Embedded Control System of Apparatus for Measurement of Thermal Conductivity

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Abstract: - The paper deals with an original control system embedded in an apparatus for measurement of thermal conductivity of electrically conductive materials. The measurement method is based on one-dimensional heat conduction in a bar-shaped specimen heated by internal heat source with ends cooled by water. The control system consists of main computer, which communicates with four external measuring units. The computer contains a multiply-function card with A/D converter. A control program is written in LabVIEW environment. The algorithm carries out controlling of the specimen temperature according to a setting point, controlling of heating active mirror to compensate specimen radiation for the purpose of achieving one-dimensional heat conduction state in the specimen as well as data acquisition. Two methods of automatic control are described in the paper.

Key-Words: - thermal conductivity, metals, alloys, internal heat source, calorimeter, embedded control system, non-sinusoidal, input power, PID controller, virtual instrument

1 Introduction

Knowledge of basic thermo-physical properties of metals and alloys including coefficient of thermal conductivity is required for design of engines and equipments, optimization of technological processes and their mathematical modelling. An original experimental apparatus for measuring thermal conductivity for electrically conductive materials has been built at the Department of thermal engineering at the Technical University of Ostrava, the Czech Republic [1]. Although the equipment is used mainly for measuring thermal conductivity of steels up to temperature 1200 °C, it enables determination of thermal conductivity coefficient of metals and alloys for temperatures ranging from ambient to the melting point.

The experimental method is based on differential equation for unidirectional heat conduction with consideration of internal volume heat source

$$\frac{d^2 t}{dx^2} + \frac{q_V}{\lambda} = 0 \qquad (\mathrm{K.m^{-2}}) \tag{1}$$

where t is temperature (°C), x - coordinate (m), q_V - power of internal volume heat source ($\mathrm{W.m^{-3}}$) and λ - coefficient of thermal conductivity ($\mathrm{W.m^{-1}.K^{-1}}$).

To comply with the theoretical postulate of one-dimensional heat conduction, a number of technical and algorithmic problems have been solved including implementation of embedded control system.

2 Laboratory apparatus description

A core of the apparatus is a vacuum chamber where a bar-shaped specimen with diameter 10 mm and length 178 mm is placed. The specimen is heated by electric current. Electrical energy input is measured and calculated with high accuracy as product of the current and voltage across the specimen. The specimen is fastened in two electrical terminals, which have a function of continuous flow calorimeters. The terminals are water-cooled and enable measuring of heat flow from the specimen to cooling water.

To ensure one-dimensional heat transfer, heat removal from the lateral area of the specimen by convection and radiation must be eliminated. Heat convection is eliminated by means of vacuum. The vacuum 10^2 Pa is generated by two-stage rotary oil pump and turbo molecular vacuum pump. To eliminate heat loss by radiation, the specimen is placed into coaxially surrounding molybdenum tube. The tube is heated by electric current in the same way as the specimen and the ends are water-cooled. Specimen radiation is compensated by radiation of the tube, which has a function of so-called active mirror.

Heat radiation of the specimen is fully eliminated, when the system is in stationary state and an electrical power input into the specimen P_{sp} equals heat flow to cooling water measured by calorimeter P_{cal}. It means that a condition for thermal conductivity measuring consists in achieving equality of both energy flows $P_{sp} = P_{cal}$. As surfaces of the specimen and mirror have generally different coefficients of absorbability (which depend on temperature), the temperatures of the specimen and mirror are different even though radiation rates between surfaces are in equilibrium. For this reason, setting of the desired state of the system manually is not easy, that is why a control system has been embedded into the apparatus.

3 Embedded control system

The control system of the experimental apparatus has two main functions. The primary one is automatic control of the specimen and mirror temperatures for a purpose of achieving heat flow equilibrium. The second function is data acquisition for the reason of coefficient of thermal conductivity evaluation.

3.1 Points of measurement

Points of measurement are shown in the figure 1. Voltage of the specimen supply is sensed via parallel connection at specimen terminals U_{sp} while the current is measured as voltage drop across a shunt U_{sh} in the electric circuit of specimen power supply. Thermocouples are welded on a surface of the specimen at accurate predefined positions and sense temperatures t_{sp}, t_{s1} a t_{s2} at three points along the specimen length. One of them t_{sp} is exactly in the middle of the specimen length and it is reference for controlling the specimen temperature. The other two thermocouples t_{s1} a t_{s2} serve for evaluation of thermal conductivity. The neighbour thermocouples leads serve as voltage probes as well for measuring voltage U_{s1} across a section of the specimen, which is used for evaluation of thermal conductivity. Another thermocouple measures a temperature of the active mirror t_m.

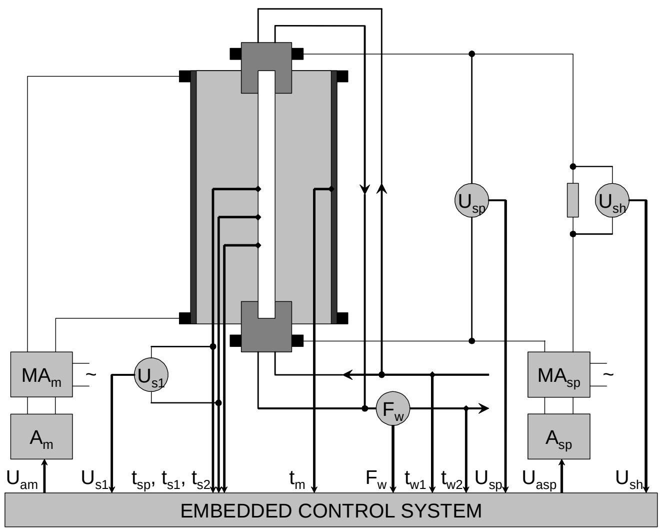

Fig.1 Scheme of the apparatus supply and control

For the reason of evaluation heat flow through the ends of the specimen, RTD sensors measure temperatures of input and output cooling water t_{w1}, t_{w2}. Water mass flow rate F_w is measured by an incremental measuring method using electronic weight.

3.2 Actuators

Both DC and AC power supplies for the specimen and mirror have been tested. Because two separate special regulated power supplies (for voltage of the order 0.1 V and current of the order 10^2 A) were not accessible, they had to be designed and assembled on site. The DC supply is better from the point of view of minimal interference with measuring signals, but it requires introduction of costly solid-state module for current reversing for the reason of elimination temperature profile deformation caused by electron flow. An AC power supply with phase control by tyristor is not suitable for an intensive interference with measuring thermocouples signals.

Recently power supplies both for the specimen and for mirror based on magnetic amplifiers proved to become admittedly transitional, but fully suitable and cost-effective solution. Magnetic amplifiers MA_{sp} and MA_m are controlled by DC excitation current from power amplifiers, which are controlled by voltage outputs U_{asp} and U_{am} of the computer card. The magnetic amplifiers generate AC voltage with content of harmonics but the frequency spectrum is much more favourable from the point of view of interference in comparison to the phase control. The disadvantage of this technical solution is a necessity of higher-order measuring and processing methods for non-sinusoidal voltage and current.

3.2 The embedded control system architecture

The main part of the control system is a computer, which communicates with four external units via various buses, as shown in the figure 2. Thermocouples and RTD sensors are connected to the data logger HP 34970A, which performs measuring with very low level of interference. The data logger is connected to the computer via GPIB bus. The electronic weight for measuring water mass rate communicates with the computer via serial bus RS232.

The unit ADE 7753 provided with a microchip, which, in addition to sampling, calculates an average electric power, solved the problem of measuring non-sinusoidal current and voltage in the power circuit of the specimen. There are two of these units used, one evaluates a total power input to the specimen P_{sp}, and the second computes a power input to the section of the specimen between two thermocouples P_{s1}. Both units are connected to parallel port LPT of the computer and communicate via a special serial protocol.

Output signals for actuators handling U_{asp} and U_{am} are generated by voltage outputs of multi function card PCI-6024 with A/D converter located in the control computer.

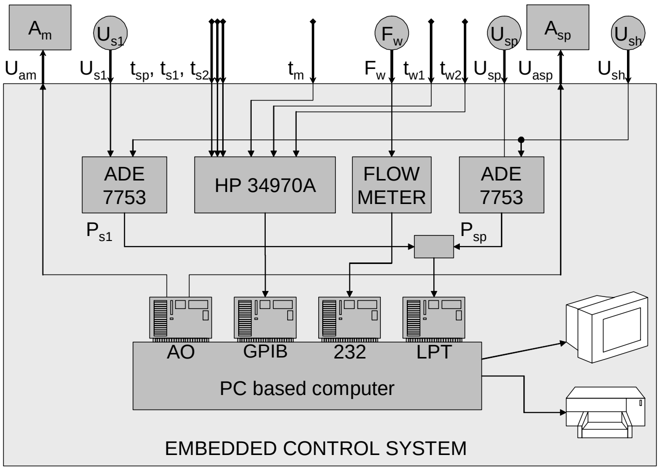

Fig.2 An architecture of the embedded control system

3.2 Algorithm of automatic control

The control algorithm has been programmed in the LabVIEW environment. It deals with a control of quantities at two objects, namely the specimen and the active mirror. There is a coupling caused by radiation between the objects. The coupling is non-linear and its character is dependent on temperatures of both objects. Characteristics of each object separately are also non-linear as follows from laws of heat transfer by conduction and radiation, while physical parameters are dependent on temperature.

The effect of coupling between the specimen and the mirror is apparent from the figure 3, which shows time dependences of specimen t_{sp} and mirror t_m temperatures and voltage across the specimen U_{sp} and mirror U_m. Temperature of the specimen varies because of changes of supply voltage U_{sp}. Temperature of the mirror varies even though the mirror supply voltage U_m is constant, in a consequence of specimen-mirror coupling.

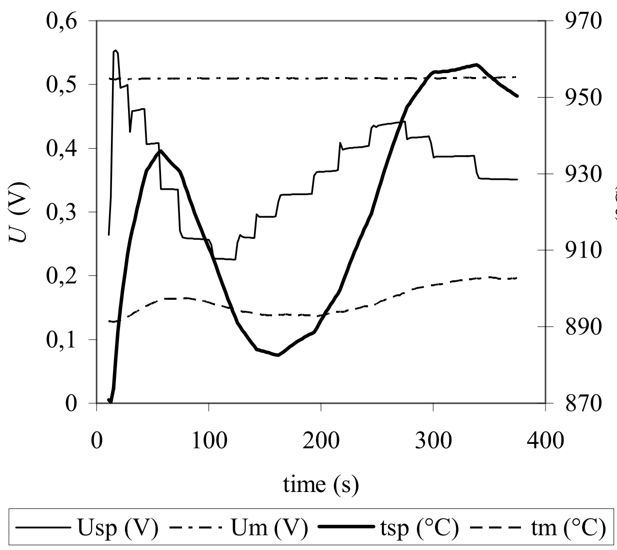

Fig.3 Specimen and mirror temperature response

Response time constants of the system are of the order of 10^1 seconds. In view of control system time demands for measuring non-sinusoidal quantities, as well as calculations and communications, the minimal reached period of the control loop processing is 1 s, which is sufficient for good-quality control.

Two different methods of controlling the specimen temperature and heat flow equilibrium have been developed and verified. The first method uses two control loops as well as two virtual PID controllers, figure 4. The loop of the controller PID 1 accomplishes controlling of the specimen temperature, where measured value is a temperature in the middle of the specimen t_{sp} and actuating signal is an analog voltage U_{asp} controlling the excitation of the magnetic amplifier MA_{sp}.

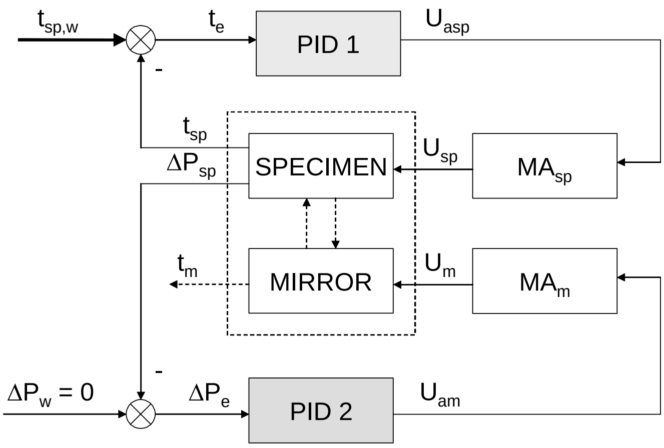

Fig.4 A diagram of the control method with two closed loops

After achieving and stabilizing desired temperature of the specimen, the second control loop of the controller PID 2 is switched on. Its task is controlling the heat flow equilibrium by heating the active mirror via magnetic amplifier MA_m, in other words to keep a zero difference of energy flows $\Delta P_{sp} = P_{sp} - P_{cal} = 0$. As the both loops interact through the radiation coupling between the specimen and mirror, it is a case of multi-parametric control.

The main virtual instrument display of the control system is shown in the figure 5. It contains control elements and shows values of measured quantities, calculated electrical power to the specimen P_{sp}, the heat flow from the specimen to cooling water P_{cal}, PID controllers settings, panel for monitoring of measuring mass increment of the flown cooling water, parameters for calculation of specific enthalpy of cooling water and a deviation from heat flows equilibrium ΔP_{sp}.

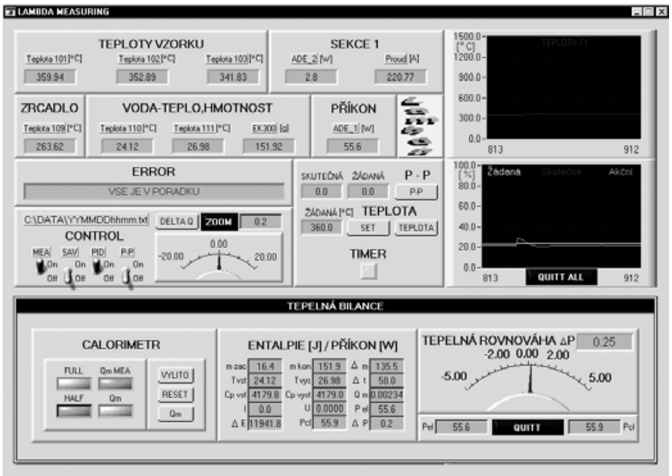

Fig.5 The main virtual instrument display of the control system

The second control method uses only one closed loop with PID controller, labelled PID 3 in the figure 6. The task of the loop is controlling the heat flow equilibrium by means of heating the specimen. Furthermore, the system has one open loop, which actuates heating of the mirror. The actuating quantity for the mirror heating U_{am} is set for each measuring point as a result of a function f. The function argument is a specimen temperature setting value $t_{sp,w}$. The function was derived during the system development and pilot experimental measuring.

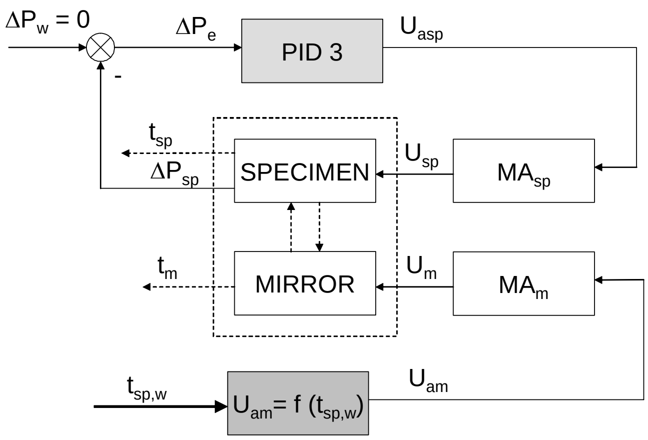

Fig.6 A diagram of the control method with one closed loop

Automatic control of the apparatus by the second method is more favourable from the point of view of stability and setting time by reason that only one closed loop is active. Negligible disadvantage of the method consists in the fact, that the heat flow equilibrium arrives at slightly different specimen temperature t_{sp} from the setting value $t_{sp,w}$. It is caused by an absence of feedback from the specimen temperature.

3.3 Measured data evaluation

The control system accomplishes, in addition to automatic control, data acquisition for the reason of thermal conductivity evaluation, which is executed off-line by a special program written in Visual Basic for Excel [3]. An example of final results - thermal conductivity coefficient dependence on temperature for a concrete steel grade measured on the apparatus at temperatures ranging from 300 °C to 1200 °C, is shown in the figure 7 [2].

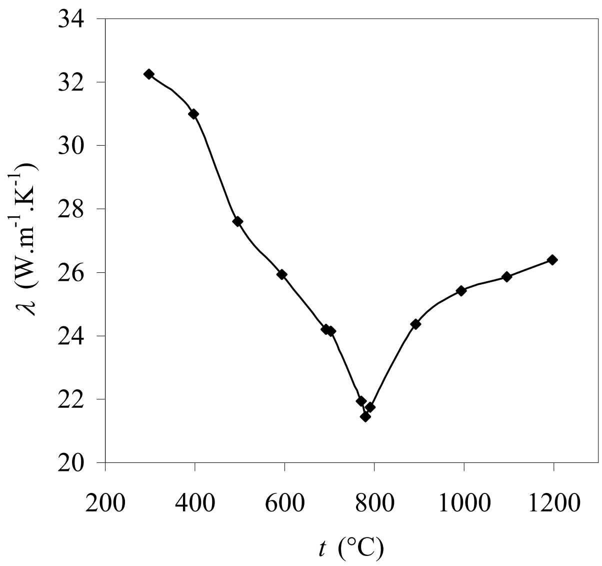

Fig.7 Measured dependence of thermal conductivity coefficient on temperature

The real measuring proved that the loop of specimen temperature control is able to keep a steady-state temperature error ±0.5 °C. Maximal deviation from the heat flow equilibrium is less than 1.5 % of the specimen electric power input, which is sufficient from the point of view of thermal conductivity measuring accuracy.

4 Conclusion

An embedded control system of laboratory apparatus for measuring thermal conductivity of electrically conductive materials has been developed and realized. The system satisfies demanding requirements on controlling thermal equipment with non-linear characteristics and couplings between controlled parameters. Measuring of non-sinusoidal current and voltage including evaluation of input power has been solved by special external modules. The system accomplishes controlling of a specimen temperature and equilibrium between energy input and heat removal. Two control algorithms have been developed and tested. First method is based on two closed loops for the specimen temperature (controlled by specimen heating) and for energy flows equilibrium (controlled by mirror heating). The second method uses one closed control loop for equilibrium (controlled by heating the specimen) and one open loop for handling the mirror heating. Maximal deviation from equilibrium of the energy flows is 1,5 % of specimen total input power, which is satisfactory from the point of view of accuracy of thermal conductivity measuring.

The apparatus for measurement of thermal conductivity coefficient is based on the original principle of specimen radiation compensation by controlled active mirror [1]. Consequently the embedded control system is original from the point of view both of control algorithm and of system architecture.

Acknowledgements
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