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FINDING THE BEST COOLING SCHEME FOR PAROSENI POWER PLANT

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Abstract: The paper studies the best cooling scheme for the K-9115 condenser from Paroşeni power plant. The condenser is the part of the power plant which has a strong influence on the produced electric power and specific consumption of the plant.

Key words: condenser, vacuum, electric power, specific fuel consumption, cooling scheme.

1. INTRODUCTION

A power plant is a complex system whit a huge number of installations, and his appropriate operation depends on the correct operation of all subsystems within the designed parameters.

A special place within a power plant is occupied by the cooling water system, which provides the cooling water for all the equipments.

The condenser is the equipment of a power plant whit the highest cooling water demand, it condensates the steam processed by the turbine, and the pressure (vacuum) in the condenser has an important influence on the produced electric power, specific fuel consumption and the efficiency of the power plant.

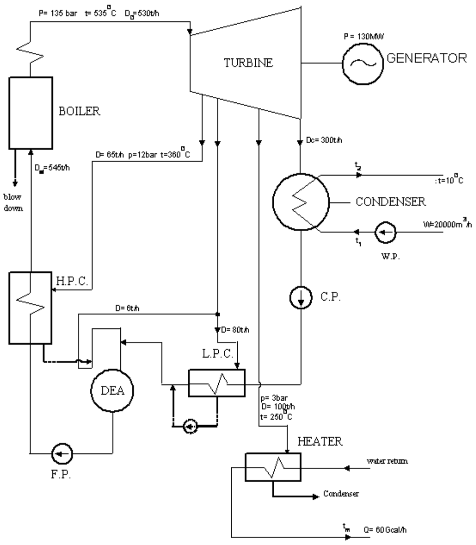

Fig. 1. Simplified flow diagram of the thermal electric plant

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In fig. 1 are the simplified flow diagrams of the thermal electric power plant Paroşeni [1], where the studied condenser's place in the system can be identified.

2. COOLING WATER SYSTEM

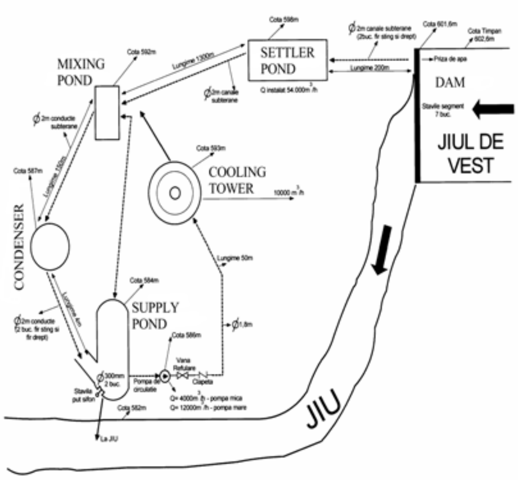

Fig. 2. The cooling water system

The cooling water system provides the cooling water for the entire power plant, and is a very complex system as shown in fig. 2.

Its main objective is to provide cooling water for the condenser, but also provides the cooling agent to other subsystems, like the turbine's bearings. As shown in fig.2 the cooling water is taken from Jiu de Vest river, and also the cooling towers are used to reduce the temperature of water in case of close circuit operation. In case of close circuit or mixed cooling, the atmospheric air is used to cool the water coming from the condenser. After cooling in towers the water returns in the Settler pond where is mixed up with the added water from the river.

Tabel 1. **Average values of environmental parameters**

Month	Average temperatures for Jiu de Vest river[ºC]	Average flow rate for Jiu de Vest river [$m^3 \cdot h^{-1}$]	Average atmospheric temperatures [ºC]	Average atmospheric pressure [mmHg]	Relative humidity [%]	Average flow of recycled water [$m^3 \cdot h^{-1}$]
January	3	6300	-3	710,0	84	16000
February	3	6300	-3	711,6	86	16000
March	4	6300	2	699,9	86	16000
April	6	10000	8	700,0	88	12000
May	10	10000	14	700,0	88	12000
June	15	14000	20	706,1	84	8000
July	18	14000	22	706,7	80	8000
August	18	10000	20	706,8	72	12000
September	16	10000	18	709,6	75	12000
October	12	7000	13	707,7	78	16000
November	8	7000	7	708,2	80	16000
December	6	7000	2	708,2	84	16000

Conclusively the temperature of cooling water depends on the temperature of the water from the river, but also on the parameters of atmospheric air. Average values of water temperature and air parameters are found in table 1 [1], these values are used to perform the calculus.

The structure of cooling circuit can be observed in fig. 2 [1]. In case of using closed circuit cooling, or mixed cooling, two common edges can be identified between the Mixing pond and Supply pond.

3. THE K-9115 CONDENSER

The K-9115 condenser is a welded surface condenser, and is made of the condenser itself and a connection. The condenser has two ways for the passage of cooling water.

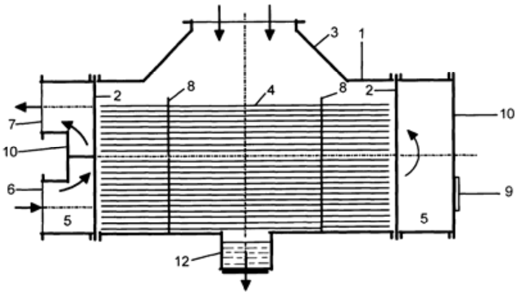

Fig. 3. The condenser:
1 – the external layer (mantle); 2 – tubular plate; 3 – steam inlet; 4 – cooling tubes;
5 – water chamber; 6 – cooling water inlet connector; 7 – cooling water outlet connector;
8 – baffle plates; 9 – inspection cap; 10 – condenser cap; 12 – hotwell.

The cooling water reaches the lower part of the chamber through the tubes of the first flow path, and after that arrives in the back chamber from which turns back through the tubes of the other flow path in the upper part of the front chamber, from where the heated water leaves the condenser through the outlet.

At surface condensers – condensate will not mix with the cooling water, the steam from the turbine has no grease so can be reused to feed the boiler unit, with no treatment. That’s why the surface condenser moves the same amount of water in the connecting piping: boiler – turbine – condenser – boiler. Only small amounts of treated water are necessary to compensate losses.

In order to highlight the influence of different parameters on the condenser’s vacuum the expression of the condensation temperature can be established using [2]:

$$t_s = t'_w + \frac{i_v - i_w}{m \cdot c_a} + \delta t \tag{1}$$

Results from above that the vacuum is depending on:

- Inlet temperature of the cooling water t'_w;

- Specific consumption of cooling water m;
- Minimum water-steam temperature difference δt.

The equation can be written [2]:

$$t_s = t'_w + \frac{\dot{Q}}{\dot{m}_w \cdot c_w}\left[\frac{1}{e^{\frac{A \cdot k}{m_w \cdot c_w}} - 1} + 1\right] \tag{2}$$

where the meaning of terms are same as above, indices w are for water, v for steam, $\dot{m}_w$ - cooling water flow rate [kg·s^{-1}], c_w - specific heat capacity kJ·(kg·K)$^{-1}$, $\dot{Q}$ - transmitted heat flow [kW], A – required heat exchange surface [m^2], k – global coefficient of heat transfer [kW·(m^2·K)$^{-1}$].

The global coefficient of heat transfer can be calculated using [3]:

$$k = \varphi_1 \cdot \varphi_2 \cdot \varphi_3 \cdot C \cdot \sqrt{w}, \quad \frac{W}{m^2 \cdot K} \tag{3}$$

Where: φ_1 is a coefficient depending on tube material, φ_2 coefficient depending on inlet water temperature, φ_3 coefficient depending on tube dirtiness, C basic coefficient of heat exchange in W·(m^2·K)$^{-1}$, w water velocity in tubes m·s^{-1}.

4. THE COOLING TOWER

As we can see in fig.2, in case of using close circuit or mixed cooling, cooling towers have an important influence on the cooling water temperature, and as a result, this influence must be taken into account. In the closed type atmospheric cooling towers (fig. 3), air is moved using a draft tower built of hyperbolic shaped concrete. At Paroşeni power plant can be found 5 R.P.R. type hyperbolic cooling towers.

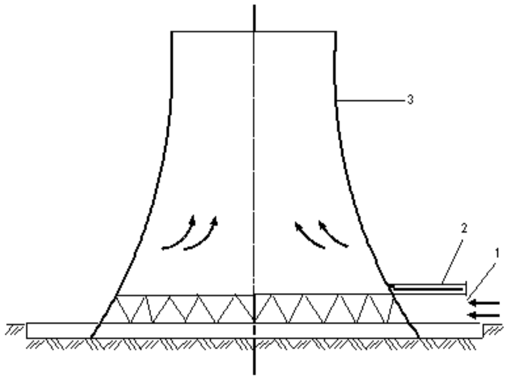

Fig. 3. Atmospheric cooling tower:
1 – water inlet; 2- water distributing flume;
3 – draft tower.

When water in the river Jiu de Vest is too cold, and the air temperature is low, cooling towers 1 and 3 have bypass valves, in order to mix the cooling water to reach minimum 6 ºC at condenser inlet.

The heat-balance for the cooling tower using the simplified thermal balance [2][3][4]:

$$Q = D_1 \cdot c \cdot (t_1 - t_2) = k \cdot D_a (h'_2 - h'_1) \quad kW \tag{4}$$

where: D_1, D_a water and air flow rates in kg·s^{-1}; t_1, t_2 – inlet and outlet temperature of water in °C; h_1, h_2 specific enthalpy of air at tower inlet and outlet in kJ·kg^{-1}, c - specific heat capacity kJ·(kg·K)$^{-1}$, k=1-0.0018·t_2 [2] is a coefficient used to take into account the evaporated water.

As the specific enthalpy of air is well-known, the heat exchanged through cooling of water by the air can be written [3], [4]:

$$Q = D_a\left[c_{au}\left(t_2' - t_1'\right) + l_v\left(x_2 - x_1\right)\right] \quad kW \tag{5}$$

where:

$$c_{au} = c_a\left(1 - x_m\right) + c_v \cdot x_m \quad \frac{kJ}{kg \cdot K} \tag{6}$$

and x_m is the average humidity of air in the cooling tower:

The evaporated water flow rate is [4]:

$$D_{ev} = D_1 - D_2 = D_a\left(x_2 - x_1\right) \quad \frac{kg}{s} \tag{7}$$

In practical calculations the air flow rate in the tower must be established in order to evaluate the evaporated water flow rate.

For natural draft towers the expression of air flow rate is [2]:

$$D_a = \varepsilon \cdot A_b \sqrt{\left(\rho_a'^2 - \rho_a''^2\right)\frac{g \cdot H'}{\zeta}} \quad \frac{kg}{s} \tag{8}$$

where ρ_a', ρ_a'' are the specific density of air at the tower inlet and outlet kg·m^{-3}, H′ effective tower height, meaning tower height plus half of the filling's height in m, ε coefficient of tower area contraction, A_b tower base area in m^2, ζ overall drag coefficient of the tower.

This overall drag coefficient is given graphically depending on area of the base of the tower, and in this case, ε can be considered 1, because ζ is given depending on the average air speed in the entire section of the tower.

Virtually is difficult to determine the outlet temperature at the top of the tower because of the huge outlet area, so iterative calculus will be performed, using also the equation which gives the outlet air temperature depending on the tower's air heating coefficient γ [2],[3],[4],[5],[6]:

$$t_{a2} = \frac{\gamma\left(t_1 + t_2\right) + t_{a1}\left(2 - \gamma\right)}{2 + \gamma} \tag{9}$$

in which t_1, t_2 are the inlet and outlet temperatures of water in °C, and t_{a1} the inlet air temperature in ºC.

5. RESULTS

There are three possibilities to operate the cooling water system: open circuit, closed circuit and mixed circuit.

Using data from table 1 and considering the characteristic of K-9115 where the designed flow rate of water is given as 20812 $m^3 \cdot h^{-1}$ it's obvious that the cooling water system can't be operated in open circuit since there is not enough water in the river Jiu de Vest. In order to perform a comparison the hypothetic case of open circuit will be calculated, using data from table 1. Additional data are: steam rate flow 540 $t \cdot h^{-1}$ at 135 bar pressure and 535 ºC temperature rated P=130 MW, with a specific fuel consumption of c=330 $g \cdot kWh^{-1}$, in the given circumstances through the inlet section of the condenser passes steam at flow rate of 300 $t \cdot h^{-1}$.

In order to perform the calculus the following assumptions are made: there is no heat transfer as the water flows through pipes and tubes, the heat exchange occurs in the condenser and cooling tower only; the mixing of water at different temperatures is instantaneous and occurs in the entire volume of the mixture; the only flow rate losses are through evaporation.

Further analyzing fig. 2 reveals that using mixed cooling; the cooling network can be defined as a graph with cycles, having common edges, the pipe from the Supply pond to the Mixing pond. At the inlet, the system must provide cooling water to other subsystems demanding cooling, at a flow rate of 455 $m^3 \cdot h^{-1}$, this flow rate will be distributed from the Mixing pond.

Solving graphs having cycles can be made using iterations, and the first step in order to simplify the problem is to transform the graph into a tree (an acyclic graph), as in fig.4. The different flow rates for the acyclic graph are presented in fig. 4, as common edges where replaced with suitable virtual flow rates D-overflow, D-tower from Settler pond and Cooling Tower.

Results obtained are presented in fig. 5 for open circuit cooling.

In open circuit, as cooling water from river Jiu heats up, de pressure in the condenser grows, the vacuum drops (fig. 5), and the turbine power output drops too.

Using diagram in fig. 6, given by the provider of the turbine, the amount of power loss can be determined using the appropriate power coefficient depending on condenser pressure (vacuum) and steam flow rate. Using results obtained (fig. 5) and performing calculus based on diagram from fig.6 and a similar diagram for specific fuel consumption coefficient; in fig.7 are represented results for the power and specific fuel consumption coefficient, depending on data represented in fig. 5 and 6.

The diagram from fig. 7 reveals that, as the pressure in the condenser increases, and the vacuum is worse, the power coefficient is < 1, and as a result de power generated by the turbine will drop, in the same time the specific fuel consumption coefficient grows > 1, and the fuel consumption increases.

As a conclusion, the water temperature at the condenser inlet must be carefully controlled, not to exceed a certain temperature, otherwise the turbine power will drop and the fuel consumption will increase. As seen above the cooling water system cannot be operated in open circuit because of the small amount of water in the river Jiu de Vest, especially in the summer.

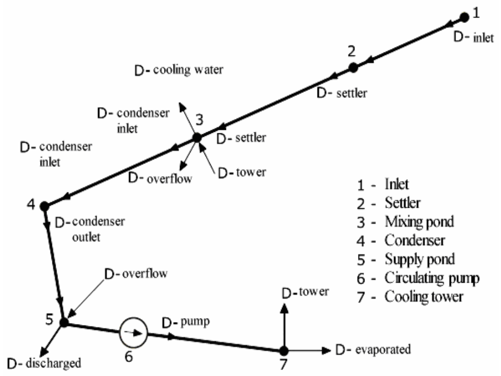

Fig. 4. Transformation in acyclic graph

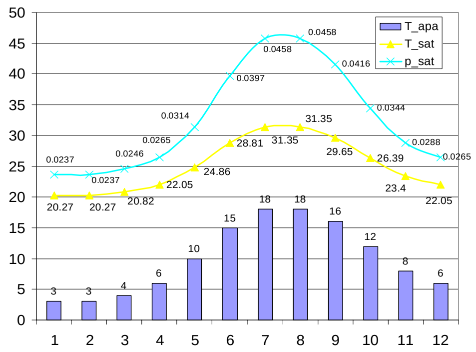

Fig. 5. Temperature *T_sat* [ºC] and pressure (vacuum) *p_sat* [bar] in condenser depending on water temperature *T_apa*[ºC] in Jiul de Vest river, open circuit

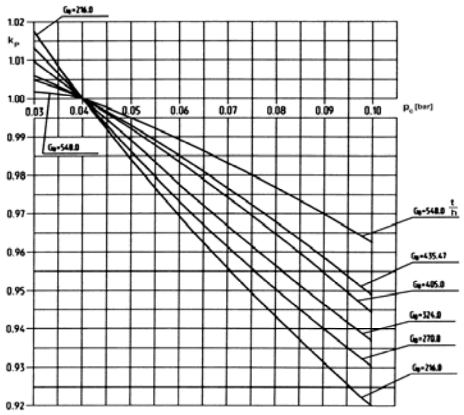

Fig. 6. Power coefficient k_P depending on condenser pressure p_c [bar] for a specific flow rate of steam G_a [t·h^{-1}]

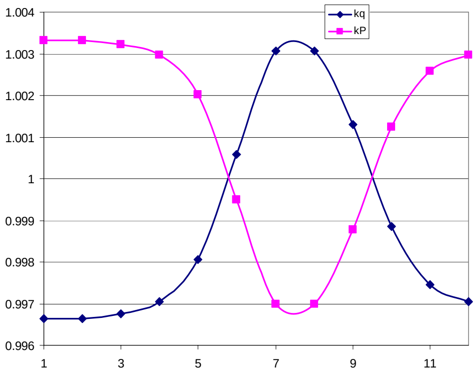

Fig. 7. Power k_q and specific fuel consumption k_P coefficient (open circuit)

Calculus is performed in case of close circuit operation of the cooling water system. Even in this situation a limited amount of water is taken from the river in to replace the water evaporated in the cooling towers, and to supply cooling water for other equipments.

As a result of pump capacity and number, the maximum water flow rate that can be pumped into the towers is 20000 m^3·h^{-1}. Therefore the difference between the designed flow rate in the condenser 20812 $m^3 h^{-1}$, and the flow rate that can be sent to the towers for cooling is 812 $m^3 h^{-1}$.

This flow rate will be sent to the Mixing pond from the Supply pond at an increased temperature after leaving the outlet of the condenser.

The increased temperature of this water will have a negative influence on the water temperature from the Mixing pond, which represents the cooling water supply for all the equipments of the power plant.

In fig. 8 are presented the results obtained for close circuit operation of the cooling water system, using 3 cooling towers.

Data in fig. 8 reveals the variation of temperature and pressure which very similar with the case of open circuit operation. In fig. 8 the influence of cooling air parameters can be distinguished especially in August (8) when, despite of the higher air and water temperature, lower humidity of air, leads to better water cooling.

In fig. 9 are presented the results obtained for mixed circuit operation of the cooling water system, using 3 cooling towers. In this case, the rate flow of cooling water depends on the water rate flow and temperature in the river, and as a result, every month, different amount of water is used from the river. The temperature and the pressure in the condenser is varying as in the cases shown above, but as a characteristic of the diagram, the influence of different water flow rates can be distinguished, especially in April (4).

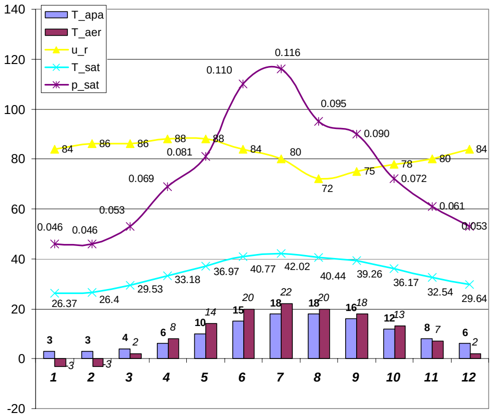

Fig. 8. Temperature T_sat [ºC] and pressure (vacuum) p_sat [bar] in the condenser depending on the water temperature T_apa [ºC], air temperature T_aer [ºC] and humidity (u_r [%]), in close circuit

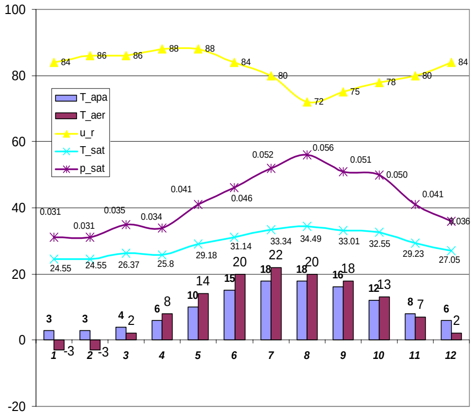

Fig. 9. Temperature T_sat [ºC] and pressure (vacuum) p_sat [bar] in the condenser depending on the water temperature T_apa [ºC], air temperature T_aer [ºC] and humidity (u_r [%]), in mixed circuit

6. CONCLUSIONS

In order to improve data analysis results obtained for the considered cases are represent same diagram, fig. 10. The diagram reveals that the best cooling scheme is the open circuit cooling as the pressure in the condenser is the smallest. Unfortunately, this solution cannot be applied because of lack of cooling water in river Jiu de Vest. The worse solution is operating the cooling water system in close circuit, since the pressure in the condenser is the highest, so the produced power will be the lowest for the considered cases. Mixed circuit operation of system gives results close to open circuit, so it’s advantageous.

The pressure values in condenser are close to the values obtained in open circuit, so this is the appropriate solution to operate the cooling water system. In order to highlight the influence of condenser pressure on power production and specific fuel consumption, calculi are performed using diagrams as presented in fig. 6 for power production. Results for electric power production are represented in fig.11 and for specific fuel consumption in fig.12.

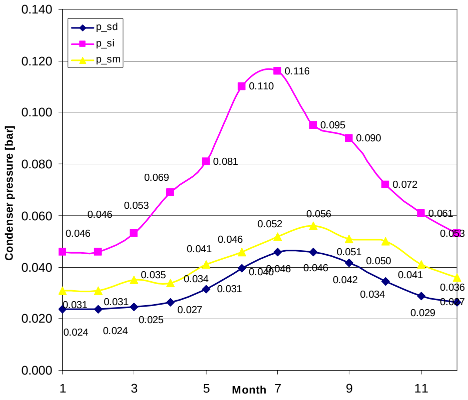

Fig. 10. Pressure in the condenser for different cooling schemes

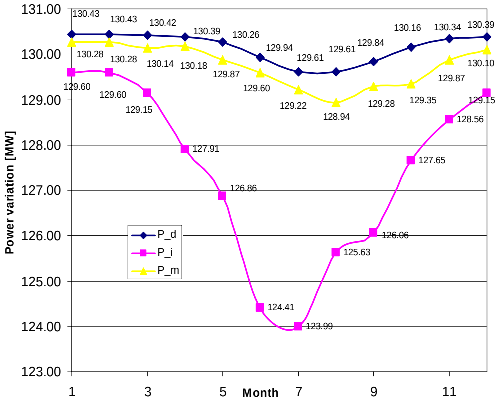

Fig. 11. Produced power variation for different cooling schemes

For close circuit operation, in case of high condenser pressure, the power production can drop to 123.99 MW, versus 130 MW as reference for 0.04 bar condenser pressure. In open circuit operation the pressure in the condenser is in the worst case 0.046 bar (fig. 10), resulting a minimal power drop to 129.61 MW.

Regarding the specific fuel consumption, as shown in fig. 12, highlights the results obtained for the produced power, as the higher condenser pressure induces higher fuel consumption, and as stated above, the best operating scheme is in open circuit, and the worse is in close circuit.

Values obtained for mixed circuit operation are close to those obtained for open circuit operation, so from technical point of view, mixed circuit operation of the cooling water system worth to be considered.

As open circuit operation is impossible for reasons shown above, the final comparison in terms of power gain and fuel economy was made between result for mixed and close circuit operation of the cooling water system.

Based on data from fig. 11 and 12 a diagram was build in fig.13 showing the average power gain and the fuel economy in case of using mixed circuit operation of cooling water system versus close circuit operation.

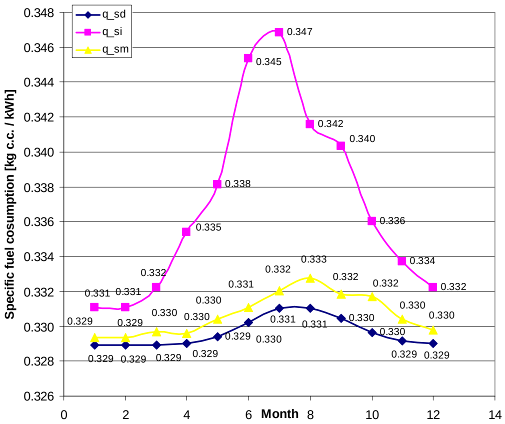

Fig. 12. Specific fuel consumption for different cooling schemes. d – open circuit, i – closencircuit, m – mixed circuit

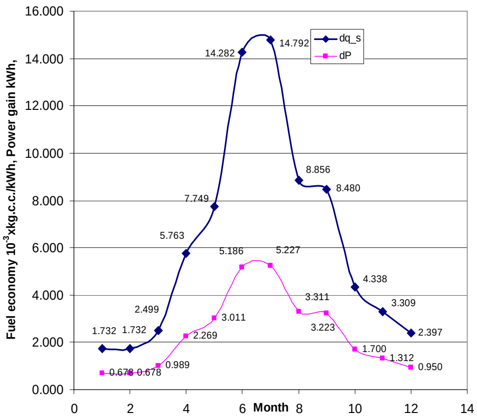

Fig. 13. Power gain dP [MW] and fuel economy dq_c [10^{-3} x kg c.c.·kWh^{-1}] in mixed circuit versus close circuit operation

In fig. 13 can be observed that the maximum power gain is 1.548 MW, and the maximum fuel economy is 3.95 g kWh^{-1}.

In conclusion, as a result of present case study in the given conditions, the mixed circuit operation of the cooling water system is the most efficient.

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