doi: 10.56761/EFRE2024.S3-O-007703

Disked-shaped wide-aperture absorbing loads of liquid calorimeters for high-power microwave pulses energy measurement

A.I. Klimov, V.Yu. Konev*

Institute of High Current Electronics SB RAS, Tomsk, Russia
klimov.1955@inbox.ru

Abstract. The possibility of using caprolon and polycarbonate as alternative materials to high-density low-pressure polyethylene in the manufacture of wide-aperture absorbing loads of liquid microwave calorimeters by numerical simulation using the CST Microwave Studio software package was investigated. The dependences on frequency of the reflection coefficients from ribbed and flat input windows of the loads, the absorption coefficients in the materials of the input windows, as well as in the working fluid of the loads of microwave power were calculated, which makes it possible to determine the correction factor for the underestimated measured microwave energy in the case of caprolon and polycarbonate. The possibility of using wide-aperture absorbing loads with a flat input windows to measure the energy of high-power microwave pulses of microwave oscillators with a fixed carrier frequency was demonstrated.

Keywords: high-power microwave pulses, liquid calorimeters, wide-aperture absorbing loads, caprolon, polycarbonate, high-density low-pressure polyethylene.

1. Introduction

Disk-shaped wide-aperture absorbing loads are used in liquid calorimeters [1–6], which have proven to be an effective devices for measuring the energy of high-power microwave pulses [7]. The operation of the calorimeters is based on increasing the volume of working fluid (usually 95% ethyl alcohol) filling the load upon absorption the energy of a microwave pulse. The calorimeters with manual [1–4] and electronic [5, 6] controls are used. The material most suitable for the manufacture the loads input windows is high-density low-pressure polyethylene (HDPE). This material has a very low dielectric loss tangent [8], so that the absorption of microwave energy in the input load window can be practically neglected, and has the required chemical resistance to ethyl alcohol. Practice [5, 6] has shown that the modulus of elasticity of the HDPE (~1 GPa) is quite sufficient for stable operation of the load in the sense of restoring its initial geometry, which changes as a result of an increase in the volume of the working fluid in each act of the calorimeter calibration or microwave energy measurement. To obtain a low reflection coefficient of microwaves from the load input window and maximum absorption of microwave energy in the working fluid, the load geometry is optimized in numerical simulation. A wide operating band with a low reflectance of microwaves can be obtained using a ribbed input window [5, 6]. The design of a wide-aperture absorbing load with a flat input window is known [2].

2. Alternative materials, numerical simulation

To expand the design possibilities when developing calorimeters with wide-aperture absorbing loads, it is of interest to study, in addition to polyethylene, other plastics for the manufacture the loads. In this work, in numerical simulation using the CST Microwave Studio software package, the possibility of using caprolon and polycarbonate as materials alternative to polyethylene was investigated. These materials have the chemical resistance and elasticity necessary for the load operation. The simulated load geometry with a ribbed input window is shown in Fig. 1, and load with a flat window presented in Fig. 2.

Tables 1 and 2 show the frequency ranges in which the simulation was performed, as well as the geometric dimensions of the loads. The geometric dimensions of the loads with ribbed input windows for all three specified materials were the same. These dimensions were determined during optimization with polyethylene. Within the framework of this work, only the effect of using other materials (caprolon and polycarbonate) was studied.

In the case of loads with flat input windows, optimizations were performed, in which the possibility of obtaining a minimum reflection coefficient with maximum absorption of microwave power in the working fluid in a certain frequency range was studied.

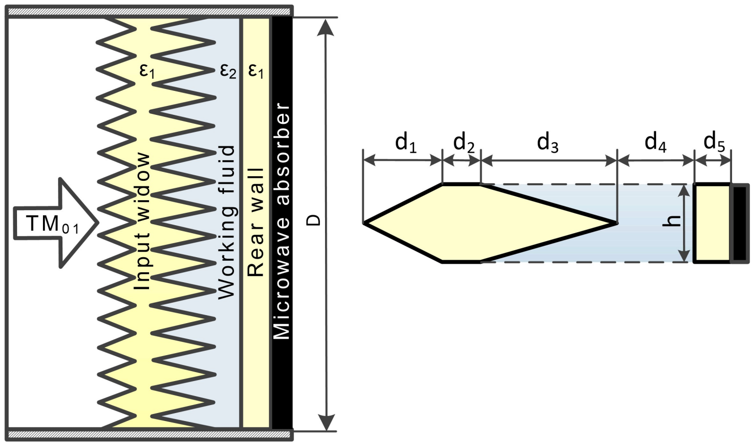

Fig. 1. Simulated geometry of a wide-aperture absorbing load with a ribbed input window.

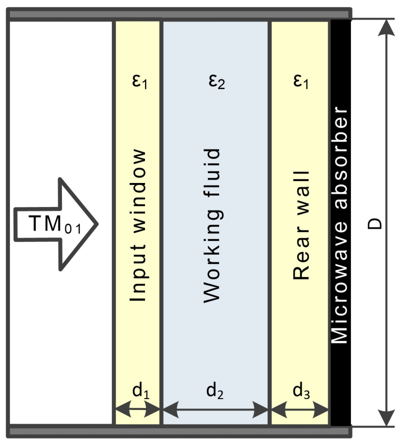

Fig. 2. Simulated geometry of a wide-aperture absorbing load with a flat input window.

Table 1. Geometric dimensions of loads with ribbed input window.

f, GHz	D, mm	d_1, mm	d_2, mm	d_3, mm	d_4, mm	d_5, mm	h, mm
1–3	600	40	20	70	40	25	40
2.5–3.5	600	35	10	35	10	25	20
9–11	200	15	23	10	30	25	10

Table 2. Optimized load parameters with flat input window.

f, GHz	D, mm	Caprolon			Polycarbonate			Polyethylene		
		d_1, mm	d_2, mm	d_3, mm	d_1, mm	d_2, mm	d_3, mm	d_1, mm	d_2, mm	d_3, mm
1–2	600	35	45	25	30	45	25	40	45	25
2–4	600	13.3	45	25	13.3	45	25	16.6	45	25
9–11	200	12.6	45	25	12.3	45	25	14.7	45	25

Calculations were performed for circular waveguides with ideally conducting walls. Each load was a three-layer dielectric–alcohol–dielectric medium. The TM_{01} wave was inputted into the waveguide. Ethyl alcohol with a concentration of 95 % was specified as the working fluid. Its dielectric constant and loss tangent (Fig. 3) were calculated based on data from [9] using the Debye formula. The dielectric constants and loss tangents of caprolon and polycarbonate (Fig. 4) were taken from [10]. The dielectric constant and loss tangent of polyethylene were assumed to be independent of frequency: ε' was 2.25, and tan delta was 10^{-4}.

The thickness of the working fluid was sufficient for almost complete absorption of microwave power. At the end of the waveguide, the condition for complete absorption of the remaining power passed through the load was set. The division of the computational domain has been optimized. For each load, an electrodynamic calculation was performed the structure of electric and magnetic fields established during the microwave pulse and the power reflected from the input window, as well as the power absorbed in the input window and in the working fluid, normalized to the incident power.

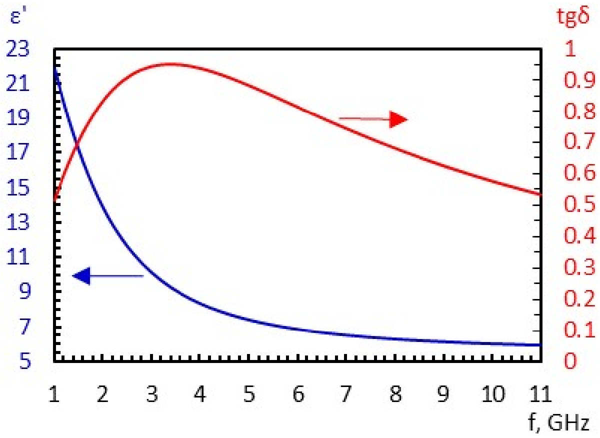

Fig. 3. Dependences of dielectric constant and loss tangent of ethyl alcohol on frequency.

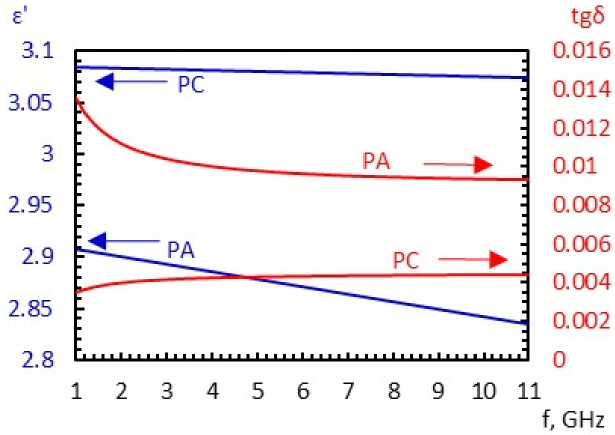

Fig. 4. Dependences of dielectric constants and loss tangents of caprolon (PA) and polycarbonate (PC) on frequency.

3. Results of simulation

Figs 5–7 show the results of simulation the absorbing loads with ribbed input windows, and Figs 8–10 present the results for the loads with flat windows.

3.1. Absorbing loads with ribbed input windows

Analysis of the dependencies shown in Figs 5–7 shows that absorbing loads with a ribbed input window have a weak dependence of the microwave power absorbed in the working fluid on frequency. The dependences of the coefficients of microwaves absorption in the input window and the reflection of microwave power from the window are also weakly expressed. This determines the broadband properties of the loads. The use of calorimeters with loads that have ribbed input windows is advisable in the case when it is necessary to perform measurements with microwave oscillators operating at different carrier frequencies.

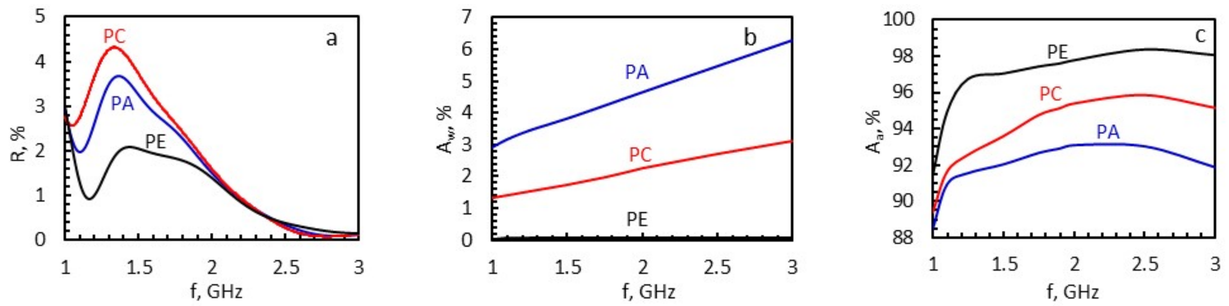

Fig. 5. Frequency dependences in the range of 1–3 GHz of reflection from the input window (a), absorption in the input window (b) and absorption in the working fluid (c) of microwave power for loads with a ribbed input window made of caprolon (PA), polycarbonate (PC) and polyethylene (PE).

The most suitable material undoubtedly is polyethylene. For the loads with a ribbed polyethylene input window the absorption of microwaves in the window can be practically neglected. In this case, the absorption coefficient of microwave power in the working fluid can be the highest and approaching to 100% (Fig. 7c). The higher absorption coefficient of microwaves in the input window in the case of caprolon and polycarbonate (Figs 5b–7b) is due to the higher loss tangent of these materials. However, analysis of the dependencies for caprolon and polycarbonate shows that the underestimation of the power absorbed in the working fluid due to its absorption in the input window is not dramatically large and can be taken into account by a correction factor obtained based on numerical simulation for a specific load.

The higher reflection coefficient for caprolon and polycarbonate at low frequencies (Fig. 5a) may be due to the less than optimal shape of the input windows. The fact that the reflection coefficient for caprlon and polycarbonate can be comparable to that for polyethylene is shown in Figs 6a and 7a. From Fig. 7a it follows that all three reflection coefficients can be less than 1%.

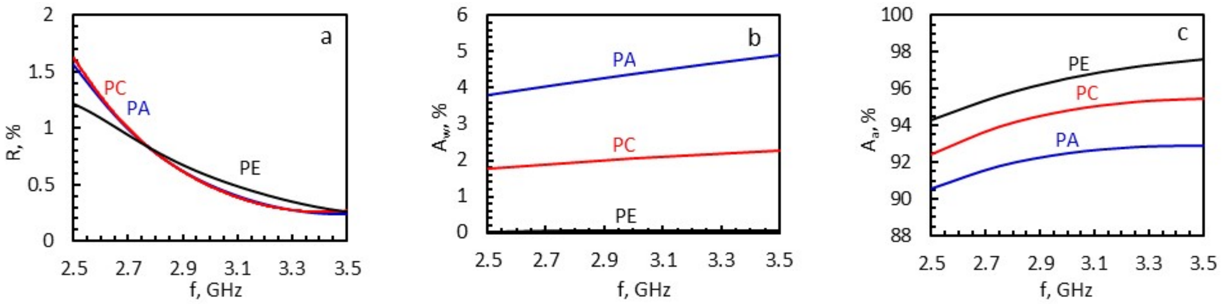

Fig. 6. Frequency dependences in the range of 2.5–3.5 GHz of reflection from the input window (a), absorption in the input window (b) and absorption in the working fluid (c) of microwave power for loads with a ribbed input window made of caprolon (PA), polycarbonate (PC) and polyethylene (PE).

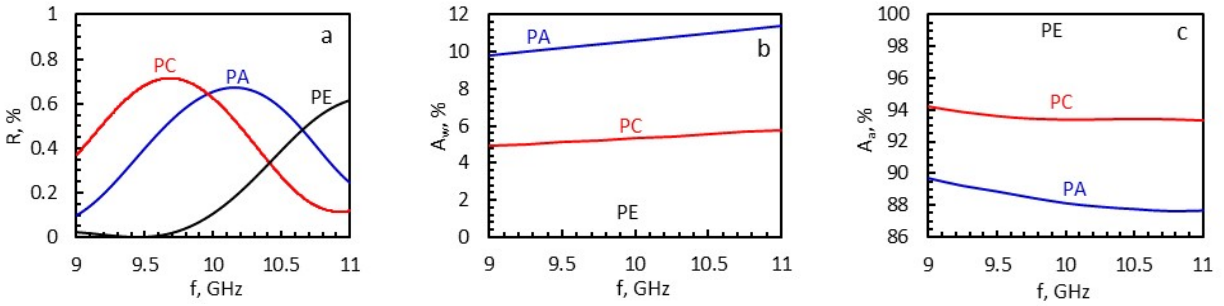

Fig. 7. Frequency dependences in the range of 9–11 GHz of reflection from the input window (a), absorption in the input window (b) and absorption in the working fluid (c) of microwave power for loads with a ribbed input window made of caprolon (PA), polycarbonate (PC) and polyethylene (PE).

3.2. Absorbing loads with flat input windows

Analysis of the dependencies shown in Figs 8–10 shows that absorbing loads with a flat input window have pronounced dependences of the reflection and absorption coefficients of microwave power in the working fluid on frequency and are not broadband. The use of calorimeters with such loads can be justified in the case of microwave oscillators with a fixed carrier frequency and an operating bandwidth of ~100 MHz or less, i.e., with a microwave pulse lenth of ~10 ns or more. From Figs 8a–10a it follows that the reflection coefficient in the case of polyethylene in all three ranges is higher than that of caprolon and polycarbonate. This is due to the fact that the imaginary part of the dielectric constant (and loss tangent) of polyethylene is significantly lower than that of caprolon and polycarbonate. Therefore, matching with a medium with strong losses (large imaginary part of the dielectric constant, large loss tangent), such as ethyl alcohol, is more difficult. However, as Fig. 10a, at high frequencies the reflection coefficient for all three materials can be quite low.

Absorption in a flat input window in the case of caprolon and polycarbonate is significantly more than that of polyethylene (Figs 8b–10b). The absorption of microwaves by a flat polyethylene window can be neglected. However, Figs 8c–9c suggest that polyethylene may not be the preferred material in the case of flat input windows. Higher microwave power absorption coefficients in the working fluid can be obtained with caprolon and polycarbonate.

Microwaves absorption underestimation can be taken into account in the same way as for loads with ribbed windows by a correction factor based on a numerical simulation the load.

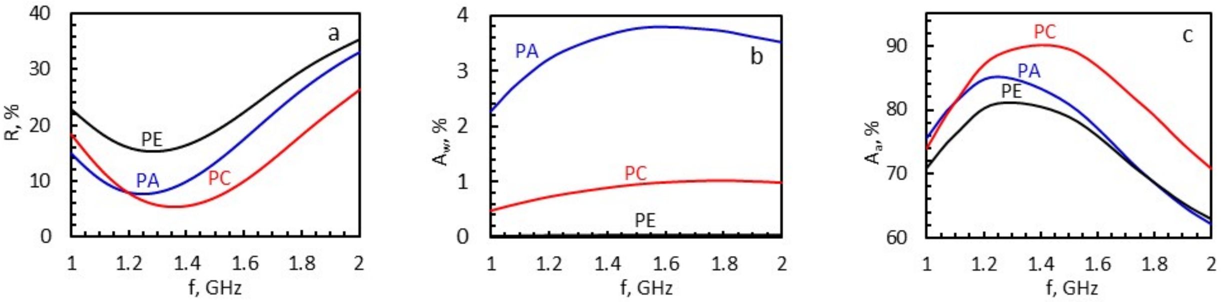

Fig. 8. Frequency dependences in the range of 1–2 GHz of reflection from the input window (a), absorption in the input window (b) and absorption in the working fluid (c) of microwave power for loads with a flat input window made of caprolon (PA), polycarbonate (PC) and polyethylene (PE).

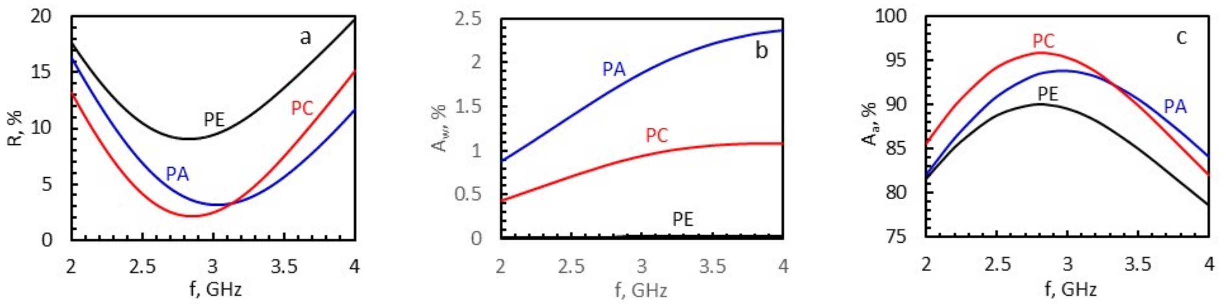

Fig. 9. Frequency dependences in the range of 2–4 GHz of reflection from the input window (a), absorption in the input window (b) and absorption in the working fluid (c) of microwave power for loads with a flat input window made of caprolon (PA), polycarbonate (PC) and polyethylene (PE).

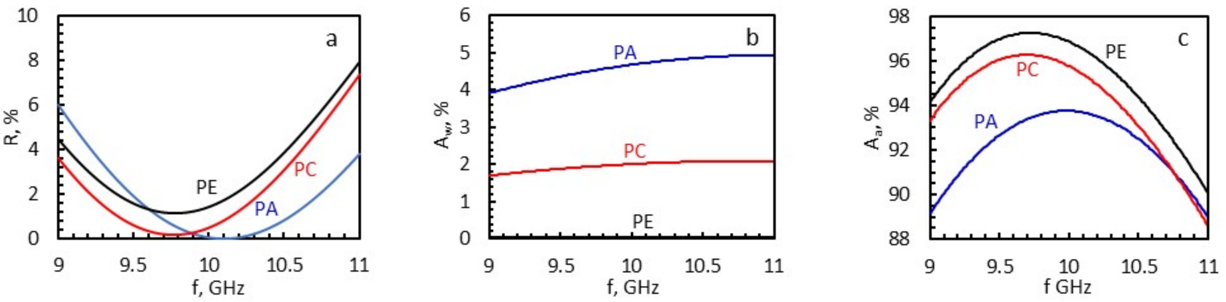

Fig. 10. Frequency dependences in the range of 9–11 GHz of reflection from the input window (a), absorption in the input window (b) and absorption in the working fluid (c) of microwave power for loads with a flat input window made of caprolon (PA), polycarbonate (PC) and polyethylene (PE).

4. Conclusion

The performed numerical simulation showed the possibility of using caprolon and polycarbonate as materials alternative to high-density low-pressure polyethylene for the manufacture the wide-aperture absorbing loads of liquid calorimeters, both with ribbed and flat input windows.

The problem of underestimating the absorbed microwave power can be overcome by using a correction factor obtained based on numerical simulation of the design of a specific load. Flat input window load designs, suitable for fixed carrier frequency oscillators, can be easier to manufacture and less expensive than ribbed input window loads.

Acknowledgement

The work was carried out within the framework of the state assignment of the Ministry of Science and Higher Education of the Russian Federation (topic No. FWRM-2021-0002).

5. References

[1] A.G. Shkvarunets, A broadband microwave calorimeter of large cross section, *Instruments and Experimental Techniques*, vol. **39**(4), 535, 1996.

[2] A.I. Klimov, O.B. Kovalchuk, V.V. Rostov, and A.N. Sinyakov, Measurement of parameters of X band high power microwave superradiative pulses, *IEEE Transactions on Plasma Science*, vol. **36**(3), 661, 2008, doi: 10.1109/TPS.2008.917300

[3] H. Ye, H. Ning, W. Yang, Y. Tian, Z. Xiong, M. Yang, F. Yan, and X. Cui, Research on calorimeter for high-power microwave measurements, *Review of Scientific Instruments*, vol. **86**, 124706, 2015, doi: 10.1063/1.4938160

[4] PLASMAIOFAN Science and Technology Center: Products: Microwave pulse calorimeter [online]; http://www.plasmaiofan.ru/prod.html#Microwave.

[5] P.V. Vykhodtsev, A.A. Elchaninov, AI. Klimov, O.B. Kovalchuk, and E.M. Totmeninov, Liquid calorimeters for measuring the energy of high-power microwave pulses, *Instruments and Experimental Techniques*, vol. **58**(4), 510, 2015, doi: 10.1134/S0020441215030264

[6] P.V. Vykhodtsev, A.V. Gunin, A.I. Klimov, V.V. Rostov, and R.V. Tsygankov, An aperture calorimeter with an optical sensor for measuring the energy of high-power microwave pulses, *Izvestiya vysshikh uchebnykh zavedenii. Fizika*, vol. **59**(9/3), 53, 2016.

[7] J. Benford, J.A. Swegle, and E. Schamiloglu, *High power microwaves*. Oxford: Taylor & Francis Group, 2016.

[8] I.V. Lebedev, *Tekhnika i pribory SVCh. T.1*. Moskva: Vysshaya shkola, 1970.

[9] J.-Zh. Bao, M.L. Swicord, and C.C. Davis, Microwave dielectric characterization of binary mixtures of water, methanol, and ethanol, *Journal of Chemical Physics*, vol. **104**(12), 4441, 1996, doi: 10.1063/1.471197

[10] A.I. Klimov, and V.Yu. Kozhevnikov, Numerical optimization of aperture absorbing loads of liquid calorimeters for high-power microwave pulses, *Russian Physics Journal*, vol. **60**(8), 1319, 2017, doi: 10.1007/s11182-017-1215-3