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Probabilistic models for designing the sea--water pump systems of ship power plant

Part II

Selection of size and number of sea-wather pumps

SUMMARY

This is the second part of a paper presenting the original method which makes it possible to select a pump arrangement by applying the statistical distribution of real demand for cooling sea-water, obtained with taking into account the statistical distributions of sea-water temperature and the total cooling heat flow of power plant during ship service.

Continuation of the first part of the paper published in the Polish Maritime Research No.1(23), March 2000.

On the condition of neglecting minor losses it can be assumed that the heat flow transferred to seawater is equal to the power plant cooling heat flow, namely :

$$Q_{sw} = Q_{SPP} \tag{22}$$

The heat flow received by sea water can be determined by means of the following heat balance equation :

$$Q_{sw} = V_{sw}\rho_{sw}c_{sw}\Delta t_{sw} \tag{23}$$

where :
- V_{sw} - sea-water flow rate
- ρ_{sw} - sea-water density
- c_{sw} - mean sea-water specific heat
- Δt_{sw} - sea-water temperature increment.

The equation makes it possible to determine required values of the flow rates :

$$V_{sw} = \frac{Q_{sw}}{\rho_{sw}c_{sw}\Delta t_{sw}} \tag{24}$$

Values of ρ_{sw} and c_{sw} should be assumed as the mean values for a given shipping route as different water salinity and temperature values occur in different sea regions.

Δt_{sw} real values result from limitations of sea-water temperature values, namely :

- inlet sea-water temperature can vary from 0 to 35° C for the unrestricted navigation region
- sea-water temperature at the outlet from the system should not exceed 45 to 50° C.

The system's designer, taking into account all above given comments and possible shipowner's recommendations as well as system solutions and other circumstances, is able to choose different assumptions as to Δt_{sw} value for different temperature values of overboard seawater (Fig.7.) :

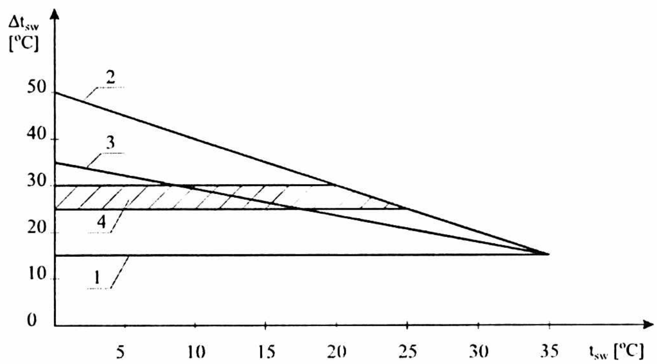

Fig.7. Selection principles of the cooling sea-water temperature increment Δt_{sw} (see text below)

Line 1 - The smallest constant value of Δt_{sw} equal to 15° C independent of overboard sea-water temperature as the temperature of tropical waters can be as high as abt. 35° C and its assumed maximum temperature at the outlet from the system should not exceed abt. 50° C. The assumption leads to the lowest utilization of the sea-water cooling capability, and therefore to higher required flow rates.

Line 2 - The largest possible value of Δt_{sw} resulting from keeping the upper value constant and equal to 50° C water temperature at outlet from the installation.
Other possible values of Δt_{sw} are contained between the above mentioned extremes, namely :

Line 3 - Intermediate values, e.g. Δt_{sw} = 35° C for the lowest temperature of the delivered seawater, and Δt_{sw}= 15° C for tropical waters.

Area 4 - Keeping the water temperature difference constant, e.g. Δt_{sw}= = 25 to 30° C for overboard water temperature within the range of 0 to 20÷25° C, and for its higher values-allowing it to decrease to Δt_{sw} = 15° C (a system with recirculation).

The above presented method of determining the distribution of sea-water demand is based on the assumption that the random variable heat flows absorbed by cooling sea water are independent of their temperature values during ship service. Relevant correlation coefficients can be determined only for the cooling heat of main and auxiliary engines on the assumption of direct proportionality of the heat flow and engine power output values (Fig.8.).

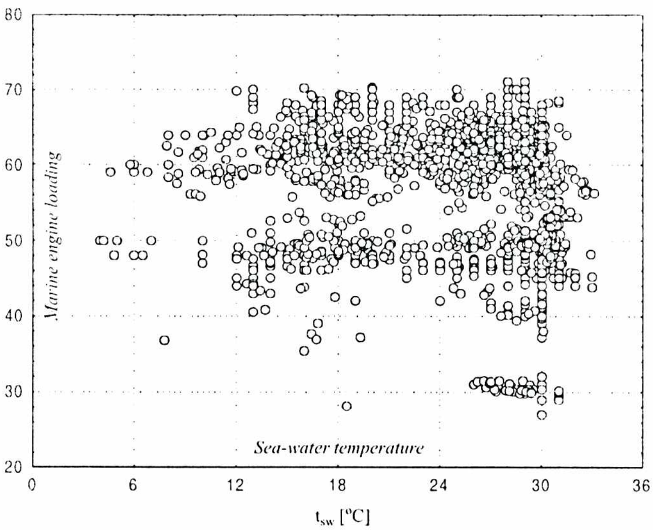

Fig.8. Simultaneous values of the main engine loading and sea-water temperature recorded on the m/s CHOPIN at sea (the main engine loading was determined as the product of the engine loading index and engine rotational speed rpm)

The performed investigations [7] revealed that the correlation coefficient values between main engine power output and water temperature values were contained within the range of R = 0.07÷0.26.

For the remaining power plant devices a diversified situation is observed :

- *for air compressors, reefer stores and air conditioning system of power plant control centre (PPCC)* : the cooling heat flows can be assumed independent of sea-water temperature as any functional relationship between the magnitudes does not exist
- *for surplus condenser, drip cooler, cargo refrigerating space and air conditioning system of accommodations* : such a relationship occurs to various extent.

Nevertheless in further considerations the relationship (24) can be assummed valid as the share of the total cooling heat flow of the last group of devices in the total cooling heat flow of the power plant is rather low (e.g. abt. 9% only for the container carrier „Contship Melbourne").

Determining the distribution histogram for the required sea-water flow rates is possible by means of the distribution histograms of sea-water-absorbed heat flows (equivalent to the histogram of power plant cooling heat flow) and those of sea-water temperatures. The histograms can be formed by using the in-advance-determined, normal distribution parameters of the random variables in question. The number of histogram should be :

→ for the sea-water temperature distribution : $j \geq 7$
→ for the distribution of the sea-water-absorbed heat flow $i \geq 10$.

A distribution histogram of the required sea-water flow rates can be formed with the aid of Tab.3.

The first two rows of it contain :

- the temperature increment values of the sea water flowing through the central cooler (Δt_{sw1}, Δt_{sw2}, ... Δt_{swj}), corresponding to seven interval values of the sea-water temperature distribution
- the interval occurrence frequencies of the sea-water temperature distribution (p_1'', p_2'', ... p_j''),

and the first two columns - the corresponding magnitudes connected with the sea-water-absorbed heat flow distribution, namely :

- the mean interval heat flow values (Q_1, Q_2, ... Q_i)
- the mean interval values of occurrence frequency of the heat flow distribution (p_1', p_2', ... p_i')

All possible combinations (configurations) of the values can occur during a long time of ship's service as the sea-water-absorbed heat flow distributions are independent of the sea-water temperature distribution. Hence the values corresponding to those combinations were put into the table, namely :

⇨ of required cooling seawater flow rate calculated according to (24)
⇨ of occurrence probability of a relevant combination, defined as the product of relevant interval occurrence frequency values, e.g. : $p_3' \times p_5''$[9].

All the values of required cooling sea-water flow rates put into the table are contained within the range of the extreme rates V_m^{min}, V_m^{max} calculated according to (24) for the extreme values of Q_i^{min} and Q_i^{max} as well as of Δt_{swj}^{min} and Δt_{swj}^{max} in compliance with the adopted principles (see Fig.7).

Tab.3. Auxiliary table for calculating the required cooling sea-water flow rates

	Δt_{swj}	Δt_{sw1}	Δt_{sw2}	......	Δt_{swj-1}	Δt_{swj}
Q_i	p_j'' / p_i'	p_1''	p_2''	......	p_{j-1}''	p_j''
Q_1	p_1'	$\frac{V_{11}}{p_1'p_1''}$	$\frac{V_{12}}{p_1'p_2''}$	......	$\frac{V_{1,j-1}}{p_1'p_{j-1}''}$	$\frac{V_{1,j}}{p_1'p_j''}$
Q_2	p_2'	$\frac{V_{21}}{p_2'p_1''}$	$\frac{V_{22}}{p_2'p_2''}$	......	$\frac{V_{2,j-1}}{p_2'p_{j-1}''}$	$\frac{V_{2,j}}{p_2'p_j''}$
.....	......	......	......	......	......	......
Q_{i-1}	p_{i-1}'	$\frac{V_{i-1,1}}{p_{i-1}'p_1''}$	$\frac{V_{i-1,2}}{p_{i-1}'p_2''}$	......	$\frac{V_{i-1,j-1}}{p_{i-1}'p_{j-1}''}$	$\frac{V_{i-1,j}}{p_{i-1}'p_j''}$
Q_i	p_i'	$\frac{V_{i,1}}{p_i'p_1''}$	$\frac{V_{i,2}}{p_i'p_2''}$	......	$\frac{V_{i,j-1}}{p_i'p_{j-1}''}$	$\frac{V_{i,j}}{p_i'p_j''}$

In order to form the histogram of required cooling sea-water flow rates the range of $V_m^{min} \div V_m^{max}$ should be divided into $m \geq 10$ equal intervals and then, by making use of the data from Tab.3, the water flow rates contained within a given interval should be assigned to that interval and the corresponding products $p'p''$ summed up. This allows to determine an occurrence frequency value for each of the water flow rate intervals and then to form the relevant histogram, frequency density curve or cummulative distribution function.

The maximum value of cooling sea-water demand should be assumed identical with 100% pump capacity, i.e. :

$$V_{sw}^{max} \cong V_{sw}^{100\%} \tag{25}$$

and be taken as the basis for the selection of size and number of the pumps.

An analysis and choice of the most favourable pump system is carried out on the assumption that the following data are known :

- ➔ the distribution of the required sea-water flow rate
- ➔ the maximum sea-water demand for the conditions of ship's operation in tropical waters
- ➔ flow characteristics and power demand of alternative pump systems.

EXAMPLE OF APPLICATION

The way of pump system selecting can be illustrated by an example of a system consisting of the pumps with different rated outputs (e.g. 2 x 80% + 1 x 20% of the required total pump output). The example illustrating the selection principles is shown in Fig.9.

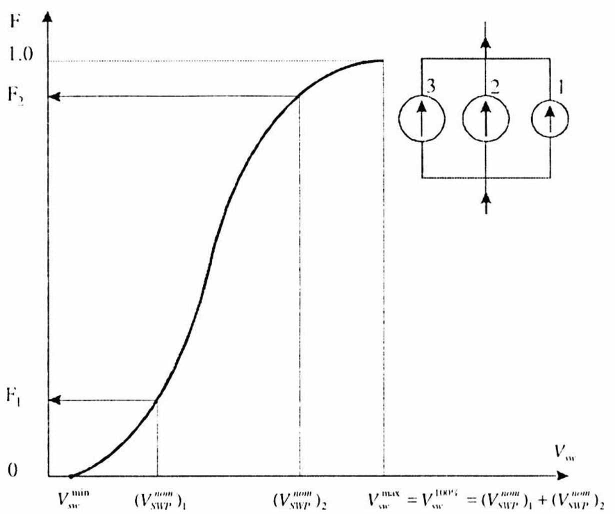

Fig.9. *Scheme illustrating the selection principles of output of the three-pump system where $(V_{SWP}^{nom})_2 = (V_{SWP}^{nom})_3$*
F = commulative occurrence frequency

It can be observed that the required maximum output would be satisfied by two pumps of different rated outputs e.g. :

$$(V_{SWP}^{nom})_1 + (V_{SWP}^{nom})_2 = V_{sw}^{max} \cong V_{sw}^{100\%} \tag{26}$$

At a low sea-water demand the „small" pump of $(V_{SWP}^{nom})_1$ output would operate, and at a demand exceeding that value it would be stopped and the „big" one be started which would operate as the only one within the output range of $(V_{SWP}^{nom})_1 \div (V_{SWP}^{nom})_2$, and at the greatest required output the „small" pump would be additionally put into operation.

Hence the operation-time share factor λ_1^{SWP} of the „small" pump will be :

$$\lambda_1^{SWP} = F_1 + (1 - F_2) \tag{27}$$

and that of the „big" pump :

$$\lambda_2^{SWP} = 1 - F_1 \tag{28}$$

The annual energy consumption of such pump system will be :

$$(E_{SWP}) = [(N_{SWP})_1 \lambda_1^{SWP} + (N_{SWP})_2 \lambda_2^{SWP}] \cdot T \tag{29}$$

The pump system which fulfils the following condition :

$$\{E_{SWP}\} = \min \tag{30}$$

can be deemed the most favourable out of all analyzed variants.

These pump-system selection principles are also valid in the case when $V_{sw}^{100\%} > V_{sw}^{max}$. It can happen in result of special shipowner's requirements or limitations imposed on a series of pump types in hand.

The principles are also valid for other pump system configurations, e.g. that of four pumps of different rated outputs (e.g. „2 x 40% + + 2 x 30%" one which permits to work at one of the following pump outputs : 30, 40, 60, 70, 80 and 100%).

As only the selection problem of size and number of pumps is considered, it is important to select the criteria and operational conditions on which a decision on either stopping or starting a given pump has to be made. For instance this can be done on the basis of the outlet sea-water temperature which can be easily measured by means of thermometers installed on each of the coolers.

Exceedance of a selected threshold value by abt. 50° C can serve as a signal for increasing the sea-water output (and vice versa), i.e. for changing the system mode of operation.

In these considerations investment and repair costs are neglected as performing an economical analysis, especially for piping installation, is only possible if its characteristics (a.o. pipe lengths, arrangement of fittings etc) and data on element durability, repair costs etc. are known.

However it is worth stressing that the application of the method in question makes it possible to select pumps of smaller outputs and in consequence smaller diameter pipes and fittings, thus to lower investment and repair costs. On the other hand it should be taken into account that applying more pumps of differentiated outputs (e.g. that of „2 x 40% + 2 x 30%") leads to substantial extending the piping system as well as to increasing the number of elements, equipment and the control devices necessary to make such sophisticated pump system work.

A.	**Basic technical parameters of ship and power plant**
Ship main dimensions	L x B x d
Main propulsion system	engine type, N_{ME}^{nom}, reduction gear, shaftline, fuel oil viscosity
Electric power plant	electric power plant service loading : N_{EPP}^{av} number and kinds of electric power sources : N_{EGS}^{nom}
Steam installation	characteristics of heat energy (steam) sources (number, type), steam balance : $D_{UB}^{nom}, D_s, D_w, \Delta D_s, \Delta D_w$, number of surplus condensers and drip coolers
Air compressors	number, type, drive power : N_{AC}^{nom}
Evaporator	type, capacity
Cargo refrigerating space, reefer stores and air conditioning systems	refrigerating capacity: Q''_{CS}, Q''_{ACS}, compressor power demand N_{CS}^{nom}, N_{ACS}^{nom}
Other devices	main working parameters
Shipping line	region of operation, annual sea voyage time

B.	**Sea water**
Assumed values of : $t^{min}, t^{max}, t^{av}, \sigma_t, t_{sw}^{min}, t_{sw}^{max}$	
Calculated parameters of : distribution histogram	

Determination of the devices taken into account in forming the total sea-water cooling heat flow of the power plant

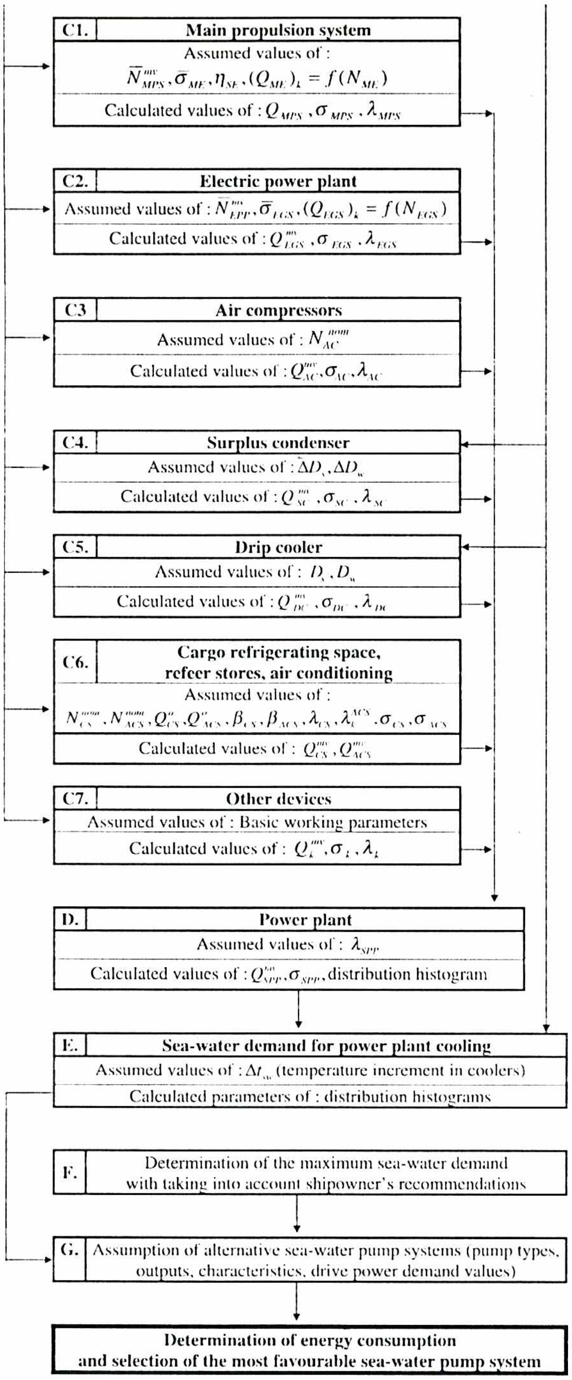

Fig. 10. Block diagram of the method

RESULTS OF EXAMPLE CALCULATIONS

Example calculations performed for the power plant of a container carrier of 17 940 kW propulsion power confirmed that the selected three-pump system (of „2 x 64% + 1 x 36%" configuration) was that of the lowest energy consumption. Its value was as low as only 54% of that of the most commonly applied system of two identical pumps (viz. „2 x 100%"configuration).

FINAL REMARKS AND CONCLUSIONS

The presented original method of the selection of sea-water pump system parameters with taking into account real operation conditions of the ship power plants, as well as results of performed analyses and calculations make it possible to come to the following conclusions :

- Application of the probabilistic models and methods presented in this paper as well as in [6] makes it possible to predict normal (or truncated normal) distribution characteristics of :

  * sea-water temperature for ships sailing on any shipping route
  * cooling heat flows for all engines and devices included into structure of the sea-water cooling system
  * total power plant cooling heat flow.

- As it was demonstrated, parameters of sea-water demand distribution can be determined because the random variables : values of sea-water temperature and power plant cooling heat flows could be deemed independent for a given mode of pump system operation.

- The largest determined value of the demand V^{max}_{sw} should be the same as or close to the 100% system output $V^{100\%}_{sw}$ used for the pump size selection. Application of the method is also reasonable even in the case if calculation conditions recommended by a shipowner cause that resulting $V^{100\%}_{sw}$ value is greater than the V^{max}_{sw} value determined by means of the method in question.

- Various pump systems satisfying the rules of classification societies can be selected by using the sea-water demand cummulative distribution function and assumed value of $V^{100\%}_{sw}$. Total energy consumption (preferably its yearly value) for each of the systems can be determined by using relevant power characteristics and after determination of an operation time share factor value for each of the pumps, and on this basis the most favourable version of the system can be chosen.

- The method, as an engineer's analytical tool, is applicable in the preliminary stage of ship design, i.e. when a specification list of all power plant machines and devices, as well as electrical energy and steam balances are completed. In such case the general operational characteristics of the ship in question (e.g. mean relative loading of its main propulsion system, operation time share factors of some devices) are also necessary.
  The method can also be useful for feasibility considerations of modernization of existing ships.

NOMENCLATURE

c - mean specific heat
D - steam mass flow rate
E - annual energy consumption
F - cummulative occurrence frequency
N - loading (power)
p - mean interval occurence frequency
Q - heat flow, cooling heat flow
Q^0 - refrigerating capacity
T - time
t, t_{sw} - sea-water temperature
V, V_{sw} - sea-water flow rate
V_{SWP} - sea-water pump volumetric capacity
β - loading factor
λ - operation-time share factor
ρ - density
σ - standard deviation

AC - air compressors
ACS - air conditioning system
CS - cooling system
DC - drip cooler
EGS - electric generating sets
EPP - electric power plant
ME - main engine
MPS - main propulsion system
PPCC - power plant control centre
SC - surplus condenser
SE - shafting elements
SPP - ship propulsion plant
SWP - sea-water pump
UB - exhaust gas utilization boiler

Indices

i - index number of successive interval of absorbed heat flow distribution histogram
j - index number of successive interval of sea water temperature distribution histogram
k - index number of successive device
m - index number of successive interval of cooling water flow rate
mv - mean value
nom - nominal (rated), or required
s - summer
sr - shipping route
sw - sea water
w - winter
– - relative value

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Conference

Science - Practice - Education

Already for many years the Mechanical Faculty, Technical University of Gdańsk cooperates with the Machine Construction Faculty, High School of Bremen. Within the cooperation common symposia take place under the heading : Science-Practice-Education.

On 18 and 19 May 2000 the tenth (jubilee) scientific meeting of the kind was held in Gdańsk. It was hosted and organized by the Mechanical Faculty, Technical University of Gdańsk. 52 Polish scientific workers participated in it, and from Germany, apart from 4 repersentatives of the High School of Bremen, also15 persons of the similar schools of Köln, Stralsund and Braunschweig took part.

During 6 sessions, altogether 24 papers were presented of highly diversified themes due to the Symposium's slogan.

Generally, they dealt with the following issues :

★ European aspects of science and education
★ Experience and education models of the engineering education of women for economy needs
★ Rescue engineering as a new study line
★ Fuzzy-logic application in practice
★ Simulation of economy systems
★ Internet-aided rationalization of design and production processes
★ New production methods and team-effort effectiveness
★ New material engineering processes in machine construction
★ Quality management for production processes
★ Environment versus health.

A novel technology of manufacturing Ti-alloy vessels (applicable to satellites), gyroplane of a new rotor blade design, and a solar-energy-propelled wheel car drew special interest of attending persons.

The Symposium contained also a poster session where 17 reports dealing with results of variuos research investigations and design proposals were presented.

Miscellanea

IMAM 2000

Representatives of Polish scientific circles took also part in IX Congress of the International Maritime Association of Mediterranean, held from 2 to 6 April 2000 in Ischia (Italy).

Scientific workers of Gdynia Maritime Academy prepared 7 papers, namely :

❖ *Maintainability design system for ship equipment* (by W. Tarełko)
❖ *Improving feasibility of free-fall systems to evacuate casualties of marine accidents* (by Z.Wiśniewski)
❖ *Robust track-keeping control system for ships* (by L.Morawski and J. Pomirski)
❖ *Fuzzy tracking ship controller* (by L.Morawski and M.Tomera)
❖ *The safe ship control process with application of fuzzy dynamic programming* (by J.Lisowski)
❖ *Maritime transportation strategies in the Baltic Euroregion* (by J.Kubicki)
❖ *Transeuropean transportation corridors in the Central Europe : Problems and prospects* (by J.Kubicki)

Specialists of the Technical University of Szczecin prepared the following papers :

✱ *The Baltic Sea as a reservoir of pollutants* (by T.Graczyk and L.Piskorski)
✱ *Problems relating to optimization of welfare onboard ships and ways of solving such problems at designing stage* (by A.Wolanowska and M.Markowski)
✱ *Underwater monitoring as a tool to define sea water pollution* (by T.Graczyk, M.Matejski and W.Skórski)
✱ *Information as an important element ensuring the quality of technical and organizational processes in shipbuilding* (by R.Michalski and W.Zeńczak)
✱ *Research on physical and numerical models of ship diesel engine cooling systems to improve design quality* (by R.Michalski and W.Zeńczak)

A.Charchalis and A. Grządziela of Polish Naval Academy, Gdynia, presented the paper titled : *Diagnosing the ship shafting alignment by means of vibration measurements.*