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A simulation model of flow of working media within auxiliary systems of ship main engine

SUMMARY

In the paper a non-linear model of hydraulic flow network as well as a way of its numerical solving is presented. The proposed flow network model can be applied to real-time simulation. In order to verify the model the simulation of main engine auxiliary systems was performed.

INTRODUCTION

This is the last of three papers devoted to simulation of control processes of ship power plant systems. The problem of modelling the flow network is presented on the example of the cooling and lubricating systems of the ship medium-speed main diesel engine. Basic assumptions and principles of the simulation were highlighted in [12]. A plate cooler simulation model was described in [13].

Thermodynamic behaviour of the auxiliary cooling and lubricating systems of the diesel engine is characteristic of large time constants and lag. As far as their hydraulic behaviour is concerned they can be represented by inertialess objects described by static characteristics only. Their working media are water and oil. The liquids are assumed incompressible within the pressure range applicable to such systems [15,16]. Length of piping branches of the systems is not large. The systems are of circuit type and do not include any pressure vessels which could involve inertia of flow.

Two models are presented below :

- ⇨ of a flow network and
- ⇨ of a three-way valve applied as final control element of temperature control unit.

FLOW NETWORK MODEL

The piping network can be accordingly compared to an electric network [6]. However, in the hydraulic systems capacitance and inductance can be neglected. The systems include only resistance and pressure, and flow rate sources. The inductance-free and capacitance-free systems are treated as proportional objects. To elaborate the flow network model the following assumption were made :

The piping networks together with their resistance elements and sources are considered - with respect to hydraulic phenomena - as inertialess objects.

The electric resitstance elements are mainly linear and described by the Ohm law :

$$u = Ri \tag{1}$$

However, the hydraulic resistance elements are nonlinear. That depends on a type of flow determined by Reynolds number (Re) value. For $Re < 2000$ the flow is laminar and the flow equation linear. For $Re > 2400$ the flow is turbulent and described by the parabolic equation [8,9] :

$$p = Rm^2 \tag{2}$$

In the case of the connection network, change of one network element causes change of pressure distribution in the remaining elements.

To make calculation algorithm effective for digital simulation it is necessary to apply digital description of the connection network and to use matrix methods for solving the nonlinear equations.

For numerical calculations of the piping networks the nodal potential method applicable to the nonlinear networks was selected [6] in which a given piping system is represented by a graph consisting of branches and nodes. The connections and branchings in the network are modelled by the nodes. The elements between nodes are represented by the graph branches, as shown in Fig.1. They can be resistances (valves, heaters, cylinders, etc) or pressure sources (impeller pumps) and flow rate sources (displacement pumps). Liquid flow direction is indicated by sense of a branch.

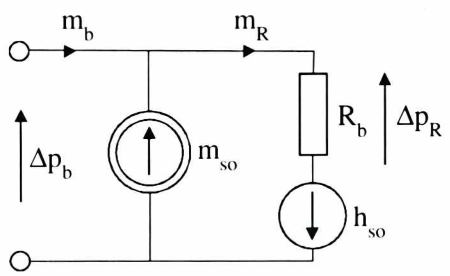


Fig.1. Model of a hydraulic network graph branch and its elements.
Notation : m_b – liquid mass flow rate through a branch
m_R – liquid mass flow rate through branch resistance
m_{so} – liquid mass flow rate of branch source; Δp_b – pressure drop in b-th branch
Δp_R – pressure drop due to b-th branch resistance
h_{so} – source pressure of b-th branch; R_b – resistance of b-th branch

Each branch of a graph is described by basic relationships which, for the example shown in Fig.1, are as follows :

$$\Delta p_b = \Delta p_R - h_{so} \tag{3}$$

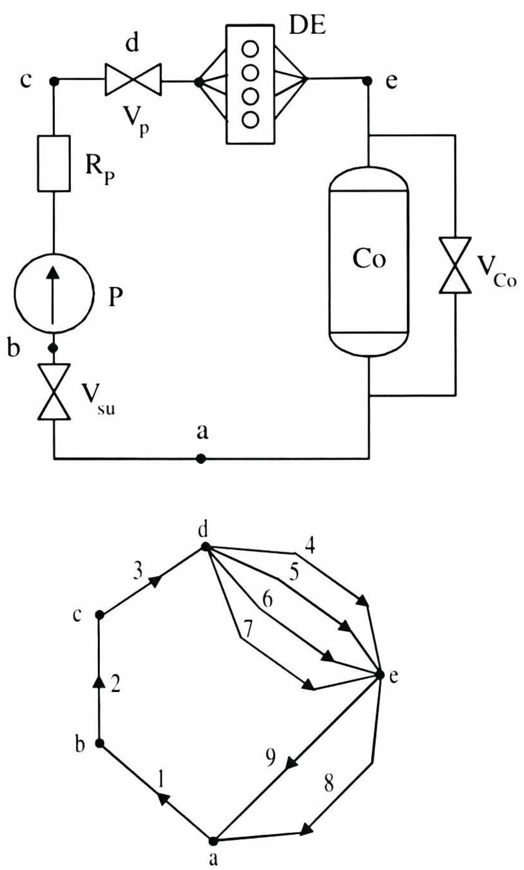
$$m_b = m_R - m_{so} \tag{4}$$

$$m_R = \sqrt{\Delta p_R}\,\frac{1}{\sqrt{R_b}} \tag{5}$$

An example main engine cooling network and its graph is presented in Fig.2.

a)

b)



Rys.2. Main engine cooling system :
***a)** example network* ***b)** network graph*
Notation : Co – cooler; P – pump; R_p – internal resistance of pump
DE – diesel engine and its cylinders; V_{co} – cooler by-pass valve; V_{su} – suction valve
V_p – pressure valve; a, b, c ... – successive nodes; 1, 2, 3 ... – branch numbers

The vectorial equations of flow rates through the flow network branches are as follows :

$$P = P_R - H \tag{6}$$

$$M = M_R - M_{so} \tag{7}$$

$$M_R = \begin{bmatrix} \sqrt{p_{1R}}\,\dfrac{1}{\sqrt{R_1}} \\ \cdots \\ \sqrt{p_{\ldots R}}\,\dfrac{1}{\sqrt{R_{\ldots}}} \\ \cdots \\ \sqrt{p_{bR}}\,\dfrac{1}{\sqrt{R_b}} \end{bmatrix} \stackrel{\text{def}}{=} f(P_R) \tag{8}$$

For their solving the equation of flow continuity is crucial :

$$\mathbf{I}\mathbf{M} = 0 \tag{9}$$

The incidence matrix **I** is a digital representation of *a* graph, i.e. numerical description of connections in a network. Successive rows of the matrix correspond to relevant nodes of the graph except of zero-node (e.g. *a* - node), and successive columns – to branch numbers of the graph. A value of successive element of the matrix **I** is :

$i_{bn} = 1$ if b-branch is coincident with n–node and directed from it
$i_{bn} = -1$ if b-branch is coincident with n–node and directed to it
$i_{bn} = 0$ if b-branch is not coincident with n–node.

For the graph of Fig.2b the incidence matrix related to *a* - node is as follows :

$$\mathbf{I} = \begin{bmatrix} -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & -1 & -1 & -1 & 1 & 1 \end{bmatrix}$$

After several subsitutions and transformations of the equations (6), (7), (8) and (9) and by taking into account the relationship of the pressure vector P and nodal pressure vector P_n :

$$P = \mathbf{I}^T P_n \tag{10}$$

the following nodal equation for the nonlinear network is obtained :

$$\mathbf{I}\, f\left(\mathbf{I}^T P_n + H\right) = \mathbf{I}M_{so} \tag{11}$$

The Newton-Raphson algorithm characterized by quadratic convergence, was selected to solve numerically the nonlinear model of the network and to decrease simulator computation time.

The general form of the recurrent formula is as follows :

$$x_{s+1} = x_s - \left[kJ(x_s)\right]^{-1} f(x_s) \tag{12}$$

where :

$J(x_s)$ - Jacobi matrix of the function $f(x_s)$
k - algorithm convergence coefficient.

For the flow network the function $f(x_s)$ is an implicit form of (11) whose argument is the nodal pressure vector P_n :

$$f(P_n) = \mathbf{I}\, f\left(\mathbf{I}^T P_n + H\right) - \mathbf{I} M_{so} = 0 \qquad (13)$$

The Jacobi matrix of $f(P_n)$ is of the form :

$$J(P_n) = \mathbf{I} \frac{\partial f(P)}{\partial P}\bigg|_{P=\mathbf{I}^T P_n + H} \mathbf{I}^T = \mathbf{I} \frac{\partial f\left(\mathbf{I}^T P_n + H\right)}{\partial P} \mathbf{I}^T \qquad (14)$$

The substitution of (13) and (14) to (12) leads to the following equation :

$$P_n^{(s+1)} = P_n^{(s)} - \left[\mathbf{I} \mathbf{A}_b^{(s)} \mathbf{I}^T\right]^{-1} \left[\mathbf{I} M^{(s)} - \mathbf{I} M_{so}\right] \qquad (15)$$

where :

$$\mathbf{A}_b^{(s)} = \frac{\partial f\left(\mathbf{I}^T P_n^{(s)} + H\right)}{\partial P} = \frac{\partial f(P)}{\partial P}\bigg|_{P=H^{(s)}} \qquad (16)$$

$$M^{(s)} = f\left(\mathbf{I}^T P_n^{(s)} + H\right) = f\left(H^{(s)}\right) \qquad (17)$$

$$H^{(s)} = \mathbf{I}^T P_n^{(s)} + H \qquad (18)$$

The equation (15), in order to avoid inverting the matrix by computer, was transformed to the following form :

$$\left[\mathbf{I} \mathbf{A}_b^{(s)} \mathbf{I}^T\right] P_n^{(s+1)} = \mathbf{I}\left[M_{so} - M^{(s)} + \mathbf{A}_b^{(s)} \mathbf{I}^T P_n^{(s)}\right] \qquad (19)$$

In (19) appear several multiplications of the matrices and the incidence matrix **I**, which contains only zero-and one-elements of different signs. In numerical calculations the multiplication operations are substituted by transposition and summation operations of matrix elements. The last step of each iteration is solving the set of linear matrix equations until a demanded result accuracy is obtained. An assumed accuracy value decides on real computation time. For the multi-node networks the computation time appears longer because matrix equation order increases along with increasing number of nodes of the network.

Sometimes it is necessary to resign from using a nonlinear model and to apply the linear one, a result of which can be obtained after single step of matrix equation solving. However an exact result can be achieved only after few computation steps. Another way is to use a calculation algorithm applicable to sparse matrices.

The Newton-Raphson algorithm is not always convergent. How--ever, there are mathematical methods of determination of the algorithm convergence coefficient *k* which determines its convergence or only accelerates it, for a given nonlinear function. Its appropriate value for the parabolic equation (2) is k = 2 (see eq.12) which provides the fastest convergence of the algorithm in question.

MODEL OF THE TEMPERATURE CONTROL ELEMENT USED AS FINAL CONTROL ELEMENT

Temperature within the main engine auxiliary systems is controlled by splitting the working medium flow into two streams : the first one cooled in a cooler and the second one by-passing the cooler. A three-way valve fitted with movable, cylinder-controlled spindle is used as the final control element, whose alternative design schemes are shown in Fig.3.

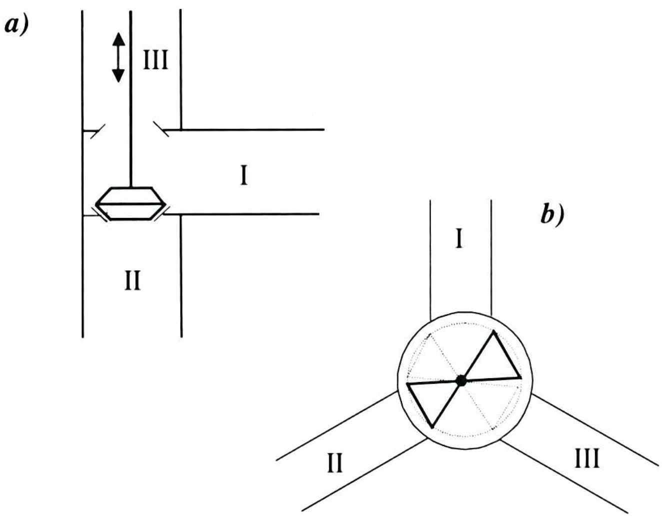


Fig.3. *Three-way valve schemes :*
a) *fitted with reciprocating spindle* ***b)*** *fitted with rotating spindle.*
Notation : *I – inlet of liquid, II – inlet of liquid to by-pass channel III – outlet of liquid to cooler*

The valves are so designed that the total area of active cross-sections is constant and equal to the sum of areas of the active channels I – II and I – III, irrespective of a control unit position. If the resistance of the flow through the channels, R, is assumed inversely proportional to the square of the cross-section area of the active channel then the resistance of I – II channel is expressed as follows :

$$R_{I-II} = \frac{R}{C^2} \qquad (20)$$

and of I – III channel :

$$R_{I-III} = \frac{R}{(1-C)^2} \qquad (21)$$

where :
C - channel opening rate coefficient, $0 < C < 1$.

The coefficient C value is dependent on the control quantity established by the control unit.

AN EXAMPLE OF COMPUTER SIMULATION OF SHIP MAIN ENGINE AUXILIARY SYSTEMS

The example of computer simulation was elaborated for the auxiliary systems of 6ZA40S medium-speed main diesel engine installed onboard B672 fishing trawler STROJNIK [11]. Three integrated cooling installations were simulated (but limited to their parts directly connected with the main engine) : of fresh-water (FWI), of lubricating oil (LOI) and of sea-water (SWI). Block diagrams of all systems in question were given in [12]. The main engine was assumed operating at 85% rated power and 466 rpm constant speed, all the installations – fault-free, and the temperature control system – under operation. The preset jump of overboard sea-water temperature was assumed first from 10° C up to 24° C and then from 24° C down to 5° C, as shown in Fig.10. Such situation can happen during a fast change of sea region. Results of the simulation in question are graphically presented below.

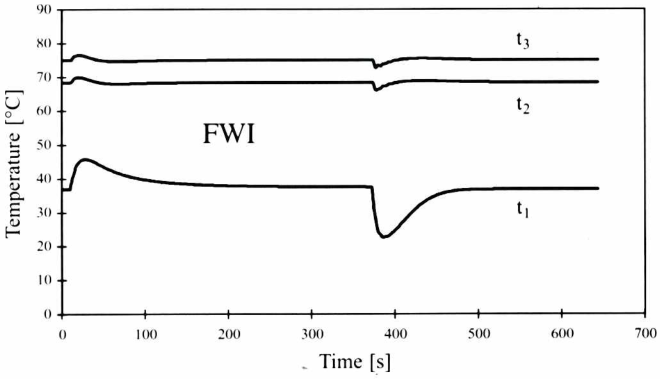


Fig.4. *Course of temperature changes versus time within the fresh-water cooling system (FWI) for the overboard sea-water temperature disturbance shown in Fig.10.*
Notation : *t_1 – fresh-water temperature behind plate cooler, t_2 – fresh-water temperature before main engine, t_3 – fresh-water temperature controled behind main engine.*

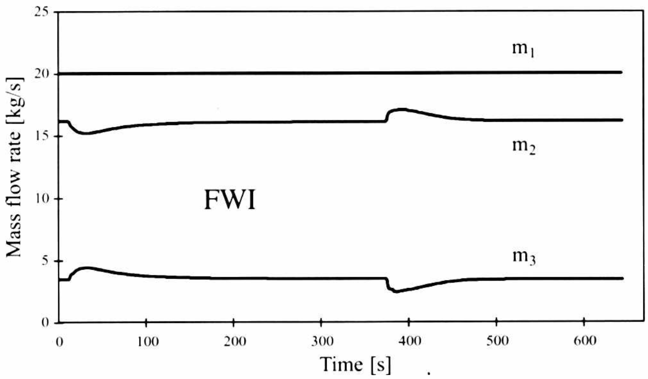


Fig.5. *Course of mass flow rate versus time within the fresh-water cooling system (FWI) for the overboard sea-water temperature disturbance shown in Fig.10.*
Notation : *m_1 – flow rate through fresh-water circulation pump and main engine, m_2 – fresh-water flow rate through cooler by-pass, m_3 – fresh-water flow rate through plate cooler.*

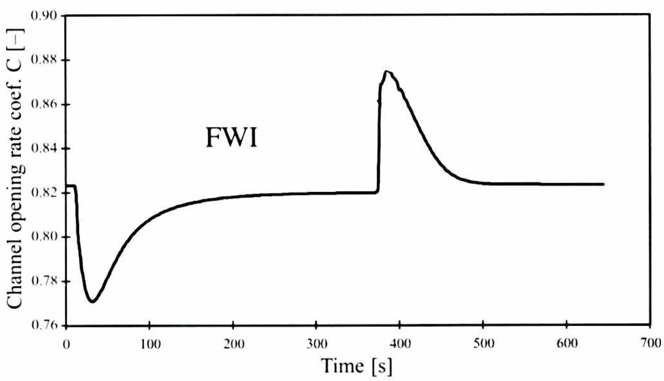


Fig.6. *Course of presetting unit position versus time of the fresh-water cooling system (FWI) for the overboard sea-water temperature disturbance shown in Fig.10.*

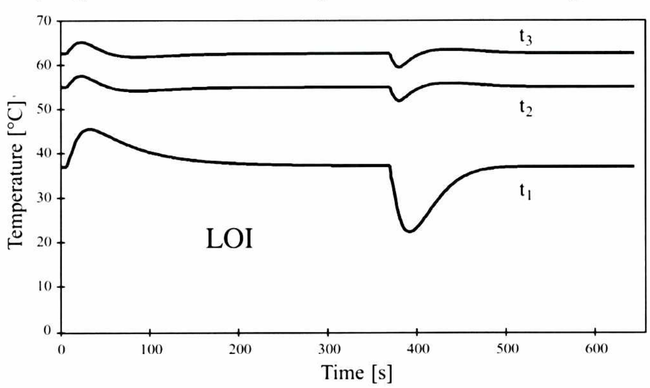


Fig.7. *Course of temperature changes versus time within the lubricating oil system (LOI) for the overboard sea-water temperature disturbance shown in Fig.10.*
Notation : *t_1 – oil temperature behind plate cooler, t_2 – oil temperature controlled before main engine, t_3 – oil temperature behind main engine - input temperature to plate cooler.*

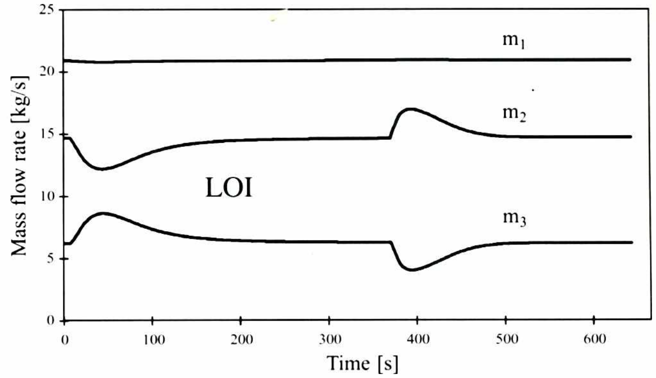


Fig.8. *Course of mass flow rate versus time within the lubricating oil system (LOI) for the overboard sea-water temperature disturbance shown in Fig.10.*
Notation : *m_1 – lubricating oil flow rate through main engine, m_2 – lubricating oil flow rate through cooler by-pass, m_3 – lubricating oil flow rate through plate cooler.*

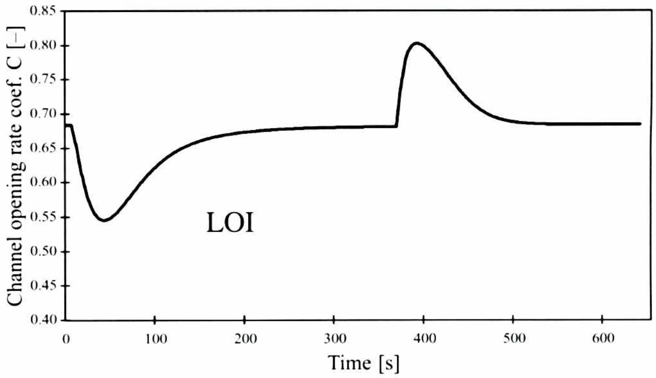


Fig.9. *Course of presetting unit position versus time of the lubricating oil system (LOI) for the overboard sea-water temperature disturbance shown in Fig.10.*

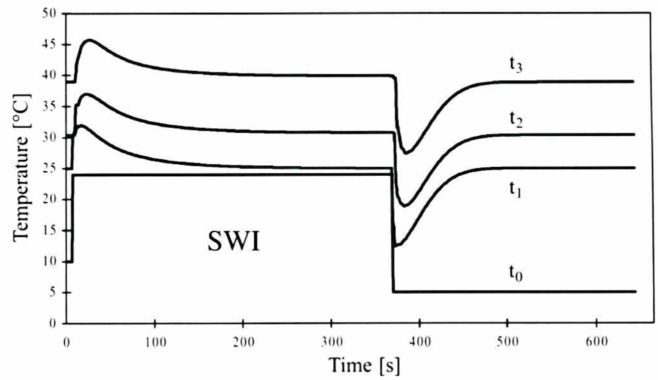


Fig.10. *Course of temperature changes versus time within the sea-water cooling system (SWI) for the overboard sea-water temperature disturbance – signal t_0.*
Notation : *t_0 – overboard sea-water temperature, t_1 – sea-water temperature controlled before oil cooler, t_2 – sea-water temperature before fresh-water cooler, t_3 – sea-water temperature at outlet behind coolers.*

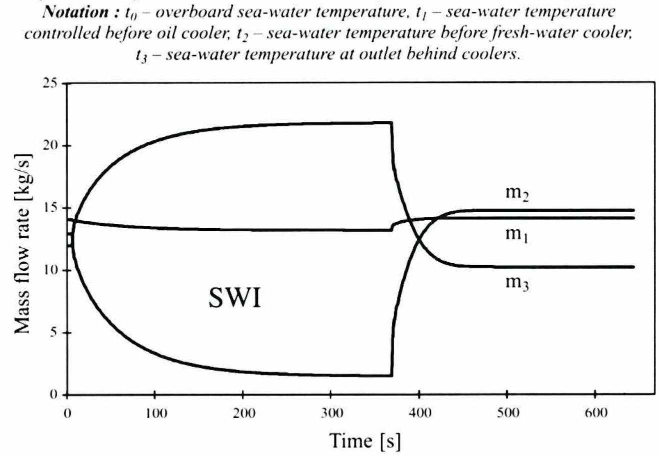


Fig.11. *Course of mass flow rate versus time within the sea-water cooling system (SWI) for the overboard sea-water temperature disturbance shown in Fig.10.*
Notation : *m_1 – sea-water flow rate through lubricating oil cooler and fresh-water cooler, m_2 – sea-water flow rate through recirculation branch, m_3 – rate of sea-water flow drained outboard.*

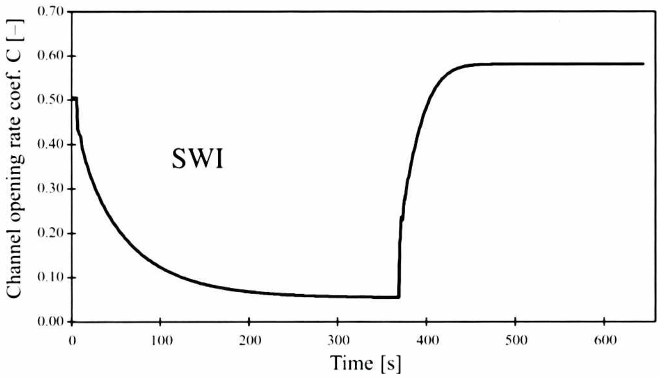


Fig.12. *Course of presetting unit position versus time of the sea-water cooling system (SWI) for the overboard sea-water temperature disturbance shown in Fig.10.*

EVALUATION OF THE RESULTS

From the above presented diagrams it can be stated that :

- In the FWI and LOI systems the temperature control follows the cooled liquid flow rate change.
- The presetting unit position, flow rate through cooler and controlled temperature is mutually connected by means of the control system.
- Sum of the flow rate through the by-pass channel and cooler is always equal to the flow rate through the main engine.
- In the SWI system the flow rate through coolers connected in series is constant and independent of control.

It means that the presented flow network model operates correctly.

FINAL REMARKS

- Matrix analysis of the flow network makes it possible to effectively determine influence of changes of any its element on the behaviour of entire network.
- By appropriate changing the parameters of the network elements, (such as the hydraulic resistance R, elevation head H or flow rate M) it is possible to shape the description of technical state of the installation and failures of its elements.
- Digital simulation of the auxiliary systems of ship power plant is feasible and provides correct results. One can this way elaborate simulators better adjusted to user's needs, and improve them on the basis of accumulated experience.

Appraised by Alfred Brandowski, Prof.,D.Sc.

NOMENCLATURE

A – admittance matrix (converse resistance of linear network branch)
h – pump elevation head
H – vector of pump elevation heads
I – incidence matrix
m – liquid mass flow rate
M – vector of liquid mass flow rates
m_{so} – source mass flow rate
M_{so} – vector of source mass flow rates
p – pressure
P – pressure vector
P_n – nodal pressure vector
R – network element resistance
t – temperature

Indices

b – branch of a graph
n – node of a graph
R – related to resistance of a given branch
s – iteration step number
so – related to source

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Conference

E A jubilee seminar

On 29 November 2001 the Regional Group of the Utility Foundations Section, Machine Building Committee of Polish Academy of Sciences, held its next scientific seminar. This time it was carried out at Gdynia Maritime Academy, and hosted by its Mechanical Faculty as it was devoted to celebration of 70[th] birthday of Prof. Jan K. Włodarski. It was his initiative to establish the above mentioned Regional Group ten years ago, and this way to form a forum for exchanging scientific experience and presenting scientific axchievements of young scientific workers from Northern Poland. The idea took source from the most important area of his interest – theory of failures and diagnostics of ship engines.

He achieved vast experience in that area during 20 years of his professional activity as an engineer and sailor. Next, on this firm basis he started his fruitful scientific and educational activity. The opening speech given by Prof. R. Cwilewicz, the Dean of the Mechanical Faculty, devoted to that issue, was titled:

Prof. Jan Kazimierz Włodarski – a sailor, scientist and tutor

During the scientific part of the seminar the following papers were presented :

- *Forms of fretting in crankshaft bearings of ship medium-speed diesel engines* – by J.K. Włodarski
- *Investigations on possible adjustment of existing ship diesel engines to complying with the standards for emission of exhaust gas toxic components* – by K. Witkowski and J. Krzyżanowski
- *Assessment of ensuing heat within engine cylinders by means of autocorrelation of instantaneous values of engine torque* – by J. Rosłanowski
- *An attempt at applying of Internet to remote diagnosing the ship engine* – by S. Kluj and R. Chlebicki
- *A method of indirect determination of angular position of ship engine crankshaft and its application to electronic indicators* – by W. Gałecki and L. Tomczak

All the authors are scientific workers of Gdynia Maritime Academy.