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Zastosowanie systemów monitoringu w systemach wspomagania decyzji

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Raport

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Pod redakcją Jana Studzińskiego i Lucyny Bogdan

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Raport zawiera 3 nieopublikowane artykuly omawiające zastosowania systemów monitoringu w systemach wspomagania decyzji. Pierwszy z artykułów będzie przedstawiony na konferencji pn. Quality, Reliability, Maintenance, która odbędzie w dniach 1 – 2 kwietnia 2004 w Oxfordzie. Dwa pozostałe artykuly ukażą się w publikacji książkowej IBS PAN w serii Badania Systemowe w 2004 r.

Spis treści

Artykuły:

Application of monitoring technologies in environmental engineering

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ABSTRACT

This paper provides an insight into the significance of monitoring as it pertains to environmental engineering. Three examples of using monitoring techniques for modelling and maintaining environmental processes are presented in this work, Firstly, computer aided decision making to maintain a wastewater treatment plant. Secondly, computer aided management of a communal water network, and thirdly modelling the forecasting of air temperature. The paper illustrates how the essential parameters of the above three disparate but related examples can be controlled through techniques illustrated in this paper.

INTRODUCTION

The rapid acceleration of the facilitation of mathematical modelling is contemporary with the advent of large storage computers as can be endorsed over the last thirty years. The models and algorithms developed here have become key tools for computer aided decisions making that are used to forecast and/or maintain various environmental processes. As a result they contribute considerably to the better protection of the environment and to satisfy better the social needs of the mankind. The base of the algorithms of modelling and optimisation of the practical use are the measurements that have to be taken fast, flawless and mostly in the real-time of the processes investigated. This can be made using computerised monitoring systems. This way they are an essential component of all computer aided decisions systems. In the following we will show the use of the monitoring data by the control of the wastewater treatment, by maintaining a water network and by forecasting the air temperature.

MONITORING IN A WASTEWATER TREATMENT PLANT

The modelled wastewater treatment plant is shown in Fig. 1. The process of the wastewater treatment is as follows: The raw wastewater enters the primary clarifiers where unsolvable solids settle down. The rest of the wastewater flows to the activated sludge basins where the organic material is decomposed biologically under aerobic conditions. The mixed liquor from the aeration tanks consisting of the activated sludge and the wastewater passes to the secondary clarifiers. Within the purification zone the sludge is separated from the wastewater by gravitational forces and the sludge particles settle down in the sedimentation zone. Part of the sludge is recirculated to the inlet of the aeration basins while the excess sludge is removed from the process as a waste. To maintain this process a computer-aided system supporting the decisions making by the process operator has been developed. This system works on the base of various mathematical models which are responsible for the realisation of the following tasks (see Fig. 2): forecasting the wastewater inflow and its waste composition, generation of the process controls which are the flow rate of the sludge recirculated and the level of the oxygen dissolved in the aeration basins, verification of the controls generated by means of the computer simulation. This latter task occurs with the help of a very detailed phenomenological model of the whole treatment process (1).

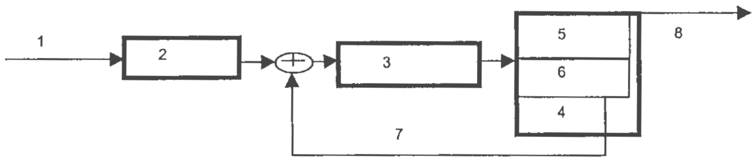

Fig. 1 Diagram of the investigated wastewater plant: 1 – wastewater inflow; 2 – primary clarifiers; 3 – aeration basins; 4 – secondary clarifiers; 5 – purification zone; 6 – sedimentation zone; 7 - extern recirculation; 8 – outlet of the purified wastewater

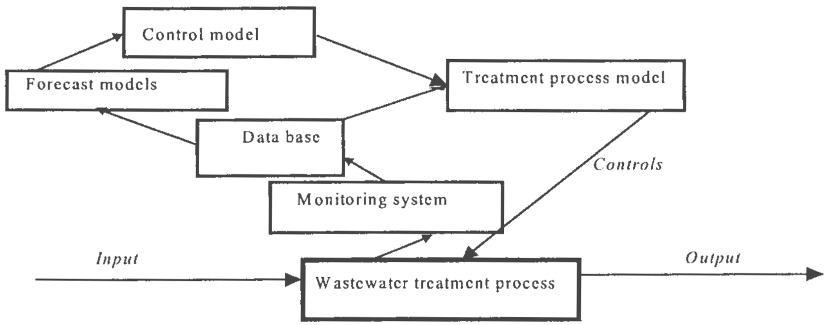

Fig. 2 Diagram of the computer system to control the wastewater plant

The development of these models and their adaptive validation is possible only with an efficient monitoring system. Such an automatic system has been installed in the wastewater plant (see Fig. 2). With this system the flows and the conductivity as well as the values of pH and REDOX of the wastewater are measured on-line. These data enable to develop and validate the forecast models of the computer system. To develop the other models some additional lab measurements had to be done and the data needed was gathered as a result of some measure experiments run on the wastewater plant.

MONITORING IN A DRINKING WATER NETWORK

An automatic monitoring system is also a key component of an integrated computer system developed for a communal water network to support the decisions making of the water net operator (see Fig. 3) (2). The system consist of 3 modules co-operating each other with the help of the Branch Data Base (BDB). These modules are: numerical map of the water net generated by a GIS named Geomedia, programmes for mathematical modelling, optimisation and control of the water net, and the monitoring system. BDB holds technical data about the structure and all elements of the water net that is used to carry out the specific tasks of the system modules such as visualisation, simulation and optimisation of the water net. With the help of the monitoring system the results of the water net hydraulic calculation are verified, the calibration of the water net model is periodically made and also the characteristics of daily water demands for typical water net nodes are set up and verified. These characteristics are used then to forecast the temporal water demand of the whole water net. The computer system was introduced as a pilot project only on a part of the investigated water net and it consists of 9 measurement points where water pressures and flows in the water net nodes and lines are monitored. The data transmission from the measurement points to the work station of the computer system occurs by means of the GSM telephony. It is an innovative and reliable solution in relation to the monitoring systems applied for communal water networks.

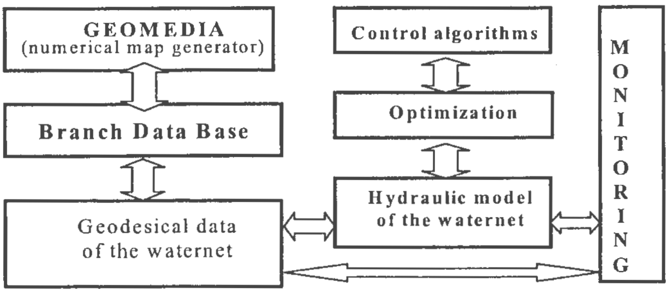

Fig. 3 Diagram of the computer system for maintaining the water network

ATMOSPHERICAL MONITORING

Automatic monitoring systems are used also successfully for measuring various atmospheric parameters such as air and soil temperatures, air humidity, wind direction and speed, rain and snow falls etc. On the base of such the data mathematical models of atmospheric events and processes are then developed that can be applied for weather forecasting and also as elements of experts systems which help to take precautions against the natural disasters. It happens sometimes however that the automatic monitoring systems work defective and they produce then the data series with sections of lacking or wrong measurements. To improve these defective data series we can use also the mathematical modelling. Such the situation occurred by monitoring the air temperature with an automation station in which the power supply has broken down for a couple of hours. By means of the models describing with neuronal networks the lacking measurements could be reliable interpolated. Some modelling experiments have been done to prove the usefulness of neuronal models by interpolating broken measurement series. In the temperature measurements produced by an automatic monitoring system some measurement sets have been eliminated and the eliminated values were then reconstructed with the help of neuronal nets (3). The number of eliminated values ranged from 1 to 12 with the measurement step of 1 hour and such the procedure has simulated some unexpected breakdowns of the monitoring system and the interpolation of the measurements lost. The results of the interpolation attained are quite satisfactory what proves the usefulness of neuronal modelling for repairing the defect data from the atmospheric monitoring (see Fig. 4 with some exemplary results of the reconstruction of 12 measurements eliminated).

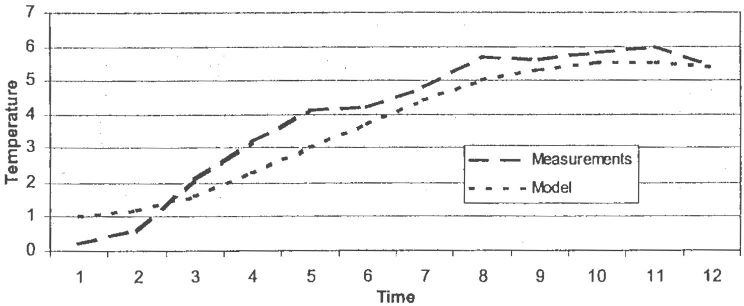

Fig. 4 Temperature values of the measurements and of the mathematical model

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Problems of Computer Aided Decision Support System for a Municipal Water Network

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Abstract: *In the paper some results of the development of a computer aided decision support system for the operator of a municipal water network are presented. The system consists of three cooperating modules: the numerical map of the water network, the monitoring system and the computer program for hydraulic calculations and for optimisation. The numerical map is based on a GIS system adapted for the needs of the water network. The modules of computer system cooperate each other using the Branch Data Base, which comprises the information about the water network structure and about its elements necessary to carry out the tasks of the modules such as visualisation, data processing and hydraulic calculations.*

1. Introduction

The system under consideration was created for the municipal water net in the polish city Rzeszow, which owns 160 000 inhabitants. The length of the municipal net is 544 km (the water mains 49 km, the distribution network 274 km and the user attachments 221 km). In the water network there are five surge tanks with capacities 1 x 3.600 m^3 and 4 x 3.000 m^3 and there are 21 pumping stations. The network is supplied from two water intakes form the river with their efficiencies of 37.000 m^3/day and 47.500 m^3/day. There are 12.201 group consumers in the network and 80% of the net works in the ring system. The main receivers of the water are the households. The amount of damages is about 500 damages/year and the damages are caused mainly by the age and age differences of the pipe material.

2. The creation of the numerical map

To work out the numerical map of the municipal water network a specialised program for creating numerical maps (GIS) was gained. The map of the water network was done on the base of vectorized geodetic maps of the town. System GEOMEDIA by *Intergraph* was bough and then adapted for the needs of the water work. Such the way of work enables to be independent from the external computer firms in the future. But the adaptation of a standard GIS causes the necessity of solving the following three tasks:

1. To define the structure of the object data basis applied by GEOMEDIA system for visualisation of the water network and for description of its parameters.
2. To define and implement the special user functions to enable the numerical map to work as a tool to manage the water network.
3. To develop a new organizing structure in the plant to enable the fast working out the numerical map and the permanent correction of it.

The numerical map consists of a scheme of the water network and of describing database attached. To enable the map to represent the real water network all characteristic network elements must be distinguished on the scheme and respectively all parameters of these elements, called attributes, must be set in the database. During the work out of the numerical map the database structure must be defined. It means that the objects of the database and their attributes must be designated. After a detailed analysis of needs of the municipal water network in Rzeszow has been done the branch database for the water net was worked out.

The special functions enable to apply the numerical map to solve the tasks realized during the exploitation of the water network. The following special functions were defined:

- Updating of the numerical map
- Geometric and describing data export/import from/to numerical map
- Identification of conflicts between different branch nets
- Disconnecting of a part of water network in case of the damage
- Printing of exploitation and damage reports.

The analysis of exploitation conditions in the plant indicates that the optimal solution for the firm using the numerical map is to create a separate numerical map laboratory. In such the place a group of people could be able to make the computer program works correctly, the current updating of the numerical map works properly as well as the task of exploitation of the water network going on rightly. Such an organizing structure was introduced in Rzeszow.

3. The creation of the Branch Data Base for the waterworks

The visualisation of the water network on the computer screen is done by application of the water network computer map – GIS. The format of the Branch Data Base and the tools programs realizing the special functions are created on the base of the standard application GEOMEDIA. The functions are connected with the water-supply needs, with the way of receiving the data for creating the numerical map and with the demands of external computer programs cooperating with the numerical map.

The creation of the Branch Data Base Format consists on defining the water network objects and their attributes. The main objects of the water works are: water pipes, pumping stations, tanks, user attachments, shutters, reducers and check-valves and their attributes are lengths and diameters of pipes, characteristics of pumps, geometric dimensions of tanks, the operating conditions and characteristics of shutters, reducers and check-valves. The Branch Data Base (BDB) is the base of working of all computers programs of the computer system.

The data for numerical map are delivered from the geodesy department as DGN files done on the base of the municipal geodetic maps of Rzeszow, which are made in the scale 1:500. That is why the tool program enabling reading DGN files, copying the graphic and description data as well as computer visualisation of the Branch Data Base had to be written for the GEOMEDIA program.. The additional program is used for data updating, i.e. for signalling and introducing to the Branch Data Base the changes done by geodesy department in the DGN files, which were previously introduced to the BDB.

The described Branch Data Base is an application enabling the visualisation of the water network in a form of numerical map. But the Branch Data Base does not enable the cooperation of the numerical map with the external applications, namely with monitoring system and hydraulic model, because the BDB does not include the specific objects used by these applications. Such objects are the nodes of the water network, which do not occur on the geodetic maps. That is why the next step during the creation of the Branch Data Base Format was defining the nodes and nodes attributes. The main nodes in the water network are sources, receivers, montage nodes and measurement nodes. Their main attributes are pressure and water distributions. The numerical map of the water network created directly on the base of the vectorized geodesic maps does not include the nodes and it is topologically incorrect, i.e. it is not continuous and not coherent. That is why the hydraulic calculations cannot be realized on the base of it. To enable it two new programs for topologisation of the water net and for generating the hydraulic nodes (nodes generator) were added to GEOMEDIA besides the mentioned previously programs for reading DGN files and for data updating.

This way the development and implementation of all additional programs mentioned made from GEOMEDIA the right waterworks application for generating the water net numerical map. It should be noticed that as a result three layers of numerical map are generated:

- *the geodesic main layer* created from DGN files delivered directly from municipal geodesy department
- *the topological geodesic layer* created from *the geodesic main layer* after checking and improving the continuity and cohesion of the water network
- *the hydraulic layer* created from *the topological geodesic layer* after introducing the nodes, creating in such a way a new net graph which may be the base of the hydraulic calculations.

4. Problems of mathematical modelling and simulation of the water network

The modelling of the water network consists of the following steps: the creation of the hydraulic model respectively to the investigated water network, obtaining the data describing the investigated water network and performing the simulation calculations and their verification on the base of the measurements.

The water network system is described using linear and non-linear algebraic equations. The number of these equations increases according to network dimensions and for typical town networks may amount from several hundreds to several thousands. The numerical solution of such great non-linear equations sets is troublesome. The water network consists of the nodes and of the connecting pipes. The nodes may be active and passive. In the network structure usually several circuits occur called eyelets. The mathematical network model consists of the equations describing the water flows in pipes and the pressures in the nodes. To calculate the network means to determine these flows and pressures whereby in the network constituting the eyelets the number of pipes(r) is greater than the number of nodes (w), i.e. $r=w+o+1$, where o is the number of eyelets. That results that the number of unknown values in the network models is $n=w+r=2w+o-1w$.

The model equations arise from the I and II Kirchoff's laws known from electrotechnics and from the Bernoulli's equation known from mechanics of fluids. From the I Kirchoff's law used for the network nodes we can get the set of w linear equations for r flows. From the II Kirchoff's law used to the eyelets we can get the non-linear equations for flows and from Bernoulli's law we can get the set of $(w-1)$ equations which are linear with regard to pressures and non-linear with regard to flows. By solving the equations we will find the flows and water pressures in the network. The calculation of the model is more difficult than its formulation because of many equations and because of their non-linearity. Generally the four methods of calculating the water networks are possible:

- Direct solution of the set of n both linear and non-linear equations regarded as a non-linear set for simultaneous determining of all flows and pressures

- Separate calculation of flows and of pressures; the flows are calculated from the set of $(w+o)$ linear and non-linear equations obtained from Kirchoff's law and the pressures are calculated from the set of $(w-1)$ linear equations obtained from Bernoulli's equation
- Separate calculation of flows and pressures; the flows are calculated iterative by turns from two equation sets – linear (from the I Kirchhhoff's law) and non-linear (from the II Kirchohoff's law) – and the pressures are calculated as previously from the linear Bernoulli's equations
- Separate calculation of flows and pressures from the three as above equations sets; the flows are calculated from two sets of equations, linear and non-linear, solved independently.

In the first, second and third methods the Newton's algorithm may be used to solve the non-linear equations and the Choleskys's algorithm for linear equations. In the third method the relaxation algorithm is used as the iterative one for alternative solution of the flow equations. The above methods are known, checked and infallible but using the Newton's method for solving the non-linear equations and the relaxation method for flows calculations takes time. This is the meaningful disadvantage especially in identification and optimisation problems because the calculations are repeated many times. The forth method concerns in using the specialised approach (Cross', Lobaczewski's and Andrjaszew's), which was worked out only for water network calculations. These methods consist in general in dividing the starting problem in three smaller and independent problems and in solving the non-linear equations set for flows using the specialised fast iterative algorithm. In our case the Cross' algorithm was used.
The own modelling program was implemented. This program uses the Cross method for solving the non-linear algebraic equations built for the water network rings. It takes into account such the objects as water works pipes, water works pipes with section distribution, water works pipes with shutters, reducers or valves, supplying nodes in the form of pumping stations or tanks, montage nodes, measurements nodes, receiving nodes in the form of tanks or being user attachments on the geodesic map, and the nodes increasing the pressure in the form of water supplies. The program is written in DELPHI. It has an extended interface and its own graphical editor what enables to perform the calculations and creating the water network graph on the computer screen independently on the numerical map.

The program data concerning the water network structure and its parameters are delivered from the numerical map using some buffer files. The buffer files concerning pipes and hydraulic nodes are generated basing on the numerical map hydraulic layer. The modelling program worked out has the possibility of using the nodes and section water distributions. This program can also execute the statistical calculations on the base of given average day or moment water distributions and can execute dynamical calculations basing on the given day hour distribution sequences. The verification of the hydraulic calculation results is performed as a comparison between the program results and the monitoring system measurements.

5. The correctness of the model

The simulation calculations were performed for the chosen part of the town water network using the mentioned modelling program. The monitoring system was installed for this part of the water network. For this part of the water net the numerical map has been created and the data could be delivered using the Branch Base Data. The chosen part of the net comprised one quarter of the town and it was about 10% of the whole municipal water network. The results obtained from the model were compared with the measurements got from the monitoring system. The comparison analysis showed the correctness of the proposed model.

6. Optimisation algorithm of water network and control algorithm in break-down states

An optimisation algorithm, which is an integral part of the modelling program, was created. It is a specialized algorithm using the specificity of the water network. The optimisation task concerns improving the pressures in the water network nodes in the case of exceeding the given pressure limit values. In the classical optimisation method the object function is based on the difference between the given pressure value and the calculated pressure value and this function is minimised depending on the water network pipes diameter values. The object function is the mean square criterion and the change of parameters takes place in the whole net what increases the calculation time in the case of large nets.

In our algorithm firstly the paths with the greatest flow resistance between supply sources and the nodes with not appropriate pressure are marked in the graph. Then the distance between the given pressure and calculated pressure in these nodes is minimised depending on the change of water network pipes diameter values only on marked paths. Such a procedure shortens the calculation time because it deals in calculations with only the marked parts of the net. The break-down algorithm concerning situations when the break-down has place in some points of the net was performed. In such a case the proper part of the water network should be cut to avoid a loss of water. The algorithm realizes this task by indicating the closest gate valves which should be closed to cut the water flow. The algorithm works on the numerical map hydraulic layer level. The new water network graph with the cut part of the break-down is received as the result of the algorithm. The hydraulic calculations for obtaining flows and pressures may be now performed on the base of this new graph.

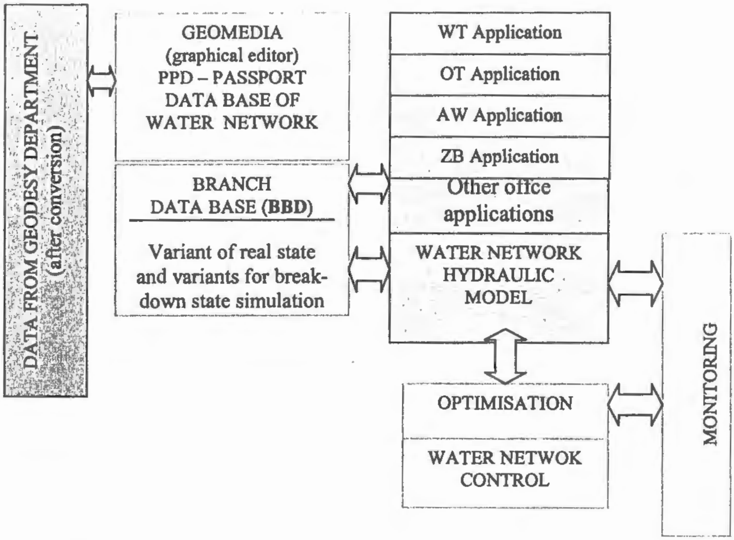
7. The computer system for the operator decision support

The computer system consists of three modules performing the functions of numerical map, monitoring system and hydraulic model with optimisation algorithm. To start the monitoring system the measurements points were given as the results of hydraulic calculations in the investigated part of the water net work. The investigated area consists of 2 pressure zones separated by water supply system. There were indicated 9 measurement points, i.e. 2 water network supply points, 2 water output points (from the investigated area to not investigated net areas), 2 measurement points in the first pressure zone in the place of minimal and maximal pressure, 2 measurement points in the second pressure zone in the place of minimal and maximal pressure, and 1 measurement point in the water supply system separating two pressure zones.

The water flows and the pressure are measured in the points of water inflow and outflow as well as in the water supply system. Only the pressures are measured in the rest measuring points. PROCON system based on the original German system using the controllers by SIEMENS was bought to perform the monitoring system.

The measurement transmission system from measurement points to the computer with the PROCON program installed is based on the GSM system. The system works in the computer net consisting of tree computers.

The computer system scheme [4]



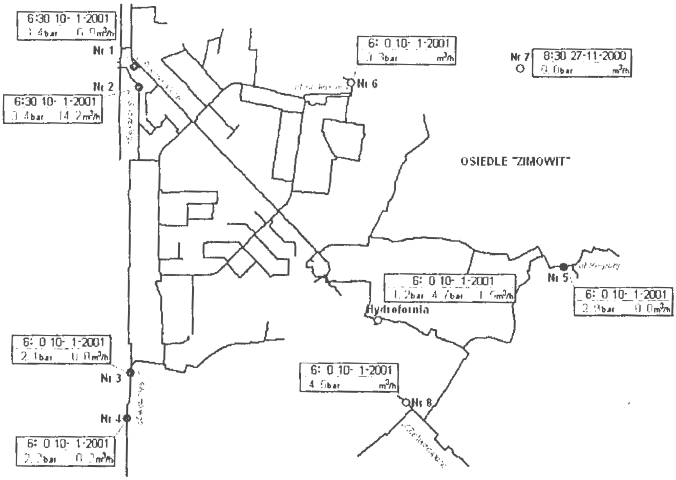
During testing the tool programs connected with numerical map and enabling the cooperation among the numerical map, the hydraulic model and the monitoring system, it appeared that the additional program modules performing managing functions and some other functions, would be useful. There are the following additional preferable modules (applications):

- WT Application –program for technological conditions maintenance
- OT Application – program for technical receivers, which cooperates with WT Application
- AW Application – program for break-down maintenance and water network inspection maintenance
- ZB Application – program for water sewage disposal maintenance
- Other Application – office software.

The presented computer system consists of seven computers in which three computers cooperate with numerical map, two computers are used for monitoring system maintenance and the last two computers are used for the maintenance of hydraulic model and optimisation program. The data transmission is done using the GSM system. It is an innovation solution in the water networks monitoring systems. It secures the transmission reliability but unfortunately it is not cheap. It is why the economical scheme of measurement data transmission was worked-out. In this scheme if the measured flows and pressures do not exceed some given limit values the transmission takes place only in some chosen time moments. There are now the following hours of transmission: 6:00, 14:00 and 22:00.

In the case when the limit values are exceed or for the operator demand the alarm mode transmission may start any moment. In such a way the transmission costs are minimal if the water network works in regular mode.

The measurement points scheme in monitoring system [4]



8. Remarks

The presented system is an original system developed for one municipal water network and it uses the possibilities of integrated systems for computer aided decision making. Numerical maps, hydraulic models and monitoring systems work autonomously in some Polish water networks usually as independent programs and the possibilities of cooperation of this programs in one system are unfortunately not used.

9. References

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Computer modelling, simulation and identification of molten glass furnaces

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A new method for computer aided modelling, simulation and identification of flow dynamics in molten glass furnaces is presented and numerically analysed. The process of the construction of glass tank furnace models occurs in several steps on which the sub-models with differentiated mathematical descriptions (with distributed or lumped differential equations) and dynamical features (with inertial and oscillatory characteristics and with slow and fast changeable dynamics) are setting up. The method proposed makes possible to prepare the models of glass tank furnaces of high degree of accuracy, described with the equations of rather high orders. The models are suited well to estimate technological parameters of glass tank furnaces and to control the glass melting processes.

1. Introduction

The glass production is a very complex technological process. For this reason there is very difficult to set up its mathematical models that could be useful for practical applications, such as computer simulation, control or estimation of technological parameters. The modelling of glass tank furnaces occurs usually under separated application of Distributed or Lumped Parameter Equations (DPE or LPE models) and the result is that they are very complicated (DPE models) or very simplified (LPE models). That is why their practical usefulness is very limited. This situation is caused by lacking of adequate identification methods. Thus in the following a numerical algorithm is presented for setting up molten glass models under consideration of both arts of mathematical description. This way their drawbacks could be eliminated and their advantages retained. The algorithm presented consists of two general stages. On the first stage a DPE model is formulated with the quasi-linear Navier-Stokes and energy equations and with an equation added that describes the glass mass composition change in the molten glass. On the second stage a complex LPE model is prepared using the DPE model previously identified. All computations are done using real data from an industrial glass tank furnace. The fitting of the DPE model to the data occurs by using static optimisation methods. To estimate the structure and the parameters of the LPE model an indirect identification method is used, developed especially for setting up continuous dynamic models of higher orders.

2. DPE model formulation

To model the glass mass flow in a tank furnace by the partial differential equations the following description is used [2]:

$$\begin{cases} \mu(T)(D_1^2 v_1 + D_2^2 v_1) = D_1 p \\ \mu(T)(D_1^2 v_2 + D_2^2 v_2) = D_2 p - \rho g \beta (T - T_o) \end{cases} \tag{1}$$

$$\lambda(T)(D_1^2 T) + \lambda(T)(D_2^2 T) = \rho c_v (v_1 D_1 T + v_2 D_2 T) \tag{2}$$

$$D_1 v_1 + D_2 v_2 = 0 \tag{3}$$

$$\frac{\partial z}{dt} + e_1 v_1 \frac{\partial z}{\partial x_1} + e_2 v_2 \frac{\partial z}{\partial x_2} = D(T)(e_3 \frac{\partial^2 z}{\partial x_1^2} + e_4 \frac{\partial^2 z}{\partial x_2^2}) \tag{4}$$

where the parameters mean: v_1, v_2 – longitudinal and vertical glass mass velocities in x_1 and x_2 directions, p – pressure, T – temperature and T_0 – reference temperature, z – chemical composition of the melt, t – time, μ – dynamic viscosity, ρ – density, g – gravitational acceleration, β – thermal expansion, λ – thermal conductivity, c_v – specific capacity, D – diffusion coefficient, e_1 to e_4 – some fitting coefficients (to fit the model to an object).

Equations (1), (2), (2) are known in the classical fluid mechanics as the Navier-Stokes (or motion), energy and continuity equations, respectively, and they are formulated on the base of the momentum, energy and mass conservation laws. These equations describe the distributions of the temperature and the glass melt velocities in a tank furnace induced by the free and forced convection currents in the molten glass. Equation (4) describes the glass mass composition changes induced by the convection currents and the diffusion. While setting up the equations several simplified assumptions were made that took into consideration the specific properties of the glass mass flow and also the hypothesis that the glass melt is an incompressible and Newtonian liquid [3]. The scheme of a glass tank furnace modelled and the main convection currents occurring in the molten glass are shown in Fig. 1.

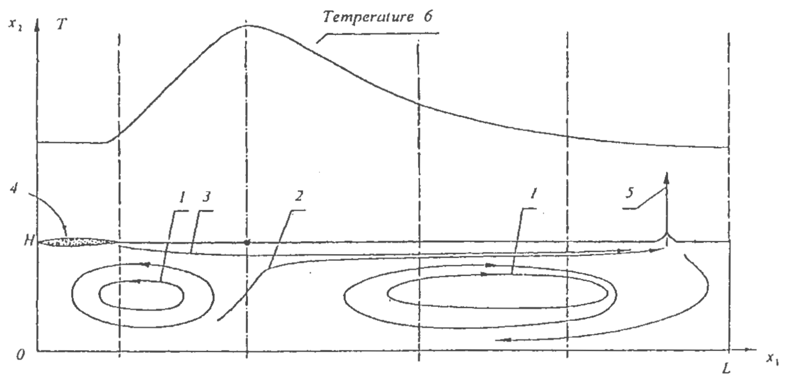

Figure 1. Longitudinal section of the glass tank furnace and the main currents occurring in the melt; 1,2,3 - rotating, withdrawal and surface current, respectively, 4 - raw materials input, 5 - glass take-out, 6 - temperature distribution on the free surface of the glass melt.

3. DPE model identification

Equations (1-3) make together a two-dimensional DPE model of the glass mass flow in a tank furnace. After some boundary conditions are given and the temperature and velocities values are calculated from equations (1-3), one can calculate subsequently the glass melt composition at each point of the tank by solving equation (4). To get the numerical solution of the model equations the finite difference method is used and a theoretical analysis of the numerical solvability of the model is made [3]. On the first step of the model computing equations (1-3) are solved. The boundary conditions for the function p are unknown and this makes necessary to transform the equations. It is done by replacing the velocities v_1, v_2 by the current function ψ what results in a new model form consisting of only two equations contrary to the four ones in (1-3). The reduction of the number of equations causes in general a better convergence when solving the model numerically. A discrete approximation of the model equations occurs by the help of difference quotients. The use of standard difference quotients leads, however, in the case of high order derivations of equations to a bad stability of the resulted difference schemes at the edges of the knotted grid. To improve the approximation some new central difference quotients have been developed for the high order derivations of ψ. The difference schemes resulted from equations (1-3) are solved by means of the relaxation method using an iterative algorithm. For the numerical calculation the values of the physical coefficients and of the space dimensions of the model were chosen according to those ones of a real tank furnace. The convergence of the iterative algorithm was relatively fast with highly satisfactory accuracy of the calculation. Some results of the temperature and current fields computed are shown in Fig. 2. One can see in Fig. 2 that only the rotating and withdrawal currents but not the surface current (as it is shown in Fig. 1) are determined after the simulation of model (1-3) was made. This current could not be obtained with a two-dimensional DPE-model.

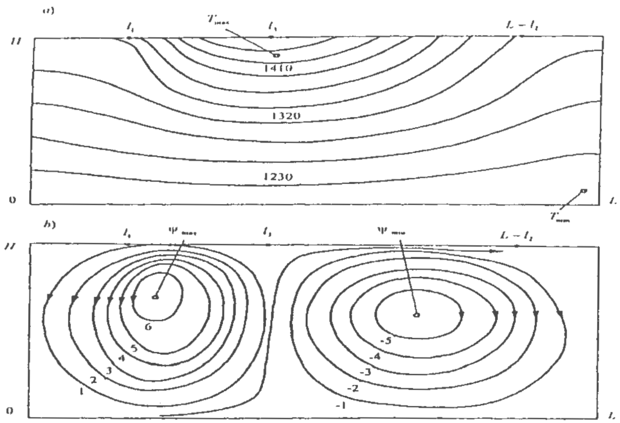

Figure 2. Computed temperature (figure a) and current distribution (figure b) in the glass melt for the longitudinal section of the glass tank furnace.

The numerical solution of equation (4) occurs on the second step of the modelling. To approximate (4) some central difference quotients of the finite difference method are used and as a result a new difference scheme with some fitting coefficients is obtained. The glass tank model described by equations (1-4) constitutes an approximation of a real object. Such an approximation is usually not exact although the parameters and dimensions of the model correspond to those ones of the tank. The possible inaccuracies occur while the model equations and boundary conditions are formulated and the parameter values are determined. Also the numerous simplifications made during the setting up the model are responsible for many inaccuracies and this is practically unavoidable. Then the fitting of the model to the object can be realised by the help of equation (4) and some measurements data obtained from the tank furnace under investigation (see Fig. 3). To do it the following identification problem is formulated:

$$\min_{e_i} Q(e_i) = \min_{e_i} \sum_{k=0}^{K} (\hat{z}^k - z^k)^2 \quad (5)$$

where $\hat{z}^k$ and z^k mean the measured data and the discrete values of the model output that is calculated by solving equation (4) (the glass composition z is here considered as the radioactivity of the glass melt that has been measured while realising an isotope experiment on the tank furnace).

To solve problem (5) a static non-gradient optimisation method is used [4]. The criterion function $Q(e_i)$ is strong non-linear relating to e_i. Because of that the start points for the optimisation runs had to be chosen very carefully and close enough to the optimum. The model output obtained from the calculation is shown in Fig. 3. One can see that the output fits well to the data in the farther section of the curve where the influence of the rotating and withdrawal currents on the glass mass flow is the strongest. The approximation of the data with the model output in the initial section of the curve is much worse but there the surface current determines the data which is noticeable through the high oscillations of the curve. This situation can be explained through the omission of the surface current in the DPE model. This current could be considered in a three-dimensional DPE model but unfortunately such a model would be hardly possible to identify because of its great complexity.

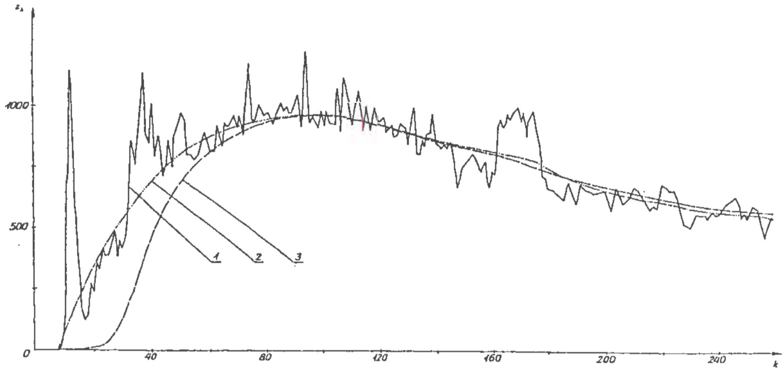

Figure 3. Isotope data for modelling the glass mass flow dynamics; 1,2- noisy and smoothed data, respectively, 3 - output of the DPE model.

4. LPE model and its identification

The glass mass flow in a tank furnace can be described using also LPE models. Their parameters have no physical meaning and this gives interpretation troubles when comparing the models and objects. On the other side the setting up of such the models is easier than PDE models regarding the work complexity and the computing time needed for simulation and identification. Usually the non-linear regression methods are used for developing the lumped parameter models. These methods are generally successful if models of lower orders have to be set up but they are not effective in more complicated cases. The main problems then are connected with the choice of an adequate model structure and with the fixing a start point possibly closely to the optimum while making the identification. The methods of non-linear regression converge usually to the local optimal points if the start points are not right. To overcome these problems an indirect identification method was developed to model linear dynamic objects of higher orders from their sampled impulse responses [1]. This method has been adopted for setting up the LPE models of glass tank furnaces by using a multistage modelling approach [4].

The mathematical description of an object modelled is now in the form of the homogeneous ordinary differential equation:

$$\frac{d^R z}{dt^R} + a_{R-1}\frac{d^{R-1} z}{dt^{R-1}} + \ldots + a_0 z = 0 \qquad (6)$$

with the non-zero initial conditions added:

$$\begin{cases} z(0) = b_{R-1} \\ z^{(1)}(0) = b_{R-2} - a_{R-1} z(0) \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ z^{(R-1)}(0) = b_o - a_1 z(0) - \dots - a_{R-1} z^{(R-2)} \end{cases} \tag{7}$$

and with the following analytical solution function:

$$z(t) = \sum_{j=1}^{J} \sum_{l=0}^{m_j - 1} t^l \exp(\alpha_j t)\left(c_{jl}\cos(\varphi_j t) + d_{jl}\sin(\varphi_j t)\right), \qquad \sum_{j=1}^{J} m_j = R \text{ and } m_j > 0 \tag{8}$$

The continuous equation (6) can be approximated by the following discrete equation:

$$z_k + s_{R-1} z_{k-1} + \dots + s_o z_{k-R} = 0 \tag{9}$$

with: $z_k = z(k\Delta t)$, k=1,2,...,K, Δt – sampling step, and with the following analytical solution function:

$$z_k = \sum_{j=1}^{J} \sum_{l=0}^{m_j - 1} k^l \sigma_j^k \left(f_{jl}\cos(\psi_j k) + g_{jl}\sin(\psi_j k)\right) \tag{10}$$

By comparison (10) and (8) one can convert very easy the coefficients of function (10) into the coefficients of (8).

The numerical algorithm realising the indirect identification method is as follows:

1. Fitting the difference equation (9) to the impulse response obtained from the object, using a standard time series identification method.
2. Estimation of the coefficients in the time discrete function (10) using a standard optimisation method (e.g. the linear regression) and the parameters identified in (9).
3. Calculation of the coefficients in the time continuous function (8) converting the coefficients of function (10) with the help of some simple algebraic formulas.
4. Calculation of the parameters of equations (6) with the help of the parameters of (8).

The main idea of the indirect identification method is that at first a discrete model is found and afterwards it is converted into the time continuous one. In this way the search for a continuous model is realised „indirectly", i.e. using a discrete model that is much easier to develop from the numerical point of view. In the case of complex objects it is well-advised to divide the modelling process into several stages at which sub-models with different dynamics features are constructed and afterwards put together to one overall model. On each stage of modelling different data sequences must be used for identification and they are to be isolated from the original measurements. The currents distribution occurring in the glass melt (see Fig. 1) suggests that the features of the melt mixing dynamics in a tank furnace depend in a different way on the character and velocities of the currents. The slow-running withdrawal current decides on the dynamics of the slow-varying inertial character and the fast-running surface current, as well as the rotating currents decide on the dynamics of the different-varying oscillatory characters. Also the isotope data for identification display both the inertial and oscillatory characters (see Fig. 3). The above remarks justify the application of the multistage approach for modelling glass tank furnaces. The choice of the best („optimal") sub-models as well as of the best overall model occurs by means of the residual sums.

Some models have been developed for the glass tank furnace under consideration using this multistage approach They fit well to the farther part of the data curve (where the „slow" dynamics of the object dominate) but their adaptation to the initial phase of the curve (where the oscillatory components dominate) is much worse. The modelling of this initial data section depends considerably on the division of the whole data sequence into the components which are used for setting up the sub-models. This makes the main trouble when using the multistage modelling approach with the LPE description of the models. Since the runs of the data components are not known from the beginning, they can be guessed only in general and the appropriate data curves are obtained using various smoothing algorithms. This leads, however, to great inaccuracies of the proceeding.

5. Combined algorithm of molten glass modeling

To avoid the disadvantages of the above modelling approaches a combined algorithm for modelling glass tank furnaces has been developed. The final models obtained by means of this approach are described by ordinary differential equations but a DPE model is used at the first level of the modelling. The conception of this combining modelling resulted from the experience which was gathered after the models with distributed and lumped parameters were developed separately. In the latter case the modelling of the oscillations appearing in the isotope data (and caused by the surface current) is not exact. The only use of smoothing algorithms does not allow to determine exactly the initial run of the data curve which is used later to set up the „slow" inertial sub-model and because of that there is not possible to get the right data for farther stages of the modelling. But these difficulties can be surmounted by help of the DPE model. It allows to isolate correctly the surface current component of the data from the component which is responsible in the main for the glass mass transport in a tank furnace. This component is caused by the withdrawal and rotating currents and it is approximated correctly by the DPE model.

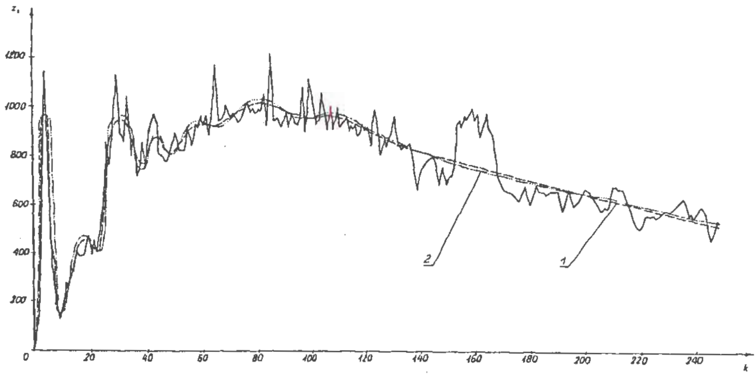

Figure 4. Overall LPE models obtained by means of the combined modelling approach without and after using the non-linear regression method (curve 1 and 2 respectively).

The two-level modelling approach is as follows:

1. Formulation of the partial differential equations describing the DPE model and its computer simulation.
2. Identification of the DPE model with the help of the measurements data and by means of an optimisation method.
3. Developing of the slow-varying LPE sub-model using the output of the DPE model as the data for the indirect identification method.

4. Preparation of the data for setting up the fast-varying LPE sub-model by subtracting the output of the DPE model from the original measurements and by smoothing the results (this sub-model will describe the contribution of the surface current in the measurement data).
5. Developing of the fast-varying LPE sub-model using the indirect identification method.
6. Putting together the sub-models into one overall model and the subsequent estimation of its parameters by means of the non-linear regression methods.

After using the combined modelling algorithm a complex LPE model of the glass mass flow dynamics was finally set up. The model has the eleventh order and it consists of two sub-models of sixth and fifth orders, respectively. The 6th order sub-model has the inertial-oscillatory character and owns two real and four complex roots in its transfer function. It fits very well to the output of the PDE model. The 5th order sub-model has either the inertial-oscillatory character and it has one real and four complex roots in its transfer function. It fits very well to the oscillations caused by the surface current. The overall LPE model fits well to the original measurements and it approximates exactly the oscillations occurring in the initial section of the data (see Fig. 4 and Table 1).

Table 1. Paramcters of the 6th order and 5th order sub-models and of the 11th order overall ODE model.

Parameters	$R = 6$	$R = 5$	$R = 11$
T_1	263.16	32.26	263.16
T_2	14.88		21.19
k_1	11.27	31.95	19.88
ω_1	237.99	27.83	33.39
k_2	1.68	3.77	11.48
ω_2	191.56	7.39	22.51
T_3			1.32
k_3			14.68
ω_3			13.45
k_4			3.29
ω_4			4.58

6. Conclusions

The problem of mathematical modelling of the glass mass flow dynamics in a glass tank furnacc is solved and three numerical approaches of modelling are presented, tested and discussed. The first approach develops two-dimensional DPE models that describe the slow-varying dynamics of the glass tanks in which the withdrawal and rotating currents occur and no surface current appears. The second approach allows the development of LPE models of relatively small order that do not describe exactly thc complex dynamics of the objects in which all kinds of the currents occur. The troubles arise while modelling by means of this approach the initial section of the isotope data where the simultaneous effects of the slow and fast varying currents are particularly strong. There is no effective algorithm to divide the data curve into the components for there is not known *a priori* in which way the individual currents influence the measurements. The third approach is a combination of the two and it makes possible to develop complex LPE models of the high order that have got the inertial-oscillator features and very differentiated parameter values. The models computed by help of this approach describe very well the dynamics of the glass mass flow and all the same they are simple and convenient enough for numerical treatment. They can be used for the development of control or stabilisation algorithms with reference to the chemical composition of the glass as well as for the calculation of the technological parameters of glass tank furnaces.

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