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S-band liquid calorimeter with disk-shaped wide aperture absorbing load for high-power microwave pulse energy measurement

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Abstract. An S-band liquid calorimeter with a disk-shaped, wide-aperture absorbing load is described, having an electronic control system that allows the instrument to be remotely prepared for operation and to control procedures of calibrating and measuring microwave pulse energy. The operating range of the calorimeter is from 2.7 to 3.3 GHz, the measured microwave energy is from 5 to 500 J, the amplitude of the input microwave power is 1 GW, and the microwave energy measurement error is about ±10 %.

Keywords: S-band, high-power microwave pulses, liquid calorimeters, disked-shaped wide aperture absorbing loads, electronic control system.

1. Introduction

Liquid calorimeters [1–6] with wide-aperture absorbing loads of various designs filled with a working fluid based on ethyl alcohol are well known as reliable instruments for measuring the energy of high-power microwave pulses [7]. The operation of such calorimeters is based on the expansion of the working fluid as its temperature increases due to absorption the microwave pulse energy. The use of the calorimeters in combination with detectors that record the pulse envelope makes it possible to determine the amplitude of microwave power. To date, calorimeters have been developed for various frequency ranges with manual [1–4] and electronic [5, 6, 8] control.

This article describes the calorimeter of S-band with an electronic control system, which, unlike that used in the prototype [6], provides greater capabilities, consisting of remote preparation the device for operation and automatic control the calibration procedure and the microwave pulses energy measurement. In this case, there is no need to perform the required manipulations with the absorbing load directly on the experimental site. The calorimeter was used to measure the high-power microwave pulses energy of a relativistic backward wave oscillator.

2. Calorimeter design

The block diagram and the appearance of the calorimeter are shown in Fig. 1 and 2, respectively. The calorimeter includes a disk-shaped wide-aperture absorbing load, a control and registration unit, a power supply with power supplies for heating the working fluid and calibrating the calorimeter, a control computer and a set of connecting cables. The operating principles of the calorimeter electronic circuit are largely similar to those described in [6, 8].

2.1. Absorbing load

The absorbing load (Fig. 1) is connected through a normally open upper valve to an expander, and through a normally closed lower valve to a measuring tube of an optical sensor of the working fluid column length. The design of the optical sensor and its operation are similar to those described in [8]. In the assembled state, the load is located on a movable stand (Fig. 2) opposite the transmitting horn antenna of the microwave oscillator. The load weight without alcohol is 56 kg. The volume of alcohol in a load is about 16 liters.

A control and registration unit covered by shielded housing is attached to the rear wall of the load. The calorimeter's power supply has a metal shielding housing and during operation is located several meters away from the absorbing load.

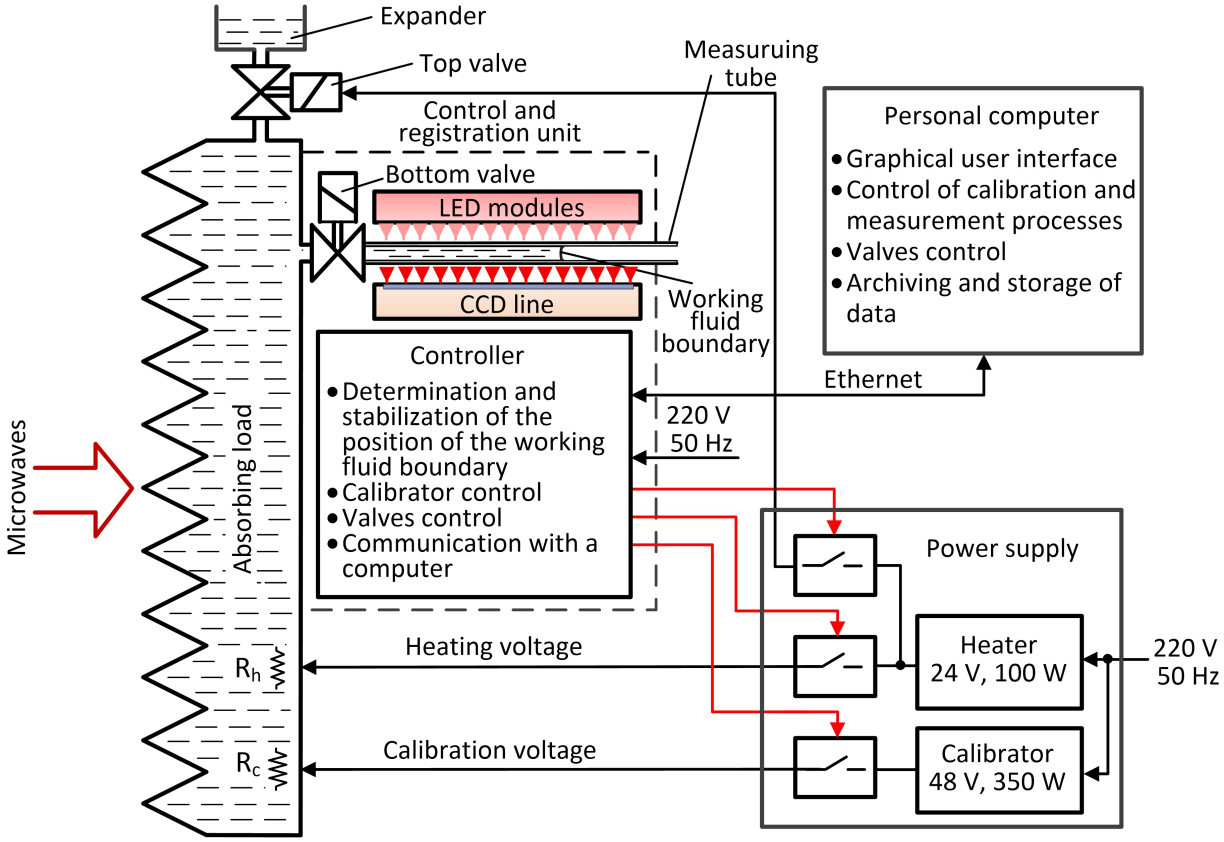


Fig. 1. Block diagram of the calorimeter.

Fig. 2. Appearance of the calorimeter: 1 – absorbing load (front view), 2 – absorbing load (rear view), 3 – expander, 4 – top valve, 5 – control and registration unit, 6 – power supply, 7 – movable stand, 8 – block of electrical connectors, 9 – mounting brackets.

Inside the absorbing load there are two resistors made of stainless steel wire. Resistor R_h is used to heat the working fluid, resistor R_c is used to calibrate the calorimeter. These resistors are supplied with voltage pulses from sources included in the calorimeter's power supply. Accordingly, a 100 W power source is used to heat the working fluid, and a 350 W power source is used to calibrate the calorimeter. The power supplies are controlled by a control and registration unit via fiber optic lines.

The load is made of high-density polyethylene PE500 and filled with ethyl alcohol with a concentration of 95%, which is the working fluid. The input load window is corrugated. The geometric shape of the load was simulated and optimized using CST Microwave Studio software for the S-band to reduce the microwave reflection from the input window. The calculated reflection coefficients of microwave power from the absorbing load of the calorimeter in the range of 2.5–3.5 GHz for waves TM_{01} and TE_{11} are of 0.3–2.2% and of 0.8–3.5%, respectively.

The calorimeter control system consists of a controller, which is part of the control and registration unit, and a control program installed on the personal computer. The controller determines and stabilizes the position of the working fluid boundary in the measuring tube, controls the operation of the valves, the power supplies for the calibrator and the heater, and exchanges data with the personal computer as well. Data exchange between the controller and the computer is carried out via an Ethernet interface with an optical data transmission medium in the form of a multimode two-wire fiber optic cable. The control and registration unit is powered from a 220 V, 50 Hz AC mains through a special 10 W isolation transformer.

The program installed on the computer includes all the controls necessary to work with the calorimeter, displays its status and operating modes. The program also controls the process of the calorimeter calibration and the microwave energy measurement. The measurement results are displayed in the form of numerical values of the measured energy, as well as the time dependence of the position of the working fluid boundary in the measuring tube on the absorbed microwave energy or calibration energy. All settings and operating modes as well as the measurement results are saved in the computer memory as a history file.

To determine the position of the working fluid boundary in the measuring tube, an optical sensor based on the TSL2014S CCD line is used. The clock pulses and clock signals necessary to work with the optical sensor are generated by the controller of the control and registration unit. The design of the sensor is shown in Fig. 3. The operation of the sensor is described in detail in [6, 8].

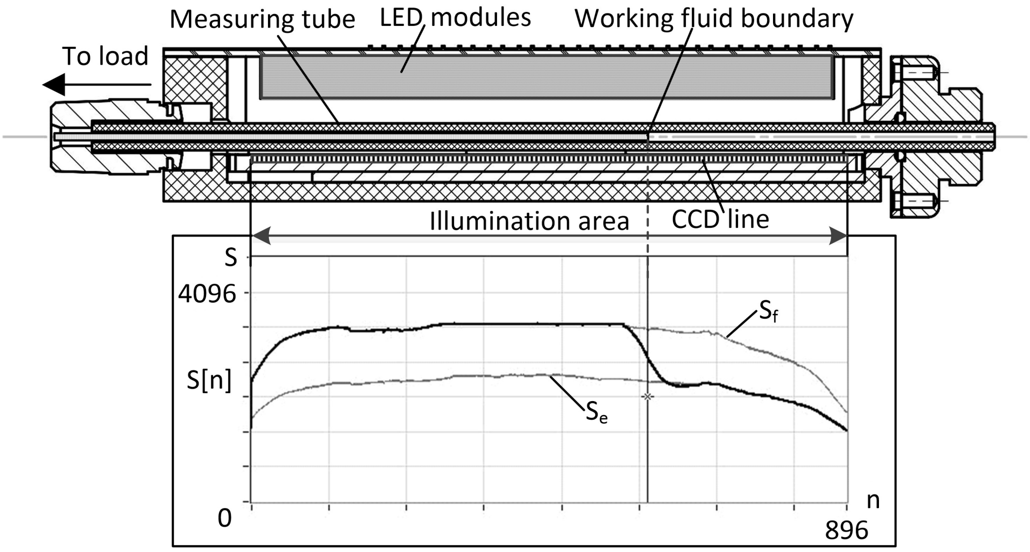
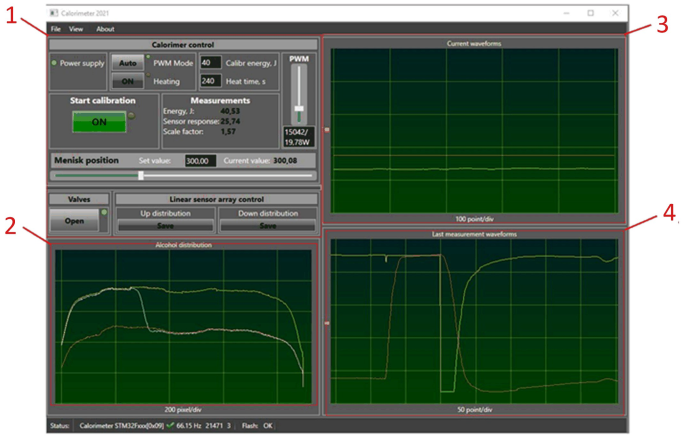


Fig. 3. Design of the optical sensor and output signals of the CCD line: S_f – when the measuring tube is completely filled, S_e – when the tube is empty.

The controller is based on the STM32F407VE microprocessor. It polls the CCD array, the result of which is an array S[n], displaying the distribution of the light flux along the measuring tube. The array consists of 896 twelve-bit binary numbers. The frequency of taking readings from the CCD line and updating the array in the microprocessor memory is 200 Hz. All operations of mathematical processing of sensor readings are also performed at this frequency. The procedure for determining the position of the working fluid boundary in the measuring tube is performed by the microprocessor based on processing the array of sensor readings using the least squares method and is described in detail in [8].

The position of the boundary of the working fluid in the measuring tube is stabilized by a programmable proportional-integral-differentiating (PID) regulator by adjusting the power of the heater. The feedback signal is determined by the current position of the working fluid boundary. The heater power is controlled by a microprocessor timer operating in pulse width modulator (PWM) mode. The output data of the PID regulator are used as its control signal. One of the microprocessor timers is used to generate a calibration pulse of adjustable duration, which determines the calorimeter calibration energy.

The appearance of the user interface of the control program is shown in Fig. 4.



Calibr energy, J: 40
Heat time, s: 240
Energy, J: 40,53
Sensor response: 25,74
Scale factor: 1,57
15042/ 19,78W
Menisk position Set value: 300,00 Current value: 300,08
Status: Calorimeter STM32Fxxx[0x09] ✓ 66.15 Hz 21471 3 Flash: OK

Fig. 4. Calorimeter control program interface.

The graphical interface of the program is visually divided into 4 areas. Area 1 contains the main calorimeter controls, fields for entering basic settings and displaying measurement results. In area 2, the optical sensor signal is displayed in the form of a light flux intensity distribution along the measuring tube. Area 3 displays the current position of the working fluid boundary and the PWM control signal. In area 4 there is a graph displaying the calorimeter signal after exposure to a microwave pulse or calibration.

3. Calorimeter operation

After connecting all the components of the calorimeter and supplying power, the control program automatically establishes data exchange with the calorimeter controller, as a result of which the controls become active. The procedure for preparing the calorimeter for operation involves preheating the working fluid. It is activated by pressing the corresponding button on the control program panel. The heating duration is about 240 s, after which the heating mode is automatically switched off and the voltage is removed from the heating resistor. The calorimeter is put into operation by also pressing the corresponding button on the control program panel. After the calorimeter is put into operation, the upper valve (Fig. 1) closes and the lower one opens. As the working fluid cools, its boundary begins move along the measuring tube towards the load. This is displayed on the control program panel. At the set moment, the position stabilization of the boundary of the working fluid is automatically activated. The stabilization process is performed by the control system controller. The process is described in detail in [6, 8].

The procedure of determining the calorimeter readiness to operation is illustrated in Fig. 5.

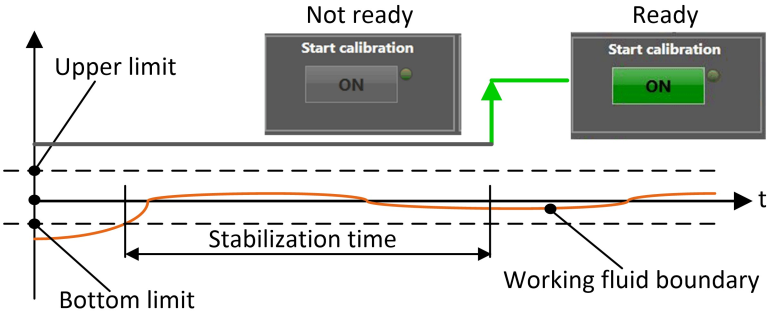


Fig. 5. To explain the procedure of determining the calorimeter readiness to operation.

This procedure is performed by a program that continuously analyzes the current position of the working fluid boundary in the measuring tube. If during a specified time interval the boundary is within set limits, the calorimeter goes into readiness mode for calibration procedures or microwave energy measurements. The readiness status of the calorimeter is also displayed on the control program panel.

The measurement of absorbed energy is illustrated in Fig. 6.

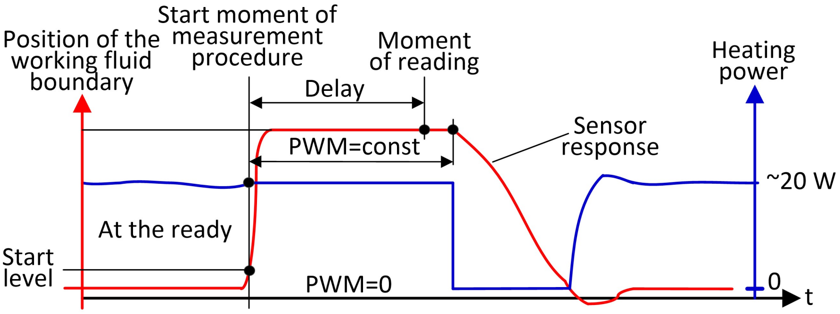


Fig. 6. To explain the procedure of energy measurement with the calorimeter.

The energy measurement procedure is automatically activated at a specified rate of rise of the calorimeter output signal. At this moment, the controller sets a constant control signal to the PWM in order to fix the power released in the heating resistor R_h (Fig. 1). The measurement procedure takes a few seconds. This interval is set in the control program and depends on the measured energy. The use the shortest possible intervals helps to reduce the measurement error caused by the drift of the working fluid boundary due to environmental influences. At the moment the readings are taken, the program determines the final displacement of the liquid boundary in the tube and recalculates it into absorbed energy, taking into account the calibration coefficient. After completing the measurement procedure, the mode of stabilizing the position of the working fluid boundary is activated again.

4. Conclusion

Thus, in this work, the previously developed scheme [6] of the liquid calorimeter with a disk-shaped wide-aperture absorbing load and an optical sensor of the working fluid displacement in the measuring tube was further developed in relation to the S-band. In contrast to [6], the electronic control system of the calorimeter automatically provides remote preparation the device for operation and implementation procedures of calibrating the calorimeter and measuring the energy of high-power microwave pulses.

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