

Mathematical Modeling – The Impact of Cooling Water Temperature Upsurge on Combined Cycle Power Plant Performance and Operation

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Abstract. This paper presents the mathematical modeling analysis on cooling system in a combined cycle power plant. The objective of this study is to get the impact of cooling water upsurge on plant performance and operation, using Engineering Equation Solver (*EES*TM) tools. Power plant installed with total power capacity of block#1 is 505.95 MWe and block#2 is 720.8 MWe, where sea water consumed as cooling media at two unit condensers. Basic principle of analysis is heat balance calculation from steam turbine and condenser, concern to vacuum condition and heat rate values. Based on the result shown graphically, there were impact the upsurge of cooling water to increase plant heat rate and vacuum pressure in condenser so ensued decreasing plant efficiency and causing possibility steam turbine trip as back pressure raised from condenser.

Keywords : heat rate, condenser vacuum, power, cooling temperature

1. Introduction

In combined cycle power plant, energy produced from the conversion gas heat and steam expansion through turbine into mechanical shaft coupled to electric generator. The magnitude of generator power depends on expansion process where gas, steam and its condensate release their potential energy (named enthalpy). Heat and steam enthalpy would change into blades rotation (mechanical energy), exhaust heat and cooling medium (sensible heat). As the energy sources generally come from natural gas and oil, then its combustion exhaust gas recovered into steam in steam generator equipment. Cooling water plays important role to give the condenser the optimum vacuum pressure or enthalpy drop in turbine system.



With principle applying heat balance in turbine and condenser, it could be known and calculated the amount cooling water and its outlet temperature for the determined output power and turbine inlet steam. When demand of output power increased, thus condenser must be able to achieve the suitable vacuum condition to expand steam optimally. Conversely if inlet temperature of cooling water increased, it could reduce the latent heat for condensation and for compensating this, steam consumption to be magnified.

The cooling water temperature upsurge is the important parameter that effects plant performance as well its reliability. Anozie, A. N. and O. J. Odejobi (2011). developed calculation model for simulation of a thermal plant at various circulation water flowrate and saturation pressure , to determine the optimum condenser cooling water flowrate for the process. The influence of circulation cooling water on the efficiency thermonuclear plant also conducted by Gañán, J., et al. (2005). to improve plant performance with appropriate cooling system. The important role of cooling system for power plant as well was concerned by Wu, J., et al. (2001) to study simulation of cooling water discharge from power plant to give contribution in feasibility studies of engineering options that increase the cooling capacity of the waterbody. This parameter is one of the most influential that affect operation variables such as condenser pressure, heat rate, fuel consumption, and cycle efficiency which had interested Sanathara,M.V., et.al (2013) and Haldkar, V., et al. (2013) to study the optimum cooling water mass flow at Steam Power Plant 120 MW. Cooling water inlet temperature and flow are the potential parameter which influence vacuum condition in condenser, as was observed and evaluated by Singh, S.P., et.al. (2014). Ibrahim, M., and Badawy, M.R., (2014) evaluated the effect of cooling water site condition parameters to heat transfer performance of condenser. Meanwhile Ali, S. H., et.al., (2014). and Boi, Rakesh, Mehta, Nirvesh, & Bojak, Khedar. (2015). have studied the back pressure of condenser would impact heat rate and steam power plant performance.

Basically in combined cycle power plant, there are two sections of energy conversion i.e. combustion heat and steam power to mechanical power. Combustion convert chemical energy (contained in fuel) into combustion heat and its high pressure utilized to rotate the turbine blades. Meanwhile at the second one, the exhaust gas from the gas turbine recovered in heat steam generator to convert into steam that used to produce power through steam turbine.

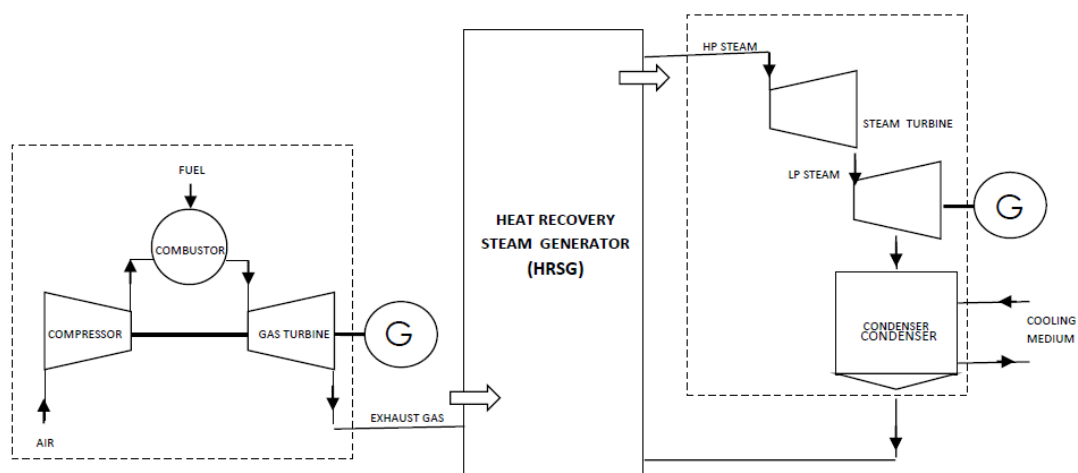


Figure 1. Principle of Energy Conversion in Combined Cycle Power Plant Modeled

System cycle efficiency indicated by the parameter of heat rate that is the ratio of the amount input energy to output power achieved. Output power depends on the turbine enthalpy drop, which determined by condenser performance for rejecting heat to cooling medium. This paper presents the study of the cooling water upsurge to power plant performance and operation using mathematical modeling heat balance on turbine and condenser system

2. Methods

Mathematical Modeling for analyzing the impact of cooling water temperature rise to plant performance and its operation, was built through principle of mass and heat balance calculation in control volume bounded at condenser and steam turbine. For this modeling, assumptions taken are steady state, heat transfer parameters at condenser as surface area, global heat transfer coefficient is constant. As the variables of analysis are operation parameters such as pressure P , temperature T , flowrate of fuel G_F , steam G_s and cooling water G_{CW} also generator power from gas and steam turbine W_{GT} and W_{ST} , those collected from the plant design, performance test/and or operation data record. Firstly it had to be identified the cycle process of gas system and steam flow to turbine and condenser as well power generator to understand the thermodynamic state and cycle of power generated.

Output power generator W_{ST} is the result of energy balance upon steam turbine and condenser. Enthalpy drop (ΔH) defined by the difference of total enthalpy inlet turbine H_{inturb} and condensation enthalpy H_{cond} . These functions are defined in the following equations based on the energy balance. And W_{GT} obtained from measured value from performance test/and or operation record.

As the performance value determined by the Net Plant Heat Rate (NPHR) based on the amount of total heat from combustion (HHV and LHV basis) and steam divided to the net total output power generator at gas and steam turbine after subtracted auxiliary power. For combustion heat calculated by variables fuel consumption and calorific value.

$$W_{ST} = (H_{inturb} - H_{cond}) \cdot \eta_{ST} \quad (1)$$

$$H_{inturb} = H_{HP} + H_{LP} \quad (2)$$

$$H_{HP} = H(P_{HP}, T_{HP}) \quad (3)$$

$$H_{LP} = H(P_{LP}, T_{LP}) \quad (4)$$

$$H_{cond} = G_{CW} \cdot h_{cond} \quad (5)$$

$$h_{cond} = h_{cond, sat}(P_{cond}) \quad (6)$$

$$H_{condwtr} = G_{CW} \cdot cp \cdot (T_{hot} - T_{cold}) \quad (7)$$

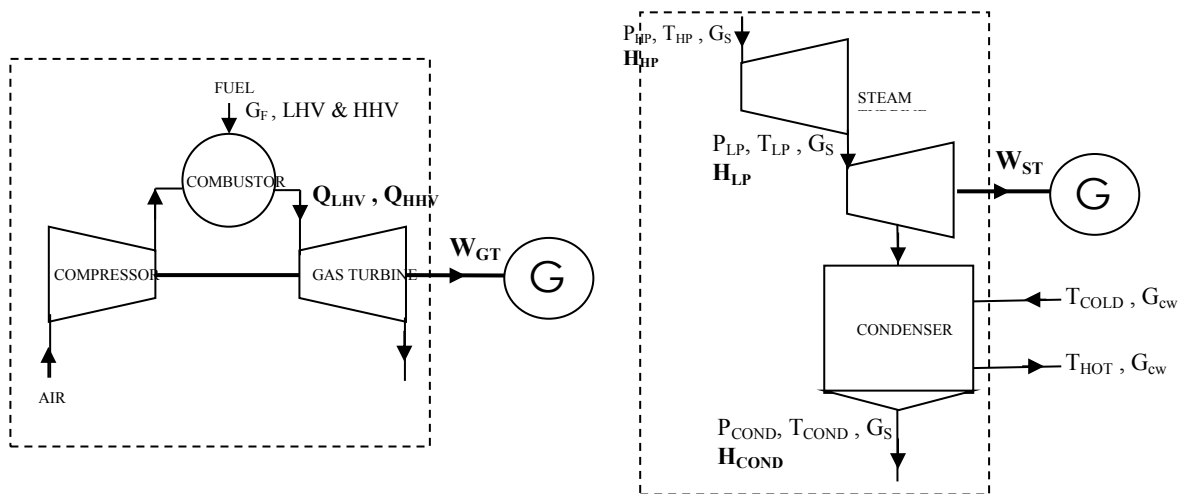
$$Q_{HHV} = G_F \cdot H_{HHV} \quad (8)$$

$$Q_{LHV} = G_F \cdot H_{LHV} \quad (9)$$

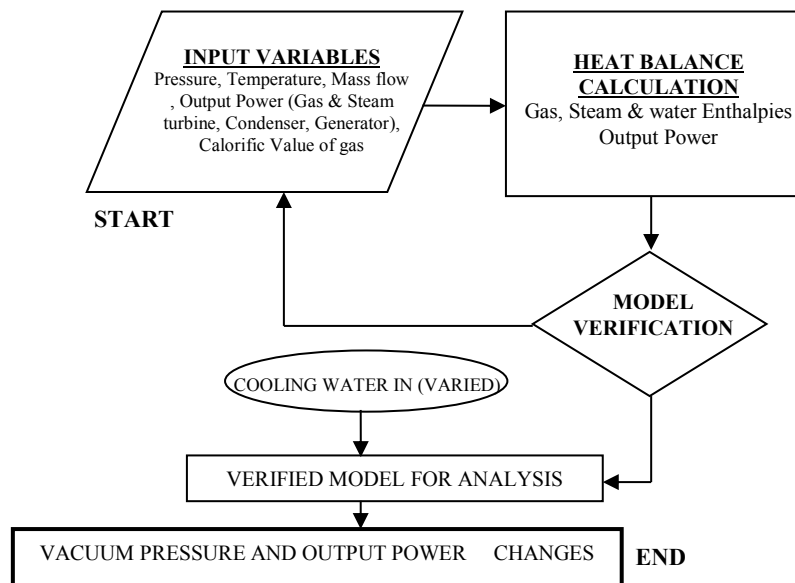
$$NPHR_{HHV} = (Q_{HHV} + H_{inturb}) / (W_{GT} + W_{ST} - P_{aux}) \quad (10)$$

$$NPHR_{LHV} = (Q_{LHV} + H_{inturb}) / (W_{GT} + W_{ST} - P_{aux}) \quad (11)$$

Where cp is specific heat of cooling water in $\text{KJ/kg}^\circ\text{C}$; all enthalpies in KJ and W in kW units. Subscripts HP and LP indicates high pressure and low pressure state conditions whereas hot and cold explained temperature for outlet and inlet from and into condenser of cooling medium. Notation η_{ST} is turbine efficiency. For h_{cond} is specific enthalpy for condensation at saturated pressure P_{cond} .



(a)



(b)

Figure 2. Volume Control analysis of heat balance (a) and flow diagram of modeling (b)

Calculation model need to be verified to ensure or know the bias (error), compared to the performance test/and or operation record. As the parameters for verification are the input variables and calculated variables. Model that has been verified, then for the analysis variable is the rise of cooling water temperature concerning to the vacuum pressure condenser and output power changes.

3. Result and Discussion

The combined cycle power plant comprises 2 blocks (block#1 and block#2) with gas turbines, HRSGs, and steam turbines system that identified from plant design/process flow diagram. Each

steam turbine has one condenser for rejecting heat from High Pressure (HP) and Low Pressure (LP) stages. Mathematical modeling verified with performance test of block#2 which input data given in table 1 below.

Table 1. Performance Test Input Data for Model Verificatio

No	Parameter	Symbol	Value	Unit
1	Gas fuel Flowrate GT1	V_{gas1}	47018	kg/hr
2	Gas fuel Flowrate GT2	V_{gas2}	47186	kg/hr
3	Higher Heating Value Gas	HHV _{gas}	13048	kCal/kg
4	Lower Heating Value Gas	LHV _{gas}	11834	kCal/kg
5	Output Power Generator GT1	w _{gen1}	230131	kW
6	Output Power Generator GT2	w _{gen2}	229402	kW
7	HP Steam massflow ST21	GHP1	247.7	ton/hr
8	HP Steam massflow ST22	GHP2	252.3	ton/hr
9	HP Steam massflow ST23	GHP3	251.8	ton/hr
10	HP Steam inlet Pressure ST21	P13	6810	kPa
11	HP Steam inlet Pressure ST22	P23	6870	kPa
12	HP Steam inlet Pressure ST23	P33	6830	kPa
13	Condenser Pressure ST21	P12	10.09	kPa
14	Condenser Pressure ST22	P22	9.684	kPa
15	Condenser Pressure ST23	P32	9.684	kPa
16	LP Steam massflow ST21	GLP1	4.531	ton/hr
17	LP Steam massflow ST22	GLP2	4.616	ton/hr
18	LP Steam massflow ST23	GLP3	4.607	ton/hr
19	LP Steam inlet Pressure ST21	P13	360	kPa
20	LP Steam inlet Pressure ST22	P23	360	kPa
21	LP Steam inlet Pressure ST23	P33	350	kPa
22	In/out cooling water Cond#1	T_{cold21}/T_{hot21}	31.9/41	°C
23	In/out cooling water Cond#2	T_{cold22}/T_{hot22}	31.7/40.8	°C
24	In/out cooling water Cond#3	T_{cold23}/T_{hot23}	32/40.5	°C
25	Spesific heat cap. water	cp	4.183	kJ/°C.kg
26	Thermal Efficiency ST	η	79-89	%
27	Output Power Generator ST21	W_{gen21}	70400	kW
28	Output Power Generator ST22	W_{gen22}	71300	kW
29	Output Power Generator ST23	W_{gen23}	70100	kW

Table 2. Performance Test Input Data for Model Verification

No	Variables	Units	Performance Test	Calculation Model	Error (%)
1	Heat Rate HHV	kCal/kWh	1830.77	1831	-0,01256
2	Heat Rate LHV	kCal/kWh	1660,45	1661	-0,03312
3	Output Power ST21	kW	70.4333	70.274	0,226171
4	Output Power ST22	kW	71.3333	70.964	0,517711
5	Output Power ST23	kW	70.1000	69.979	0,172611

To clarify the hypothesis that the raised cooling water would decrease the plant performance and operation, previously it was important to analyze the operation data. Figure 3 (from model recalculation) shows that with referring to plant design there are the most influential parameters of condenser pressure and cooling water, which values subsequently are 0.083 bar.abs and 29 °C for cold water-in for mass flow 16300 ton/hr.

But from observation when steam turbine pressure, temperature and steam flow operated at 62.99 bar; 510 °C; 276.48 kg/s (HP) and 4.72 bar; 313 °C; 69.55 kg/s (LP), the condenser actually operates at average values of pressure 10 kPa.abs and temperature below 30 °C thus output power turbine produces more than 120 MWe. Conversely when temperature cold-in higher than 30 °C corresponds to the output power below 100 MWe.

It is clearly shown that the cooling water upsurge has the impact upon output power (related to plant performance) and possibility the change of condenser pressure.

For inlet cooling temperature changing from 30 ÷ 35 °C, the condenser pressure and output power will vary with corresponding to condenser inlet heat. Inlet heat of condenser depends on thermodynamic state of steam, correlating to condensation pressure or temperature at condition of steam out from turbine. It could be seen that the higher cooling water temperature causing output power more higher, this is because latent heat of condensation at correspond pressure saturated more higher. This modeling shows averagely that the condenser pressure is still far from the limit design pressure -520 mmHg, nevertheless this bring the potential problem turbine could be tripped by the raised back pressure.

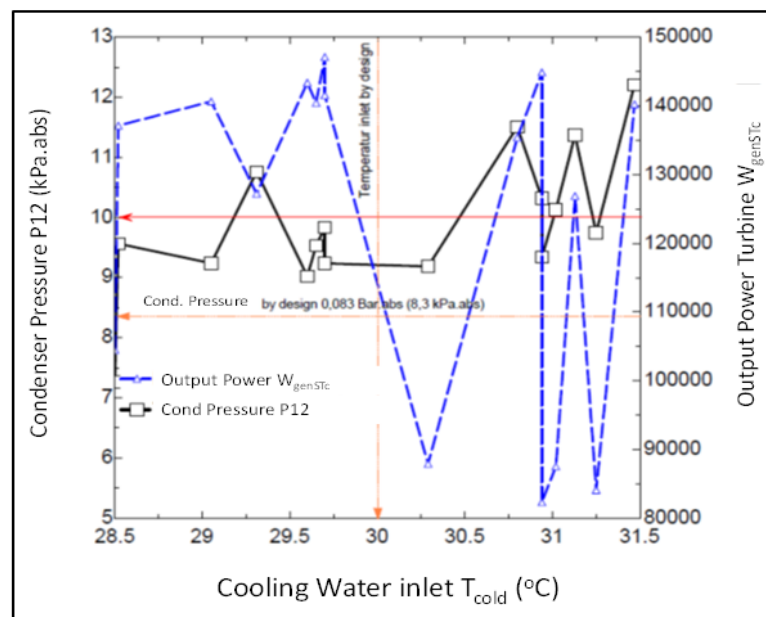


Figure 3 The Effect of Raised Cooling Water upon Condenser Pressure and Output Power

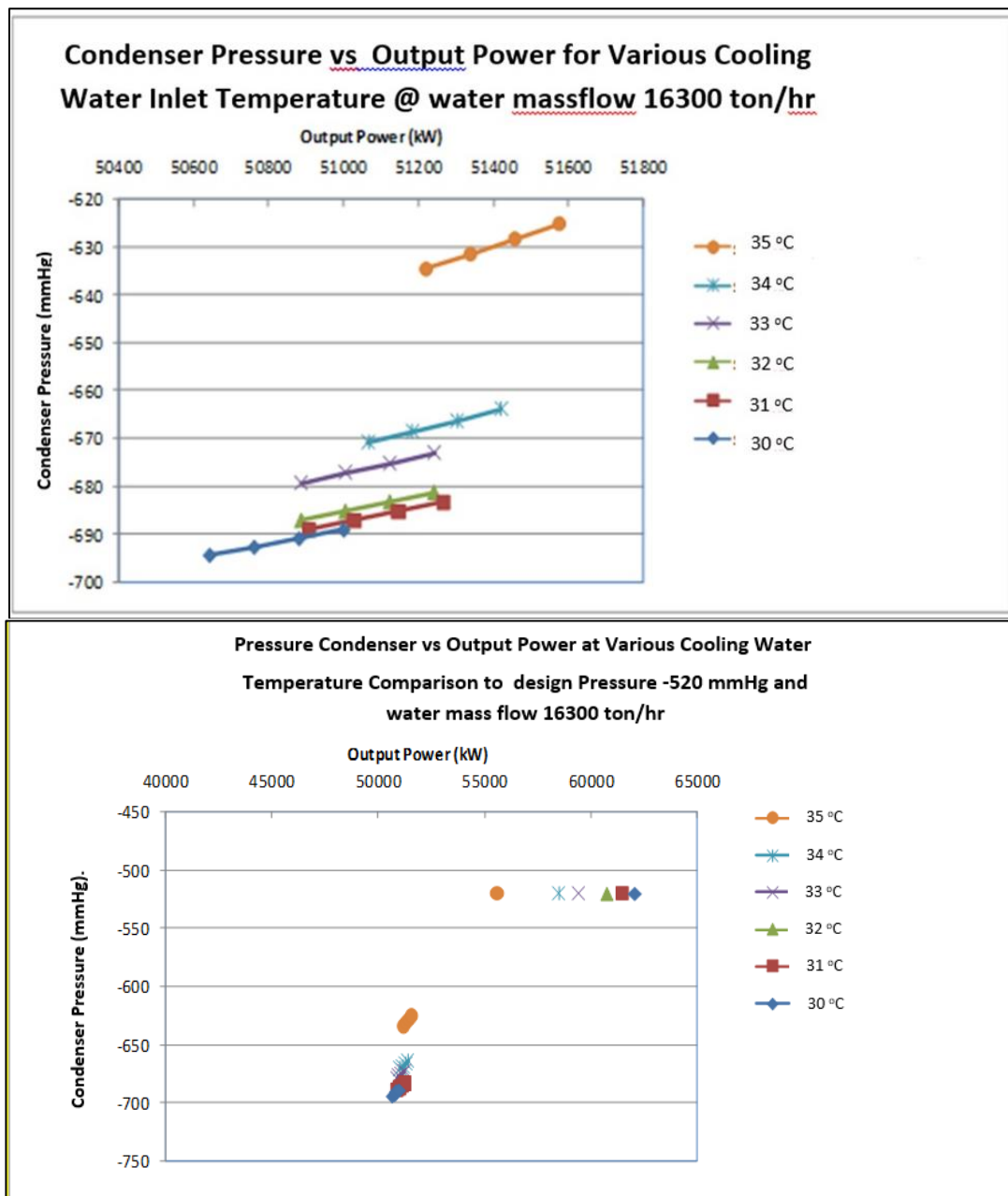


Figure 4 The Change of Condenser Pressure and Output Power for Various Cooling Water Temperature

4. Conclusion

Effect from the cooling water temperature upsurge has increased the condenser pressure as well the output power would decrease. For the change of cooling water temperature from 30 ÷ 35 °C, the condenser pressure is above 620 mmHg. abs that is still safely operated from limit pressure 520 mmHg. abs. At the lower cooling water temperature, the condenser operated at higher pressure in condenser. Otherwise, the pressure would be lower when the cooling water temperature increases. This modeling has given the good result with bias less than 1% compared to operation data.

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References

- [1] Anozie, A. N., & Odejobi, O. J. (2011). The search for optimum condenser cooling water flow rate in a thermal power plant. *Applied Thermal Engineering*, 31(17–18), 4083-4090. doi: <http://doi.org/10.1016/j.applthermaleng.2011.08.014>
- [2] Chantasiriwan, Somchart. (2015). Effects of Cooling Water Flow Rate and Temperature on the Performance of a Multiple-Effect Evaporator. *Chemical Engineering Communications*, 202(5), 622-628. doi: 10.1080/00986445.2013.858040
- [3] Gañán, J., Rahman Al-Kassir, A., González, J. F., Macías, A., & Diaz, M. A. (2005). Influence of the cooling circulation water on the efficiency of a thermonuclear plant. *Applied Thermal Engineering*, 25(4), 485-494. doi: <http://doi.org/10.1016/j.applthermaleng.2004.07.001>
- [4] Haldkar, Vikram, Sharma, Abhay Kumar, Ranjan, RK, & Bajpai, VK. (2013). Parametric analysis of surface condenser for thermal power plant. *Int. J. Therm. Technol*, 3, 155-159.
- [5] Sanathara, Milan V, Oza, Ritesh P, & Gupta, Rakesh S. (2013). Parametric analysis of surface condenser for 120 MW thermal power plant. *International Journal of Engineering Research & Technology*, 2(3).
- [6] Wu, J., Buchak, E. M., Edinger, J. E., & Kolluru, V. S. (2001). Simulation of cooling-water discharges from power plants. *Journal of Environmental Management*, 61(1), 77-92. doi: <http://dx.doi.org/10.1006/jema.2000.0396>