Liquid Calorimeters for Measuring the Energy of High-Power Microwave Pulses

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Abstract—The design of L–S-band and X-band microwave calorimeters with an ethanol-based working fluid is described. The calorimeters are automatically controlled and have an improved wide-aperture load that absorbs microwave radiation.

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The energy of a microwave pulse that is radiated by a relativistic source [1] is one of its important characteristics. To measure the energy of a single pulse or a pulse sequence, microwave calorimeters are used [2]. The joint use of a calorimeter and a detector, if this is allowed by the measurement scheme, also makes it possible to determine the peak pulse power.

The operation of calorimeters is based on the absorption of the microwave-radiation energy by the working medium and measurement of this energy using one or another method. In the practice of relativistic microwave electronics, calorimeters with a wide-aperture load that absorbs microwaves and has a dielectric casing, which is filled with an ethanol-based working fluid, have found efficient application [3–6]. Their action is based on measurement of the increase in the fluid volume that results from the microwave-energy absorption.

The load may be installed either in the aperture of the transmitting horn antenna of the microwave-radiation source instead of its output window (vacuum calorimeter) [5], or may be separated from the antenna and installed in front of its output window [3, 4, 6]. To obtain the reflection and microwave-energy absorption predominantly in the working-fluid volume but not in the load casing and to extend the operating frequency band of the calorimeter, the load design must be optimized.

The resulting expansion of the working fluid in the aforementioned calorimeters is determined by measuring the displacement of the fluid meniscus in a sensor capillary tube, which is connected to the absorbing volume. The control of the meniscus position is attained at a certain excess of the working-fluid temperature over the ambient temperature and on condition that the heat exchange between the load and envi-
The stabilization of the initial position of the meniscus and the calorimeter control can be ensured by manually controlled heating [3–5].

This paper describes the design of L–S-band and X-band calorimeters, which were developed according to the same scheme with electronic control and an aperture load, which has an improved absorbability. The block diagram of the calorimeters is shown in Fig. 1.

Each calorimeter consists of a wide-aperture absorbing microwave load, a control and registration unit (CRU), a calibrator, and a set of connecting cables. A schematic drawing of the absorbing load is shown in Fig. 2. The appearance of the absorbing load of the X-band calorimeter [6] with a heat insulator is shown in Fig. 3. The load is placed in front of the horn-antenna aperture of the microwave oscillator. The oscillator-produced flux of microwave radiation is incident on the load.

The load casing is manufactured of high-density polyethylene. Its volume is filled with an ethanol-based working fluid, so that the load is a three-layer (polyethylene–fluid–polyethylene) absorber. The use of high-density polyethylene is determined by the fact that, in contrast to, e.g., Plexiglas [3, 4], this material possesses the much higher chemical stability with respect to the working fluid and simultaneously has a satisfactory elasticity (the elasticity modulus is ~1000 MPa). The shape of the face part of the load on its outer and inner sides is corrugated.

The dimensions of the load were optimized by the numerical-simulation method in order to reduce the microwave reflection from the absorber to a negligibly low level. In this case, the results of measuring the characteristics of the working fluid were used, which were obtained at the Chair of Radioelectronics of the Tomsk State University using a PNA E8363B circuit analyzer (Agilent Technologies) according to the technique [7] with the use of a small-size coaxial probe from the Dielectric Probe Kit 85070E. The dielectric permittivity and loss tangent for polyethylene were assumed to be frequency-independent [8]: \( \varepsilon = 2.26 \), \( \tan\delta = 0.0004 \).

During calibration and microwave-energy measurements, the absorbing load must be suspended using a cord and a bearing support above the floor opposite the transmitting horn antenna of the micro-
wave oscillator. This is necessary for preventing mechanical coupling of the load to the oscillator and, as a consequence, load vibrations, because vibrations of the meniscus in the capillary tube of the sensor lead to an additional measurement error [3].

The volume of the working fluid is connected through a hole to an expander (Fig. 2). The expander has a screwing-in plug that shuts the working volume during the microwave-energy measurements and the calorimeter calibration. Two nichrome spirals whose contacts are led out to the outside are mounted in the working volume. One serves for heating the working fluid, and the other is intended for calibrating the calorimeter. A capillary-tube-based sensor, which is intended for measuring the microwave energy, is connected to the working-fluid volume. Its design is schematically shown in Fig. 4.

The sensor is manufactured in the form of a coaxial system. The outer conductor is a capillary stainless-steel tube with an inner diameter of 3 mm. The inner conductor is a stainless-steel wire with a diameter of 1 mm. The protective jacket prevents the sensor against a mechanical damage. The sensor plug closes the capillary tube when the calorimeter is in the inoperative state.

When microwave energy is absorbed in the working fluid, its volume increases in proportion to the absorbed energy, the load casing expands, and then it must return to the initial state [3]. For this purpose, the load casing must possess a certain elasticity. Within the framework of our study, it was established that the aforementioned polyethylene satisfies these requirements to a sufficient degree. The elongation of the fluid column in the sensor tube upon absorption of microwave radiation or during the calorimeter calibration serves as the measure of the absorbed energy and is determined by the measured electric resistance between the inner and outer conductors of the sensor. This resistance is measured with the CRU using a Wheatstone bridge. A block diagram of the CRU is shown in Fig. 5.

The CRU includes a set of amplifiers, a microcontroller with an analog-to-digital converter (ADC) and a pulse-width modulator (PWM), and also all the required control and indication elements. The circuit provides automatic control of the meniscus position and readout of the measurement results.

In order to prevent overheating of the working fluid and weaken electrochemical processes in the sensor tube, a repetitively pulse power-supply voltage is used, which is fed to the Wheatstone-bridge input. The pulse repetition rate is 10 Hz, and the pulse duration is 1 ms.

A pulse signal from the Wheatstone bridge is amplified by instrumental amplifier 1. This signal is then fed to the input of a sample and hold device (SHD), where it is transformed into a dc voltage that is equal to the pulse amplitude at the input. A dc voltage from the

Fig. 4. Design of the capillary sensor of the meniscus position.

Fig. 5. Block diagram of the control and registration unit.
SHD output is amplified to a required level by amplifier 1.

The gain of amplifier 1 is changed stepwise. This is necessary for increasing the circuit sensitivity and switching the measurement ranges of the microwave energy. The meniscus position is stabilized by continuous heating of the working fluid in the volume of the wide-aperture load. As was mentioned above, the fluid temperature must be slightly higher than the ambient temperature.

To control the heating power, a signal from the coaxial sensor is used as the feedback signal. The microcontroller controls the heating power using the built-in PWM modulator according to the proportional integral–differential (PID) regulation law using a feedback signal, which is measured using the internal ADC. Pulses from the PWM control a power switch that connects the power-supply voltage to the calorimeter heating spiral.

The microcontroller is also used to control the components and units of the measuring system. In addition, the CRU provides manual control of the heating voltage. For this purpose, the same PWM and power switch are used, which are used to automatically control the meniscus position with the only difference that a signal from a potentiometer, which is positioned on the front panel of the CRU, is used as the feedback signal of the PID regulator.

When the microwave energy is measured or the calibration procedure is performed, a fixed-level feedback signal, which is written in the microcontroller memory, is fed to the digital-to-analog converter (DAC), where it is converted into an analog form. Subsequently, this analog signal is fed to the subtracting amplifier (amplifier 2), where it is subtracted from the output signal of amplifier 1. This is necessary for subtracting the constant component of the desired signal from this signal and equating it to the zero value before the measurement procedure.

The gain of subtracting amplifier 2 changes stepwise in accordance with the changes in the gain of amplifier 1. This, as was mentioned above, is required for increasing the sensitivity and switching the energy measurement ranges.

The calorimeter operating modes, the measurement range, the working-fluid heating voltage and temperature, and the meniscus position in the sensor capillary tube are displayed on a liquid-crystal (LC) indicator. The CRU includes controls, which are necessary for switching both the calorimeter operating mode and the manually controlling the heating voltage, and also contains power-supply units from the ac mains (220 V) to supply the electric circuit of the CRU and the heating spiral. The maximum heating power is 75 W at a heating voltage of 24 V.

A DC POWER SUPPLY HY5003 laboratory stabilized source is used to calibrate the calorimeter. This source was modified. After the modification, it allows obtaining rectangular pulses with a peak voltage of up to 50 V and a fixed duration of about several seconds across the calibration spiral, which are necessary for calibrating the calorimeter. Figure 6 shows a typical signal at the calorimeter output in the calibration and microwave–energy measurement modes.

The process of preparation for the operation and the energy measurement are performed in the following manner. The absorbing calorimeter load is suspended vertically with a cord. The calorimeter operation substantially depends on the sensor position [3]. It was established in our experiments that the best sensor position is a slightly raised one.

Before the calibration and measurement procedure, the working fluid in the calorimeter is preliminarily heated to a temperature that is slightly higher than the ambient temperature. The fluid temperature is measured and displayed by the CRU. The sealing plug for filling the expander (Fig. 2) is open during heating.

![Figure 6. Output signal of the X-band calorimeter in the calibration mode. The calibration-pulse energy is 5 J.](image-url)
After the required temperature of the absorbing load is reached, heating is turned off, bubbles are removed from the working volume via smooth rocking of the absorbing load, the sealing screw plug of the expander is closed, and the sensor plug is opened (Fig. 4). In this case, the CRU must be shifted to the mode of automatic-meniscus position stabilization.

After the sensor plug is opened, a certain amount of the working fluid flows out of the sensor. Because the fluid in the working volume is not heated, it begins to cool and the fluid meniscus in the sensor capillary begins to shift toward the working volume. At a certain time moment, the CRU fixes the meniscus in a specified initial position owing to enabling of the automatic working-fluid heating control. The position of the meniscus stabilization point can be also set manually.

After the meniscus position becomes stable, which can be observed by the output signal of the CRU indicator on the oscilloscope screen, it is possible to carry out the calorimeter calibration or to measure the microwave energy.

Before the calibration or microwave-energy measurement procedure, the automatic meniscus-position stabilization mode is switched off. In this case, the power at the heating spiral remains constant and equal to the value at which the stabilization was attained.

The best variant is such in which the calorimeter is calibrated directly before the microwave-energy measurement and immediately after it. Note that the calibrating-pulse energy must be as close to the microwave-radiation pulse energy as possible. During the calibration and microwave-energy measurement, it is necessary to take a possible disturbance of the heat-exchange conditions, which is caused by a change in the state of the environment (e.g., as a result of a draught or enabled ventilation), into account. It may introduce a significant error into the measurement results and is displayed in the form of a distortion in the signal top, its rise or fall. Figure 6 shows a signal shape with a pronounced flat top, which is close to a regular form.

The operation with the calorimeters showed that in contrast to [3], the use of industrially pure ethanol as the working fluid does not provide the required stabilization of the device evidently because of its insufficiently high electrical conductivity. Therefore, an experimentally selected mixture of ethanol, distilled water, and salicylic acid with the following mass composition is used in the described calorimeters: distilled water, 11.4%; 100% ethanol, 88.1%; and salicylic acid, 0.5%.

The diameter of the apertures of the calorimeters’ absorbing loads is ~500 mm. The range of the measured microwave energy is 5–500 J. Some other characteristics are listed in the table.

In draughts are absent and ventilation is switched off, a typical error of the calorimeter calibration was not more than ±10%. Test measurements and measurements in actual experiments, in particular, in [9, 10], showed that the calorimeters make it possible to quickly obtain a large amount of experimental data on the energy of high-power microwave pulses and taking their envelope into account, to reliably determine the microwave-radiation power.

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