POLISH MARITIME RESEARCH 3(70) 2011 Vol 18; pp. 48-54
10.2478/v10012-011-0017-8

Operating and economic conditions of cooling water control for marine steam turbine condensers

Andrzej Błaszczyk, Assoc. Prof.
Technical University of Lodz
Jerzy Głuch, Assoc. Prof.
Gdansk University of Technology
Andrzej Gardzilewicz, Prof.
Polish Academy of Science, Gdansk

ABSTRACT

The article presents the operational and economic analysis of controlling the cooling water flow in marine steam turbine power plants. The analysis bases on selected designs of the main condenser cooling water pumps and makes use of the results of investigations performed in inland power plants. Special attention was focused on marine aspects of the operation of those systems.

Keywords: steam turbines; turbine operation; marine power plants; marine pumps; circulating pumps

INTRODUCTION

One of basic components of the steam turbine power plant is the condenser in which the steam condenses after passing its heat to the cooling water. In marine power plants the water used for cooling the steam is taken from the outside, i.e. from the water area in which the ship sails. In the majority of power plants the condenser cooling water pumps work at constant mass flow rate, but recently a more and more frequently analysed problem is an attempt to control this parameter, especially when the turbine works under changing load conditions. The main reason for applying control systems in inland turbine power plants is an attempt to save the water, the consumption of which is extremely high during steam power plant operation [1, 5, 8, 12]. Marine turbine power plants also reveal remarkable load changes. Although turbine driven tankers for transporting liquid oil-based chemicals have not been built any longer in recent years, a number of such tankers for transporting liquefied gas were launched. Therefore the economic analysis of cooling pump operation in marine power plants is fully justified, especially in case of tankers, which sail with the cargo in forward trip and return only loaded with the ballast. The above situation considerably differentiates ranges of power required by the ship propulsion system. Moreover, ships with unlimited sailing region, which are, as a rule, designed for least favourable conditions of power plant operation in the tropical zone, also sail in more moderate zones, which needs adapting the operating conditions of their cooling systems to current ambient temperatures. Another argument justifying the interest in analysing the above problem is the appearance of opinions suggesting the need for reconstruction of the global fleet of liquefied fuel tankers based on new standards [17] due to the exploitation of new deep-sea oil development areas. We can expect that in the nearest future new tankers with both engine and turbine propulsion systems will be built.

Until recently, attempts to decrease the power used by the auxiliary devices have been almost unprofitable, which was connected with the loss of turbine unit power due to the pressure increase in the condenser caused by the reduced mass flow rate of the cooling water at lower loads. It was partially justified, as the efficiency gain resulting from such an approach, which was estimated based on on-line measurements, turned out very inaccurate.

That is why the mass flow rate of the condenser cooling water was controlled rather rarely. This control referred to, for instance, changing the angular position of the blades in the rotors of axial-flow pumps, done in order to reduce the technically unfavourable power limits during pump start-ups rather than for economic and water saving reasons [15, 16].

It should be mentioned here that the "seasonal" rotation of axial-flow pump rotor blades, which was used for years, resulted from the "numerical" water flow optimisation oriented on adapting the system to tropical, moderate, or arctic conditions. The above actions were a source of operating problems connected with blade seizing in these

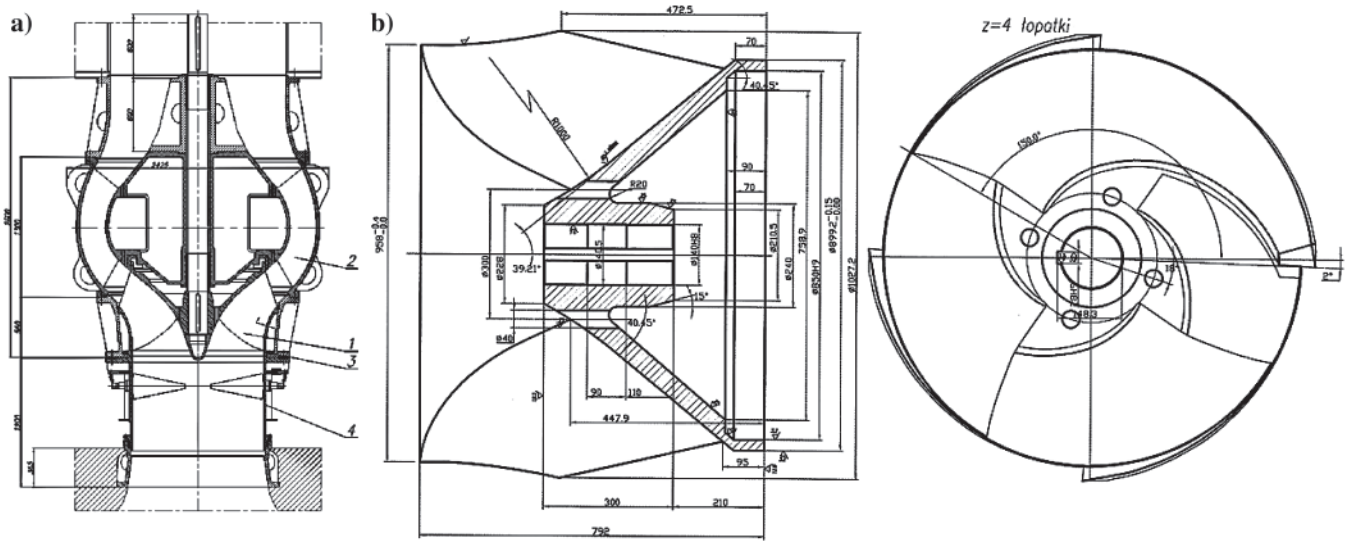

Fig. 1. *Designs of cooling water pumps used in inland 360 MW steam turbine power plants (**a**) and their rotors used in 200 MW power plants (**b**) [2, 3]*

pumps. Pumps of other types have no practical possibilities to control the water flow via changing the geometry of the rotating elements.

The article presents a comprehensive evaluation of the effect of controlling the mass flow rate of the water pumped by the diagonal pumps for cooling the condenser on the economy of operation of the entire power plant. The analysis takes into account, on the one hand, the reduction of the power needed for driving the cooling water pumps at their reduced capacity, but also, on the other hand, power losses of the main turbines resulting from the lower-quality vacuum in the condenser due to smaller rate of the cooling water. Operating aspects of such solutions which are specific for marine applications are also discussed.

PROPOSED DESIGNS OF COOLING WATER PUMPS

Controlling the cooling water mass flow rate started to be the subject of discussion when the turbine blocks in inland steam turbine power plants were to be modernised. Old pumps in those blocks were subject to failures during block operation, as they frequently worked in cavitation areas. Consequently, they did not guarantee preserving the required parameters in the repaired blocks. Castings of their rotors were made carelessly of carbon steel, which considerably affected their lifetime. Modern design and technological procedures and methods have made it possible to design new rotors which remarkably improved the efficiency of pumping and provided opportunities for better adjustment of the operation of these pumps to changing load conditions. The designs of the cooling water pumps for inland large-power turbines are shown in Fig. 1 [2, 3].

Tests of the new pumps have revealed remarkable advantages of their designs, which can be observed when comparing the operating characteristics of the old and new pumps cooperating with one turbine, see Figs. 2 and 3, [7]. The efficiency gains after modernisation amounted to over 10%, at simultaneous increase of the elevation head and water mass flow rate.

Positive tests were the motivation for designing water control systems for those pumps to adapt their operation to changing power loads and environmental conditions. The technical analysis performed for the existing configurations of the cooling systems has revealed that the best way to control the water mass flow rate is the use of guide vanes. Introducing guiding blades at the impeller pump inlet turned out operationally stable, cheapest, and very efficient when the control range was not excessively high [14]. An inlet guide vane designed and installed in the cooling water pump working in the 360 MW turbine system is shown in Fig. 4 [4]. By changing the guide blade setting angle α the cooling water flow could be changed with high efficiency by even as much as 30% reduction of the nominal mass flow rate, what can be seen on the experimentally determined operating characteristics, Figs. 2 and 3. This method turned out much better than throttling, which was used in the past for pumps cooperating with turbines and cooling towers [1].

It also turned out that the inlet guide van blades can be set with "negative" angles with respect to the direction of rotor rotation, thus introducing an opposite angular momentum of the water flow onto the rotor blades. Such an approach enabled increasing the mass flow rate of the condenser cooling water over the nominal level for unchanged pump construction. Indeed, this effect is occupied by increased power taken by the motor used for driving the pump, but it makes it possible to decrease the steam condensing pressure when the temperature of the cooling water is extremely high. This pump operation control is only possible when the (usually electric) motor used for driving the pump has excess power reserve and can be overloaded.

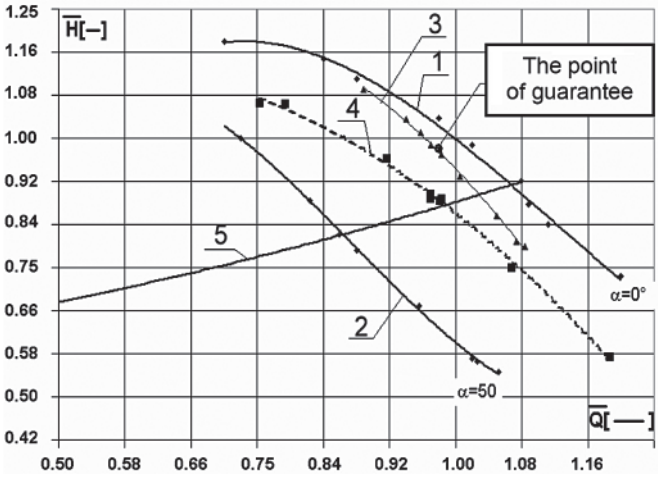

Fig. 2. *Generalised flow characteristics of the cooling water pumps installed in an inland power plant: new pump (1 ÷ 3), old pump (4), pipeline (5), [3]*

MOST WIEDZY Downloaded from mostwiedzy.pl

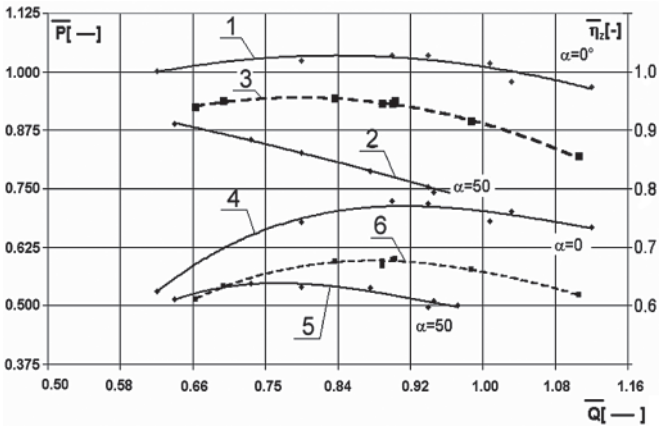

Fig. 3. *Efficiency characteristics of the old non-controlled pump (6) and the modernised pump (3), along with the electric power consumption of the cooling water pumps installed in an inland turbine system: old pump (1) and new controlled pump (2, 4, 5) [2, 3]*

COOLING WATER PUMP CONTROL IN SEA CONDITIONS

The operation of the cooling water pumps in marine turbine power plants was performed using the gas tanker driven by the main turbine of an approximate power output of 25000 kW as a sample case. A scheme of this turbine power plant is shown in Fig. 5.

The main condenser is cooled with the sea water using circulating pumps of approximate capacity 8000 m^3/h (about 2250 kg/s) each. The configuration of the condenser cooling system is given in Fig. 6, while the scheme of cooling water pump connections is shown in Fig. 7.

Since the main turbines work at changing power, it is advisable to use cooling water pumps of changing capacity. For this purpose the control systems described in the previous section which make use of the inlet guide vane can be applied. These systems have already been positively tested and checked in a number of inland power plants. It is noteworthy that the cooling water mass flow rate is controlled by changing the setting of the inlet guide blades, i.e. the immovable element. In inland condition, no traces of seizing of the setting mechanism of the guide vane blades were recorded during the pump operation. The above control method improves operating characteristics as it requires less servicing actions, a factor which is very important in sea conditions.

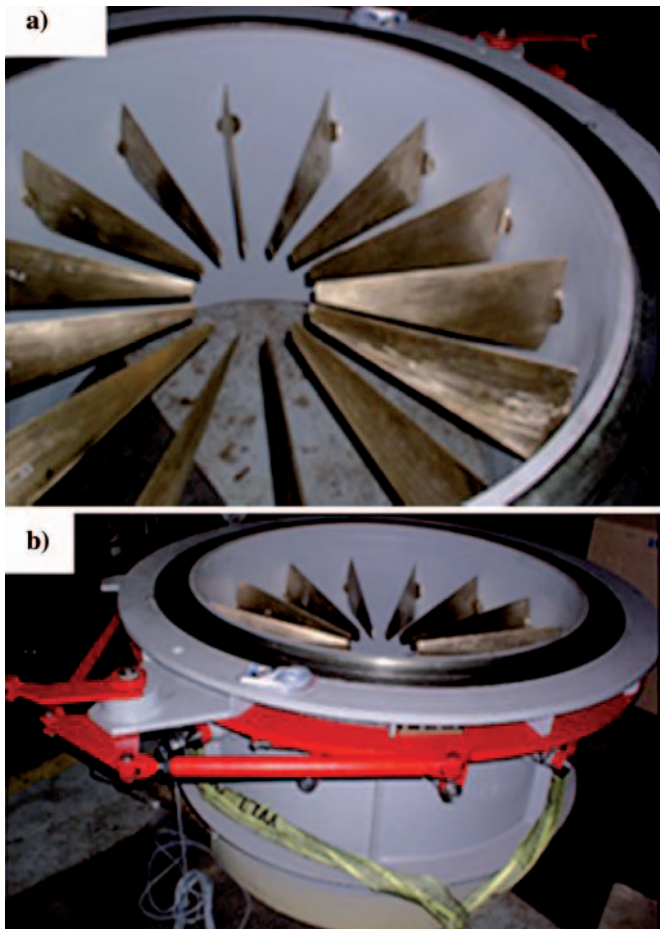

Fig. 4. *View of inlet guide vane blades (**a**) and blade setting mechanism (**b**)*

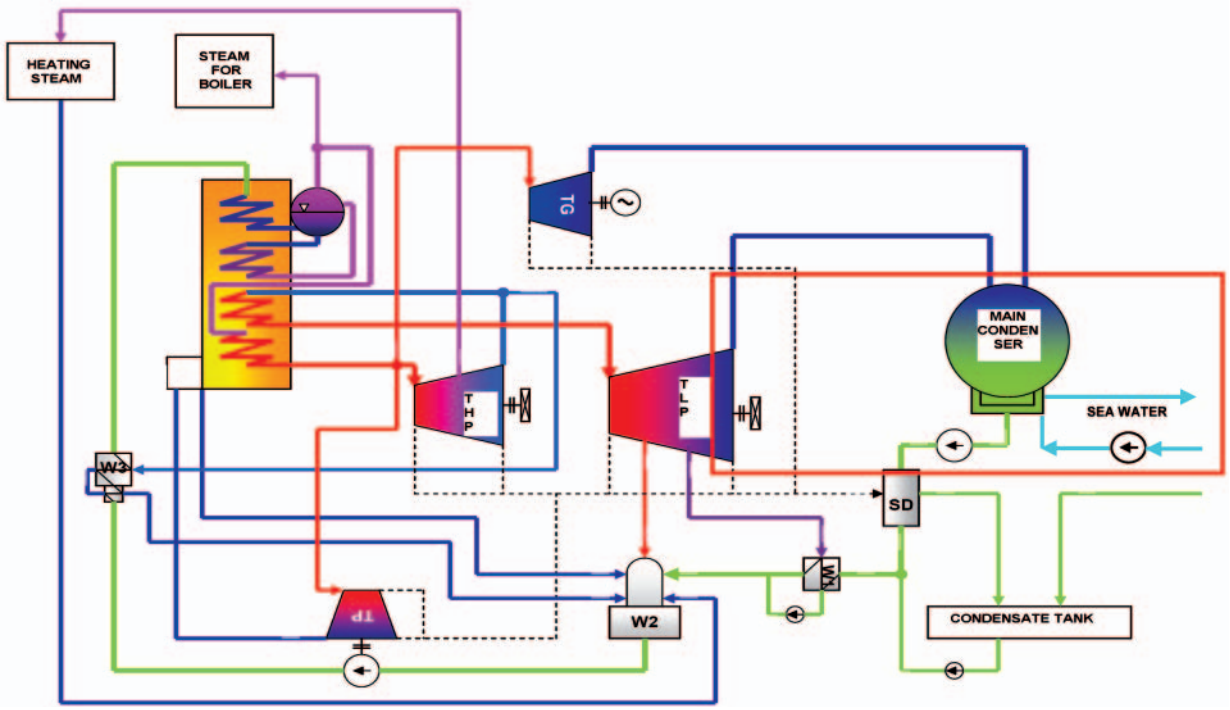

Fig. 5. *Scheme of steam turbine power plant of approximate power of 25000 kW in an LNG tanker [17]*

MOST WIEDZY Downloaded from mostwiedzy.pl

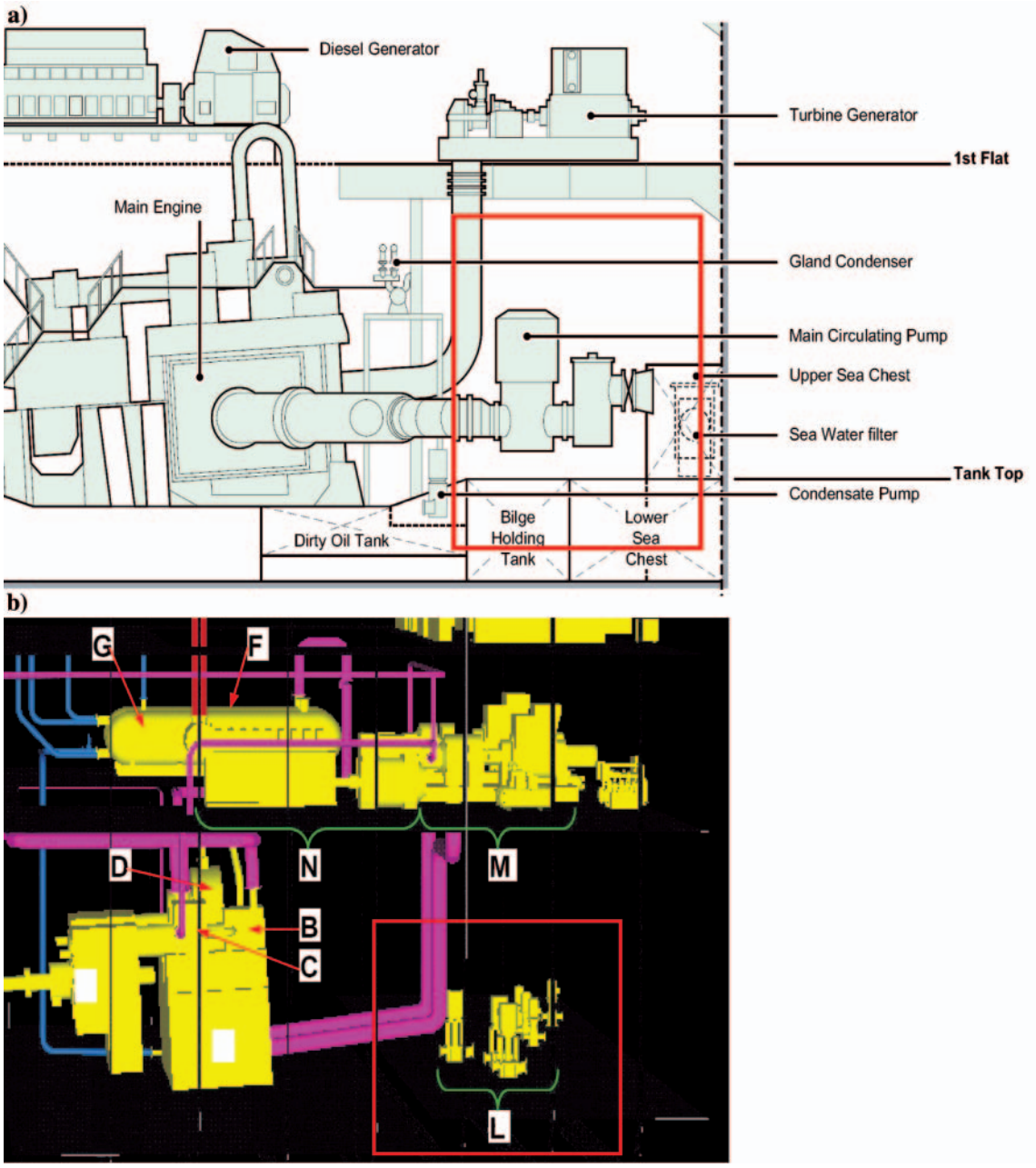

Fig. 6. Configuration of the main condenser cooling system in the steam turbine power plant of an approximate power of 25000 kW in an LNG tanker [17]; ***a)*** *cross section;* ***b)*** *view.*

A system feature which should be mentioned here is the possibility to increase the mass flow rate of the condenser cooling water by introducing the negative angular momentum at water inlet using a negative setting angle of the inlet vane blades. This solution can be profitable for the marine power plants operating in extreme tropical conditions. Another way of using this control method may consist in assuming lower sea water temperatures that those for tropical conditions when designing power plants of the ships with unlimited sailing region.

ECONOMIC AND TECHNICAL ANALYSIS OF THE USE OF COOLING WATER CONTROL

For the time being, the economic and technical analysis of the use of cooling water control systems in steam turbines to follow turbine load changes was only possible based on detailed design calculations taking into account the turbine geometry, see for instance the study by Dzierzgowski [6]. This situation originated from the fact that evaluating possible gains of such control should take into account the entire thermal cycle of the turbine set, with very accurate evaluation of the operation of so-called "cold end" apparatuses including: low pressure turbine, condenser, pumps, and the cooling water system. It was a rather difficult task as the gains resulting from the use of this control were very small compared to the turbine power output, while the physical description of thermal and flow phenomena accompanying this process, necessary for performing the above calculations, were extremely complicated.

This situation was the reason why the advantage of water control could not be uniquely evaluated, even based on warranty thermal measurements performed in steam turbine power plants [8, 12]. In inland conditions this inability was checked on 200 MW blocks, where the gains calculated using the nomogrammes obtained from the producers and describing the operation of these apparatuses [7] were at the level of calculating errors.

MOST WIEDZY Downloaded from mostwiedzy.pl

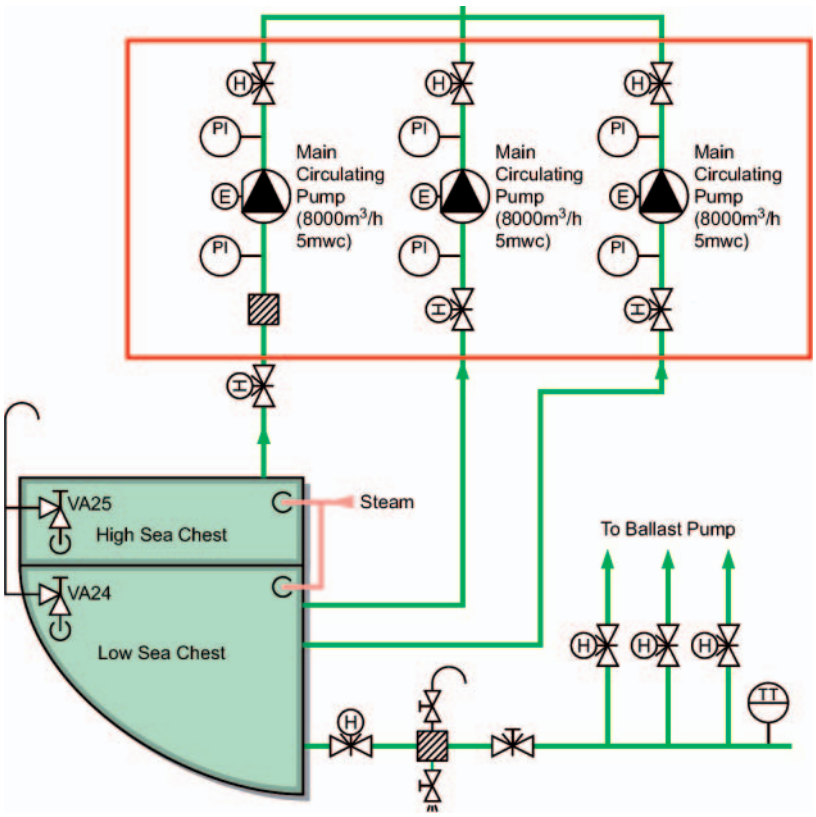

Fig. 7. *Connections of main condenser cooling water pumps in the steam turbine power plant of an approximate power of 25000 kW in an LNG tanker [17]*

In this article, the water control effects are proposed to be evaluated using the code DIAGAR [9] which was successfully used in thermal diagnostics including repair prognoses for individual apparatuses in 200 MW turbine systems in inland power plants [10, 11]. High accuracy of calculations done using this code results from the fact that the balances obtained from the measurements are currently verified by the calculations making use of detailed description of the geometry of individual apparatuses in the thermal cycle. The performed investigations have proved that this numerical "calibration" of the results of the measurements done by DCS systems in power plants provides opportunities for evaluating the operation of individual apparatuses at the accuracy level below ±30 kW [10]. The above methodology has made it possible not only to evaluate precisely the efficiency of particular apparatuses, follow the course of their degradation, and prepare a reasonable repair plan, but also to analyse possible modernisation and improvement variants, including the evaluation of advantages of particular cooling water control systems.

A numerical test of the above described cooling water pump control system was performed for a selected inland power plant turboset and for a marine power plant shown in Fig. 5. The apparatuses in the frame in Fig. 5 represent the "cold end" of the turbine and in the examined case were the subject of detailed control.

The initial version of the diagnostic calculations performed for the thermal cycles of the inland and marine power plants had omitted cooling water system components [12]. For the purpose of the present analysis these components were included in the calculations, along with relevant data about their operation, which made it possible to calculate their energy parameters in changed operating conditions. Beside pumps and pipelines, the delivered information also referred to low-pressure turbine and condenser components which had been modernised in the inland turboset. The calculated characteristics of the power plant turboset were verified by comparing them with the results of the measurements done on a real block [3, 11]. The obtained results are shown in successive figures, with labels facilitating their interpretation, to illustrate advantages of the discussed control method.

The pump characteristic shown in Fig. 3 refers to electric power and efficiency changes as a function of the water mass flow rate. In this case the gains connected with the reduction of the mass flow rate result directly from the savings of the electric power needed for driving the pumps. This was not so clear for old pumps, whose characteristics (1, 6) obtained from measurements are given in Fig. 3, for the case of throttle governing. The operating characteristics recorded for the control performed by changing the blade settings, which are shown in this figure, have been recorded in model tests [2, 3].

The characteristic of the low-pressure turbine part shown in Fig. 8 reveals that the load change, which is here equivalent to the change of the volumetric steam flow rate ($\mathbf{G_p \cdot v_k}$), can result in efficiency changes equalling even as much as 5%. For the given turboset power and the assumed steam mass flow rate **Gp,** the efficiency gains (or losses) result from specific volume $\mathbf{V_k}$ at the controlled mass flow rate $\mathbf{G_w}$ of the cooling water. The quantity $\mathbf{V_k}$ is stabilised for new conditions in the condenser as a result of pressure changes behind the turbine: $\mathbf{V_k = f(p_k)}$. These parameters can be determined directly from the condenser characteristics, which for the tested turbine are shown in Fig. 9. They are given in the form of $\mathbf{p_k = f(G_w)}$ for different mass flow rates and constant inlet temperature of the water**.**

The same efficiency changes, in percents, were assumed for the analysis of the marine power plant.

Based on the curves shown in the figures, which correspond to turbine and condenser operation at nominal and changing loads, it is difficult to evaluate precisely gains resulting from the cooling water control. It only becomes possible after the calculations of the entire thermal cycle, done by the code DIAGAR which makes use of the above operating characteristics

MOST WIEDZY Downloaded from mostwiedzy.pl

of the cold end apparatuses. The results of these calculations, which include the evaluation of power gains and the specific heat consumption of the entire thermal cycle as a function of the load with and without cooling water control, are shown in Figs. 10 and 11. They are given in the form of **ΔN; Δq = f (N/No)** for inlet water temperatures equal to 15°C and 30°C which corresponds to winter and summer conditions of turboset operation. The diagrams take into account the assumed 15% reduction of the water mass flow rate with respect to the nominal rate, which was assumed here at the level of 25000 m^3/h.

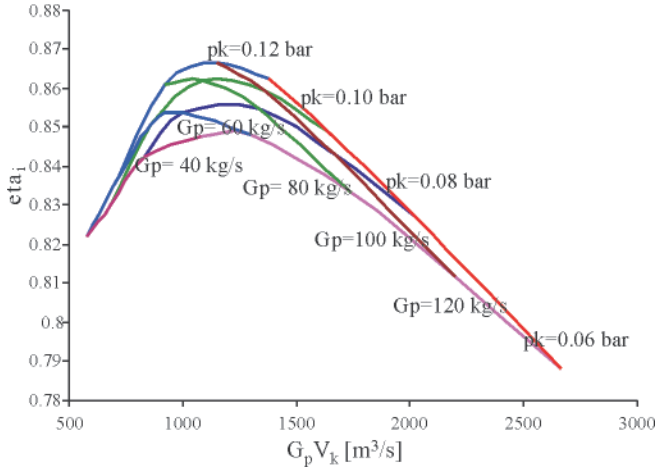

Fig. 8. *Efficiency of the modernised low part of the inland turbine vs. volumetric flow rate of steam for different mass flow rates of steam and different condenser pressures*

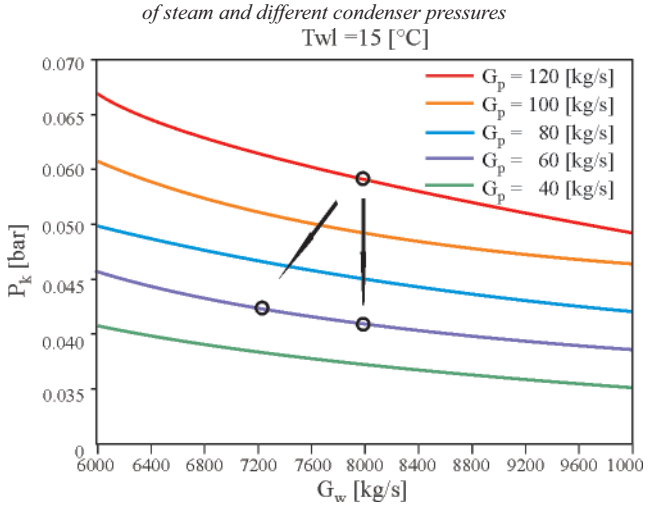

Fig. 9. *Condenser pressure changes vs. cooling water mass flow rate for different mass flow rates of steam at the assumed inlet water temperature*

The presented diagrams reveal that the 15% reduction of the water flow in winter **(t_w = 15°C)** brings gains practically within the entire operating range. At 50% load these gains exceed 300 kW (about 0.2% of the turboset power). It is noteworthy that the water flow control for low loads eliminates supercooling of the condensate in the condenser, see Fig. 10. This is a positive feature as the supercooling effect is unfavourable for the turboset efficiency. At the same time in the summer, at high inlet water temperatures **(t_w ~ 30°C)** the control brings gains only when the load decreases below 50%, while the loss at nominal load and 15% water flow reduction reaches 400 kW! In this case the cooling water flow should be increased rather than reduced. Therefore it is advisable to evaluate precisely once again the nominal cooling water mass flow rate in the cooling pumps for each turboset after its modernisation.

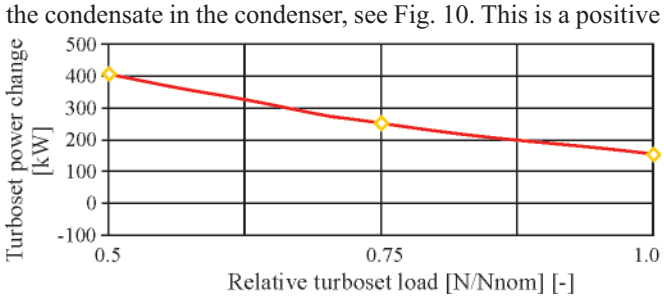

Fig. 10. *Increase of turboset power (specific heat consumption) vs. load for the cooling water mass flow rate reduced by 15% for winter conditions (t_w = 15°C)*

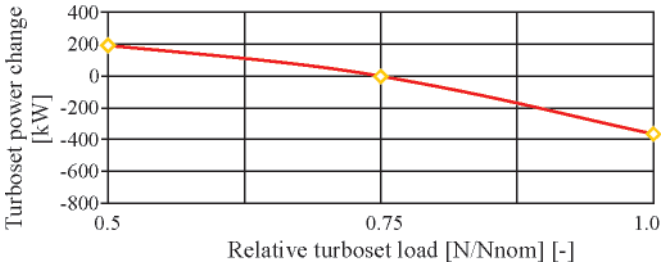

Fig. 11. *Increase of turboset power (specific heat consumption) vs. load for the cooling water mass flow rate reduced by 15% for summer conditions (t_w = 30°C)*

TECHNICAL ASPECTS OF COOLING WATER CONTROL IN MARINE POWER PLANTS

Preliminary calculations performed for the marine power plant, see fig. 5, with the aid of the code DIAGAR confirmed the opinion that the nature of efficiency changes and power gains resulting from the control of the mass flow rate of the water cooling the condenser is similar to that recorded in inland turbine power plants. However, in case of the marine power plants there are more uncertainties concerning the temperatures of the seawater taken for cooling purposes. Nevertheless we can conclude that the percent changes of power and efficiency observed in inland and marine power plants are close to each other.

That means that in the moderate and tropical zones the characteristics realised by the marine power plants will be similar to those of the inland power plans working in comparable conditions. In particular, in the moderate zone at a reduced power plant power we can expect the maximal power gains within the limits up to 0.2% of the nominal power for the entire thermal cycle, taking into account both the reduced power needs for driving the pumps, and the power loss resulting from the lower-quality vacuum in the condenser. For the marine steam turbine power plant with the main turbines of the approximate nominal power of 25000 kW it gives about 50 kW of the reduction of the ship's power plant load. Assuming that the specific fuel consumption in this power plant is approximately equal to 200 g/kWh, we can expect the reduction of the fuel consumption by about 240 kg per 24 hours. The above assessment refers to the moderate zone. The expected gains will be much higher when sailing close to the arctic zone.

In extreme conditions in the tropical zone we should increase the mass flow rate of the condenser cooling water to reach the deepest possible vacuum. We can easily obtain this effect by generating a negative angular momentum via turning the guide vane blades.

In marine conditions axial pumps can be used, as the elevation head, measured in mwc, needed for cooling the condenser is relatively small. These pumps can also be controlled using inlet guide vanes. The power and efficiency gains expected in this case can be even larger that for diagonal pumps [2].

MOST WIEDZY Downloaded from mostwiedzy.pl

CONCLUSIONS

- The presented analysis has proved that it is advisable to control the cooling water mass flow rate in steam turbine power plants to follow turbine load changes. Possibility of this control is provided in the designs of cooling water pumps installed in recently modernised large-power blocks [2, 3]. These pumps reveal cavitation-free operation and higher efficiency. Water flow changes can be realised in these pumps by changing the angular settings of the inlet guide vane blades, to response to accurately measured changes of the electric power of the turboset and the inlet temperature of the cooling water, or (alternatively) the pressure in the condenser. However, these signals are to be correlated with the calculations of the turboset thermal cycle, which can be done online using the data recorded by the power plant measuring system and a relevant computer code [13].
- Preliminary calculations making use of the results of measurements performed in inland power plants have revealed that in winter for the 200 MW blocks, power gains can be obtained within the entire range of turbine operation when the mass flow rate of the cooling water is reduced by 15% with respect to the nominal value. When the load is reduced by 50%, these gains can even reach 400 kW i.e. 0.2% of turboset power, which is equivalent to the decrease of the specific heat consumption by 15 kJ/kWh. In the summer these gains are smaller, for higher load ranges when the temperature of the cooling water exceeds 30°C it is advisable even to increase the flow of the cooling water with respect to the nominal mass flow rate, which can be done using the inlet guide vanes.
- Similar gains can be expected in case of steam turbines working in marine power plants. When the ship sails in the moderate zone and at reduced driving power we can expect the reduction in power plant fuel consumption amounting approximately to 240 kg per 24 hours. At the same time, the control making use of adjustable guide vane blades provides good opportunities for increasing the cooling water mass flow rate to obtain deeper vacuum in the condenser in the tropical zone.

NOMENCLATURE

eta_i – efficiency of turbine Low Pressure (LP) part [-],
G_p – steam mass flow rate [kg/s],
G_w – cooling water mass flow rate [kg/s],
H – pump outlet pressure [m of H_2O or MPa],
N – power of power unit [kW],
ΔN – change of power of power unit [kW],
Q – volumetric flow rate [m^3/s],
p_k – condenser pressure [kPa],
P – power of pump motor [kW],
t_{in} – inlet temperature of cooling water [°C],
v_k – specific volume of condensing steam [m^3/kg].

BIBLIOGRAPHY

1. Bilkowski E., Olszowiec R., Szybalski K.: *Production of electric energy in the Belchatow power plant in the aspect of water pump operation in its technological systems* (in Polish), Proceedings of the 10-th Forum of Pump Users, Bełchatów 2004.
2. Błaszczyk A., Popierski A., Staniszewski J.: *Modernisation of 160 D30/HP cooling water pumps* (in Polish), Proceedings of the 7-th Scientific and Technical Conference, Słok 2005.
3. Błaszczyk A., Popierski A., Najdecki A., Staniszewski: *Modernization of the hydraulic system of the 120D40 cooling water pumps*, (in Polish), Proceedings of the 7-th Scientific and Technical Conference, Słok 2007.
4. Błaszczyk A., Staniszewski J., Kużba G., Woźniak D.: *Control of the 160D30 cooling water pump,* (in Polish), Proceedings of the 7-th Scientific and Technical Conference, Słok 2007.
5. Dzida M.: *Problems of steam condensers cooling water flow control in case of turbine partial loads*, (in Polish), Proc. 2-nd Scientific and Technical Conference on Power Plants, Słok 1995.
6. Dzierzgowski J.: *Technical analysis of designing steam turbine condensers*, (in Polish), Ph.D. thesis, Faculty of Ocean Engineering & Ship Technology, Gdansk University of Technology, Gdańsk 1992.
7. Energopomiar Gliwice, *Recommendations after the control of the operation of steam turbine condensers,* (in Polish) Publications of the Ministry of Mining and Energy, Warsaw, Gliwice 1986.
8. Gardzilewicz A., Błaszczyk A., Głuch J.: *Advantages of Condenser Cooling Water Control in Large Steam Power Units*, Proc. European Conference on Turbomachinery ETC'2009, Graz 2009.
9. Gardzilewicz A., Głuch J., Bogulicz M., Jankowski T., Uziębło W.: *Code package DIAGAR for steam turbine thermal diagnostics calculations,* (in Polish), Report of DIAGNOSTYKA MASZYN, Gdańsk 1995-2009.
10. Gardzilewicz A. Głuch J., Bogulicz M., Walkowiak R., Najwer M., Kiebdój J.: *Experience in Application of thermal Diagnostics in the Turów Power Station*, Proc. ASME IJPGC, Atlanta 2003.
11. Gardzilewicz A., Marcinkowski S., Kurant B.: *Thermal and Flow Investigations in LP of Turbine Blade System*, Proc. Turbomachinery, Workshop, Gdańsk 2006.
12. Głuch J.: *Selected Problems in Determining an Efficient Operation Standard in Contemporary Heat and Flow Diagnostics*, Polish Maritime Research S1/2009, Gdańsk 2009.
13. Głuch J., A. Gardzilewicz A.: *The analysis of performance of the turbine condenser with prognosis of repair*, Proc. ASME IJPGC, Baltimore, 1998.
14. Łojek A.: *Pre-rotational and extractive control of impeller pumps,* (in Polish), Ph.D. thesis, Institute of Fluid-Flow Machinery, PAS, Gdańsk 1987.
15. Marczewski J. et al.: *Modernisation of the control system for the cooling water pumps of 200 MW turbine sets in the Połaniec power plant,* (in Polish), Internal report of the Połaniec power plant, 2001-2003.
16. Sadowski A., Łojek A., Klein M., Szerucki J.: *Modernisation of the control system for the cooling water pumps of 500 MW turbine sets in the Kozienice power plant,* (in Polish), Pompy i pompowanie.
17. Sienica K.: *A preliminary project of the steam turbine power plant for the ship transporting the liquid natural gas*, (in Polish), M.Sc. thesis, Faculty of Ocean Engineering & Ship Technology, Gdansk University of Technology, supervisor: Krzysztof Kosowski, Gdańsk 2005.

CONTACT WITH THE AUTHORS

Andrzej Błaszczyk, Assoc. Prof.
Institute of Fluid-Flow Machinery,
Technical University of Lodz, Stefanowskiego 15,
90-537 Lodz, POLAND
email: akblaszc@p.lodz.pl

Jerzy Głuch, Assoc. Prof.
Faculty of Ocean Engineering & Ship Technology,
Gdansk University of Technology,
Narutowicza 11/12,
80-233 Gdansk, POLAND
email: jgluch@pg.gda.pl

Andrzej Gardzilewicz, Prof.
Institute of Fluid-Flow Machinery,
Polish Academy of Science,
Fiszera 14,
80-952 Gdansk, POLAND
email: gar@imp.gda.pl

MOST WIEDZY Downloaded from mostwiedzy.pl