R 11 turbine is dependent on the input port characteristic of the R 11 condenser. The above behaviors are caused by the relative relationships between the inner admittances of the components, as mentioned later.

5. Modeling

5.1 Introduction of modeling

A modeling of the dynamic characteristic of the system is derived from the viewpoint of the network theory. In this case, the vapor flow rate and shaft torque are appropriated for the through variable, and the vapor pressure and rotational speed for the across variable. Therefore, the connections between the main components are represented as shown in Fig. 9. In addition, each component is regarded as a lumped parameter model, which is effective especially in a relatively low frequency range. On the basis of the lumped parameter model, the original equations for the main components in the system are written as follows.

Fig. 7 Steady-state characteristics of the R 11 evaporator

Fig. 8 Steady-state characteristics of the R 11 turbine

Fig. 9 Terminal network model of the main components

[Steam turbine]

$$G_{SV} \eta_{ST} (h_{ST1} - h_{ST2ad}) = n \tau_{ST} + n [D_{ST} n + J_{ST} (dn/dt)] \quad (1)$$

[R 11 evaporator]

$$d(W_{SV} u_{SV} + W_{SL} u_{SL})/dt = m_s G_{SV} h_{SV} - G_{SL} h_{SL} - K_E A_E (\theta_s - \theta_F) \quad (2)$$

$$d(W_{SV} + W_{SL})/dt = m_s G_{SV} - G_{SL} \quad (3)$$

$$V_{ES} = W_{SV} u_{SV} + W_{SL} u_{SL} \quad (4)$$

$$d(W_{FV} u_{FV} + W_{FL} u_{FL})/dt = G_{FL} h_{FL} - G_{FV} h_{FV} + K_E A_E (\theta_s - \theta_F) \quad (5)$$

$$d(W_{FV} + W_{FL})/dt = G_{FL} - G_{FV} \quad (6)$$

$$V_{FVE} = W_{FV} u_{FV} \quad (7)$$

[R 11 turbine]

$$G_{FV} \eta_{FT} (h_{FT1} - h_{FT2ad}) = n \tau_{FT} + n [D_{FT} n + J_{FT} (dn/dt)] \quad (8)$$

[R 11 condenser]

$$d(W_{FV} u_{FV} + W_{FL} u_{FL})/dt = G_{FV} h_{FV} - G_{FL} h_{FL} - K_C A_C (\theta_F - \theta_{wm}) \quad (9)$$

$$d(W_{FV} + W_{FL})/dt = G_{FV} - G_{FL} \quad (10)$$

$$V_{FC} = W_{FV} u_{FV} + W_{FL} u_{FL} \quad (11)$$

5.2 Modeling of turbine

The turbine converts the thermal power of working fluid to mechanical power, and has two thermal ports and one mechanical port. For the thermal ports, the input port characteristic is represented as a throttle element, paying attention to the dependence of the flow rate on the inlet pressure. On the other hand, the output port characteristic is determined as a through variable amplifier, the amplitude of which is one; this characteristic means the through variable source to the downstream process because the flow rate depends on the input port characteristic, and the outlet pressure depends on the downstream process.

The following equation is derived from Eq.(1) for the mechanical power of the steam turbine:

$$\Delta \tau_{ST} = \tau_{ST}^* - \sum Y_{RSi} \Delta n, \quad (12)$$

where the first term on the right-hand side τ_{ST}^* expresses the generating torque of the turbine. It is represented as the through variable source, as shown in Table 3, the generating torque of which is governed by the steam flow rate and outlet pressure. In the second term, the following four factors are included:

- 1) effect of the change of rotational speed,
- 2) effect of the rotational conductance,

Table 3 Factors in the steam turbine

Symbol	Content
Y_{RS1}	$\frac{\tau_{ST0}}{n_0}$
Y_{RS2}	$2D_{ST}$
Y_{RS3}	sJ_{ST}
Y_{RS4}	$-\frac{G_{SV0}}{n_0} (h_{ST10} - h_{ST2ad0}) \left(\frac{\partial \eta_{ST}}{\partial n} \right)_0$
τ_{ST}^*	$\frac{1}{n_0} \eta_{ST0} \left[(h_{ST10} - h_{ST2ad0}) + \left(\frac{\partial h_{ST1}}{\partial P_{ST1}} \right)_0 \left(\frac{\partial P_{ST1}}{\partial G_{SV}} \right)_0 \right] \Delta G_{SV} - \frac{\eta_{ST0} G_{SV0}}{n_0} \left(\frac{\partial h_{ST2ad}}{\partial P_{ST2}} \right)_0 \Delta P_{ST2}$

Fig. 10 Model of the steam turbine

- 3) effect of the rotational inertia,
- 4) effect of the change of internal efficiency.

These are represented in Table 3. As a result, the model of the steam turbine is derived, as shown in Fig. 10. The model of the R 11 turbine is also derived in the same way.

5.3 Model of R 11 evaporator

The R 11 evaporator transfers the thermal energy of the steam turbine exhaust to R 11. The models of the steam condensing process and the R 11 evaporating process are derived independently, and are joined taking into account the contact points. The following equation is derived from Eqs.(2)-(7) for the steam condensing process:

$$\Delta G_{SV} = \sum Y_{Si} \Delta P_{SE} - T_s \Delta P_{FE}, \quad (13)$$

where the following five factors in the heat exchanger are included in the first term on the right-hand side:

- 1) effect of heat capacity owing to the heat capacity change of the medium,
- 2) effect of the change of medium temperature,
- 3) effect of the change of specific volume of the steam,
- 4) effect of the change of latent heat of the medium,
- 5) effect of the change of overall heat transfer coefficient.

These are expressed as shown in Table 4 in the case where the specific volume of liquid and its change are

Table 4 Factors in the condensing process of evaporator

Symbol	Content
Y_{S1}	$s \frac{1}{m_s r_{s0}} \left[W_{SV0} \left(\frac{d h_{SV}}{d P_s} \right)_0 + W_{SL0} \left(\frac{d h_{SL}}{d P_s} \right)_0 \right]$
Y_{S2}	$\frac{1}{m_s r_{s0}} K_{ED} A_E \left(\frac{d \theta_s}{d P_s} \right)_0$
Y_{S3}	$- s \frac{W_{SV0}}{m_s v_{SV0}} \left(\frac{d v_{SV}}{d P_s} \right)_0$
Y_{S4}	$- \frac{G_{SV0}}{r_{s0}} \left[\left(\frac{d h_{SV}}{d P_s} \right)_0 - \left(\frac{d h_{SL}}{d P_s} \right)_0 \right]$
Y_{S5}	$\frac{A_E}{m_s r_{s0}} \left(\frac{\partial K_E}{\partial P_s} \right)_0 (\theta_{s0} - \theta_{F0})$
T_s	$\frac{1}{m_s r_{s0}} K_{ED} A_E \left(\frac{d \theta_F}{d P_F} \right)_0$
Y_{S6}	$\frac{v_{SL0}}{v_{SV0}} \frac{1}{R_s}$

Table 5 Factors in the evaporating process

Symbol	Content
Y_{F1}	$s \frac{1}{r_{F0}} \left[W_{FV0} \left(\frac{d h_{FV}}{d P_F} \right)_0 + W_{FL0} \left(\frac{d h_{FL}}{d P_F} \right)_0 \right]$
Y_{F2}	$\frac{1}{r_{F0}} K_{ED} A_E \left(\frac{d \theta_F}{d P_F} \right)_0$
Y_{F3}	$- s \frac{W_{FV0}}{v_{FV0}} \left(\frac{d v_{FV}}{d P_F} \right)_0$
Y_{F4}	$\frac{1}{r_{F0}} G_{FV0} \left[\left(\frac{d h_{FV}}{d P_F} \right)_0 - \left(\frac{d h_{FL}}{d P_F} \right)_0 \right]$
T_F	$\frac{1}{r_{F0}} K_{ED} A_E \left(\frac{d \theta_s}{d P_s} \right)_0$

much smaller than those of vapor. In the second term, the change of heating rate owing to the change of R 11 vapor pressure is represented as an apparent change of the steam flow rate. That is, this factor is expressed as the through variable source, the steam flow rate of which is governed by the R 11 vapor pressure. The discharge flow rate of the condensate is controlled by the steam pressure in the evaporator, the atmospheric pressure and the lift of the regulating valve at the evaporator outlet. This is represented as a simple throttle, listed in Table 4 as Y_{S6} .

For the evaporating process, in the same way as for the condensing process, the following equation is derived:

$$\Delta G_{FV} = T_F \Delta P_{SE} - \sum Y_{Fi} \Delta P_{FE}, \quad (14)$$

where the admittances in the second term on the right-hand side are formed by the factors corresponding to 1) to 4) in the steam condensing process. These are expressed in Table 5. In this process, the effect of the change of the overall heat transfer coefficient is

Fig. 11 Model of the R 11 evaporator

not included because the change of the overall heat transfer coefficient mainly depends on the condensing process. In the first term, in the same way as the condensing process, the change of the heating rate owing to the change of steam pressure in the condensing process is represented as an apparent change of the vapor flow rate. This factor is expressed as the source of the R 11 flow rate which is decided by the steam pressure.

The model of the R 11 evaporator, as shown in Fig. 11, is obtained and combined with the preceding models of the steam condensing and R 11 evaporating processes, taking into account the effect of the heat capacity of the tubes estimated as a first-order lag element⁽¹¹⁾. The condensing and evaporating processes are essentially similar. In the binary turbine system, the only difference between the two processes is a large admittance in the condensing process and a small one in the evaporating process as compared with that of the processes located before and after each one.

5.4 Modeling of R 11 condenser

The R 11 condenser is a heat exchanger, the cooling medium of which is normal-temperature water. With a sufficient and constant flow rate of cooling water, the dynamic model of the condenser is the same as the condensing process in the R 11 evaporator, i.e.,

$$\Delta G_{FV} = \sum Y_{Ci} \Delta P_{FC} + \Delta G_{FV}^*. \quad (15)$$

The factors of admittances in the first term on the right-hand side correspond to 1) to 4) shown in the condensing process in the evaporator. Because the dominant factor in the overall heat transfer coefficient of the condenser is the flow rate of cooling water in the tubes and the cooling water flow rate is kept constant, factor 5) need not be considered. Further-

Fig. 12 Model of the directly combined binary turbine system

Fig. 13 Frequency response of turbine rotational speed to change of generator load

Fig. 15 Frequency response of steam turbine torque to change of generator load

Fig. 14 Frequency response of R11 flow rate to steam flow rate with change of generator load

Fig. 16 Frequency response of R11 turbine torque to change of generator load

more, since the condensate is discharged at a constant flow rate, the factor corresponding to Y_{S6} in Table 4 is negligible. In the second term, the change of the heating rate owing to the change of water temperature in the tubes is represented as an apparent change

of the R11 vapor flow rate.

5.5 Model of the system

In addition to the modeling of each component mentioned above, the models of the steam boiler, that is, the first heat source regarded as a through variable

Table 6 Operating point at the frequency response tests

Item		Condition
Control valve inlet pressure	MPa	2.5
Steam turbine inlet pressure	MPa	1.1
Steam turbine outlet pressure	MPa	0.13
Steam flow rate	kg/h	530
R11 turbine inlet pressure	MPa	0.70
R11 turbine outlet pressure	MPa	0.20
R11 vapor flow rate	kg/h	4600
Turbine rotational speed	rpm	3600
System output power	KW	30

source, the rotational inertia of generator, that is, a turbine load, the rotational conductance and the load resistor are integrated, bearing in mind the volume effect of piping, to derive the dynamic network model of the whole system shown in Fig. 12.

6. Experimental Result of Dynamic Behavior

In the experiments on the dynamic characteristics of the system, the frequency responses to the changes of generator load are investigated. The results of the frequency response tests are shown in Figs. 13 to 16, including the results calculated by the model. The operating conditions at the start of the tests are shown in Table 6. From the results, it is clear that the dynamic behavior of the system is strongly dependent upon the characteristic of the R 11 evaporator, especially in the low frequency range.

In Fig. 12, it is obvious that the R 11 evaporator and R 11 condenser are parallel to the mechanical power generation of two turbines. These two thermal components influence the system in the low frequency range, about 1 cpm or less because their heat capacities are large compared with the rotational inertia of the turbines and load generator. In the high frequency range, about 5 cpm or more, the turbines and load generator as a rotational machine have dominant effects on the dynamic characteristics of the system. The effects of both the thermal components and the rotational machines are clearly manifested in the frequency responses.

7. Conclusion

The dynamic characteristics of the directly combined binary turbine system has been clarified both experimentally and theoretically. In the experimental investigation, the frequency responses of the system to the changes of generator load were measured, taking into account the test results on the steady-state characteristics of the system and components. In the theoretical study, a simple network model on

the dynamic characteristic of the system was derived from the viewpoint of the network theory. This model makes it easy to estimate the dynamic behavior and the power generation under the steady- and unsteady-state conditions not only in the binary turbine system discussed in this paper, but also in similar turbine systems.

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