INTENSIFIED DRYING OF CAPACITORS WITH LIQUID INTERMEDIATE HEAT CARRIER

I. F. Pikus, N. A. Gudko, A. G. Voskhodov, and S. I. Zhukov

UDC 621.319.4

The article presents the results of experimental investigations of a highly intensive method of vacuum drying power capacitors with heat supply from a liquid intermediate heat carrier.

In a previous article [1], the thermophysical and technological foundations, and also the technicoeconomic advantages, of a new and highly efficient method of drying power capacitors, assembled into housings, with individual evacuation and heat supply from a liquid intermediate heat carrier [2] were explained. The results of experimental and pilot tests, carried out by the Institute of Heat and Mass Transfer, Academy of Sciences of the BSSR, and NIPKTIK on large laboratory stands and a prototype installation USPK-1 [3], showed that when this method is used, the time of thermovacuum treatment of power capacitors can be approximately halved while the quality of the drying is good. The use of this method in practice entails certain technical difficulties and requires a much more complicated design of the vacuum pump system of the dryers. However, if the intermediate heat carrier is a liquid that is compatible in its physicochemical, electrophysical, and technological properties with capacitor tissue and the liquid impregnating dielectric, or which is even more rational, if the heat carrier is the impregnant, then there is no need of individual evacuation of capacitors that are to be dried, at least at the stage of their heating and drying in deep vacuum. The principal foundations, technological, and technical and economic substantiation of this simplified variant of the new method of drying power capacitors were established at the Institute of Heat and Mass Transfer, Academy of Sciences of the BSSR, as a continuation of work [1, 2]. From the point of compatibility with capacitor tissue, and also of correspondence to the technological and thermophysical properties of a number of the most frequently used liquid dielectrics that can function as intermediate heat carriers, there are synthetic electrically insulating liquids, viz., chlorinated diphenyls, in particular, trichlorodiphenyl (TCD). This liquid dielectric as heat carrier is marked by heat resistance, relatively low viscosity (in the temperature region above 100°C), and also by relative explosion- and fireproofness [4, 5]. Therefore in a fairly wide temperature range (from the flash point to the boiling point) liquid TCD does not ignite, i.e., this substance is not liable to catch fire and burn on its own when ignited from outside. In regard to the conditions of thermovacuum treatment of unsealed capacitors, a very important characteristic of TCD as heat carrier is its volatility, which is evaluated according to such parameters and properties as evaporability, boiling point, and vapor pressure.

Special investigations showed [4] that up to 100°C, evaporability changes very little, in the interval between 100 and 150°C evaporability increases to 2%, and at 180°C evaporability attains 10% (evaporability was determined by the loss of weight of a 20-gram weighed batch from a weighing bottle with 44 mm diameter within 6 h). In the temperature range corresponding to the recommended optimum drying regime of paper capacitors (125-145°C), the saturated-vapor pressure of TCD does not exceed 1-4 mm Hg. The boiling point of TCD at normal atmospheric pressure is 322°C. All this confirms that TCD has thermophysical properties that make it perfectly suitable for use as heat carrier in the process under examination.

To verify whether it is possible in principle to intensify the drying of unsealed power capacitors by using the method of heating with a liquid heat carrier washing the casings of the drying capacitors, experimental drying and impregnation of series-produced power capacitors were carried out on an experimental stand of the technological laboratory of NIPKTIK by a specially devised method. The investigated objects were paper capacitors size II (sections of these capacitors were made of low-loss capacitor tissue type KON-1 with density 0.8 g/cm^3 and thickness of the sheet 12 μm, 280 mm wide; 4 sheets between plates, 45 loops). A diagram of the experimental installation is shown in Fig. 1.

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the BSSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 38, No. 1, pp. 71-77, January, 1980. Original article submitted April 16, 1979.

0022-0841/80/3801-0049$07.50

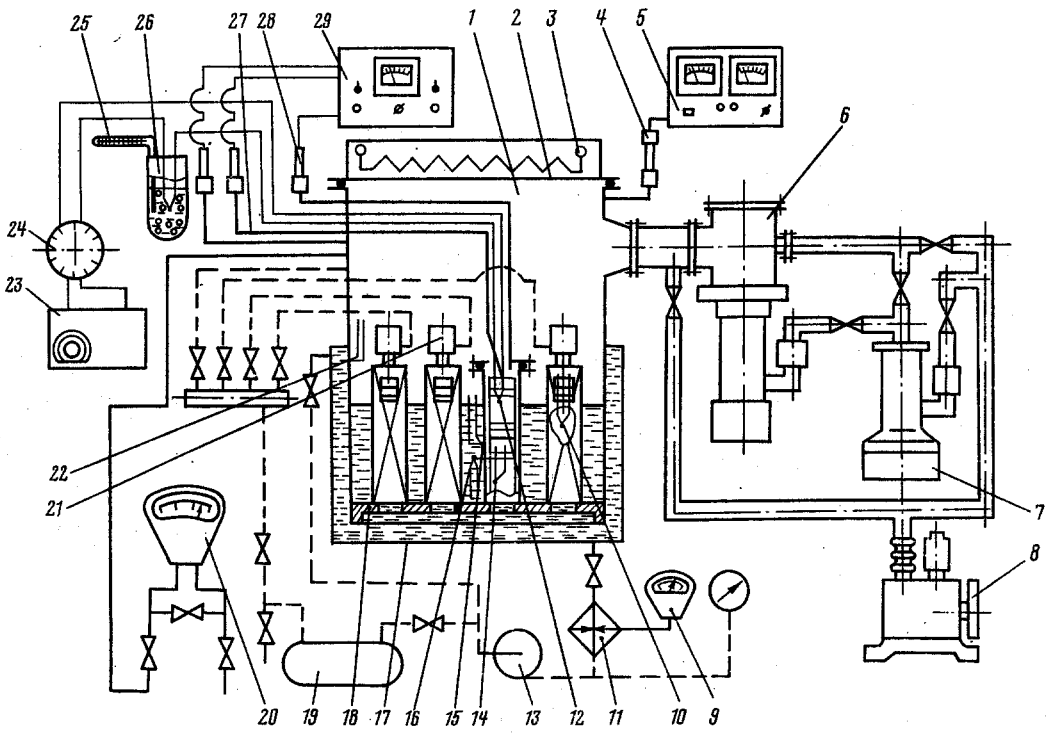

Fig. 1. Basic diagram of the experimental installation.

The vertical rectangular vacuum chamber 1 for drying and impregnating capacitors with a volume of 0.4 m^3 has a removable lid 2 with inspection windows and a panel for connecting thermocouples and pressure transducers to the measuring apparatus. The chamber is provided with a thermostating jacket 17 through which the primary heat carrier circulates. Thermostating of the lid is ensured by the built-in electric heater 3. Circulation of the primary heat carrier (which is TCD) is effected by pump 13 type TsNG-70-2, and heating by the electric heat exchanger 11 whose system of automatic control is set with the aid of regulator 9 for stable maintenance of the specified temperature (with an accuracy of ±2°C) of the heat carrier fed to the thermostating jacket of the chamber.

The vacuum-pump system of the installation contains the mechanical vacuum pump 8 type VN-1MG, booster pump BN-5S (7), and the high-vacuum oil vapor pump (6) VA-2-3PR (in our experiments, this last-named apparatus was used as condenser trap for TCD vapor and steam at the stage of atmospheric heating and preliminary vacuum drying).

Pipes from the manifold of the supply pipe from reservoir 19 for impregnating liquid are inserted into the wall of the drying chamber (the system for cleaning and circulating the impregnating liquid is not shown in the diagram).

The experimental drying process was checked by a process devised at the Institute of Heat and Mass Transfer, Academy for Sciences of the BSSR, on the basis of the results of a complex investigation of heat and mass transfer in thermovacuum treatment of paper power capacitors using a control capacitor provided with thermocouples and local internal-pressure transducers in the central zone of the center section of the stack [6]. In the experiments, the following parameters were recorded: the temperature at the geometric center of the wide lateral wall of the control capacitor (thermocouple 15); the temperature inside one of the experimental capacitors and inside the control section of the lower and upper stacks of the control capacitor (thermocouples 10, 14, 12, respectively); the temperature of the liquid intermediate heat carrier between the capacitors in the central zone of the chamber (thermocouple 16); the wall temperature on the inside of the drying chamber (thermocouple 22); the residual pressure in the chamber (the impulse pipe of one of the transducers was inserted into the control capacitor); the local internal pressure in the central zone of the center section of the stack of the control capacitor.

The temperature at the control points was measured by copper-constantan thermocouples with cold junctions (situated in the thermos flask 26 containing melting ice) together with switch 24 type PMT and potentiometer (23) PP-63. The temperature of the cold junctions was checked by laboratory thermometer 25

TABLE 1. Cyclogram of the Experimental Process of Drying Capacitors*

Drying stage	Temp. of wall of control capacitor, °C	Residual pressure in chamber, mm, Hg	Duration, h	Remark
Heating at atmospheric pressure	20—135	atm.	8	Temp. of intermediate heat carrier 50-145°C
Lowering of pressure and preliminary vacuum drying	132—138	atm. —12	13	Pump VN-1MG operates
Pouring out of intermediate heat carrier and evacuation of system	127—129	atm. —0,5	3	
Final drying in deep vacuum	129—138	0,5—0,007	24	Pumps VN-1MG, BN-5S operate
Cooling capacitors	138—66	0,005	14	The same
Pouring impregnant (TCD) on capacitors	66—60	0,005	1	Temp. of impregnating TCD 54°C
Impregnation of capacitors	60—53	0,002	3	

*The total duration of the process of thermovacuum treatment and impregnation of the capacitors was 66 h.

graduated in 0.1°C. The residual pressure in the drying chamber (in the housing of the control capacitor) and the local internal pressure in the central section of the stack of the control capacitor were measured by vacuum gauge 29 type VSB-1 together with the manometric transducers (28) MT-6. These were connected by button-shaped seals to a special bracket mounted on the wall of the drying chamber (the design of the system for measuring the internal pressure in the control capacitor is described in more detail in [6]). Besides that, the residual pressure in the chamber was measured by the differential micromanometer 20 type OM-2 (in the range 30-1 mm Hg) and the vacuum gauge (5) VIT-2 operating together with the manometer lamp (4) LT-2 (this instrument was used in the region of pressures below 1 mm Hg).

The experimental process of thermovacuum treatment of capacitors by the investigated method was carried out in the following manner.

Four power capacitors, including the control capacitor, were assembled in their casings, placed on support 18 made of angle iron situated in the drying chamber, and fixed to prevent them from rising to the surface of the liquid heat carrier. The thermocouples and the impulse pipe 27 of the pressure transducers were reliably connected by plug connections. The pouring vessels 21 were placed in the pouring holes of the capacitors, the vessels were connected by hoses to the pouring system of the impregnant, and TCD with an initial temperature of 50°C was poured into the chamber up to a level 200 mm below the capacitor lids. Then the chamber was closed, the heating and circulation system of the primary heat carrier was switched on, and the temperature of the heat carrier was raised to 140-145°C. Heat transfer from the walls to the intermediate heat carrier poured into the chamber (and heating of the capacitors immersed in it) proceeded by natural convection.

The experimental drying process was carried out in a regime presented in Table 1 and Fig. 2.

It can be seen from the thermograms in Fig. 2 that the capacitors are heated fairly intensively when heat is supplied by the liquid intermediate heat carrier, and after 8 hours of heat treatment at atmospheric pressure the temperature in the control attained 108-116°C. It should be noted that the duration of this stage was somewhat affected by thermal inertia, well visible in the cyclogram, and by the limited calorific power of the experimental installation, and also the fact that heat is supplied to the capacitors by natural (and not forced) convection. One hour after evacuation of the drying chamber had begun, the temperature of the dielectric was maximally reduced by 30°C, and then for 6 hours it increased to 130-135°C. It is worth noting that the temperature at all control points of the chamber at the stage of preliminary vacuum drying of the capacitors was almost completely evened out, and also that fairly simple and accurate temperature regulation of the capacitor insulation is possible by correspondingly changing the temperature of the intermediate heat carrier. The mentioned limiting value of residual pressure in the chamber at this stage of thermovacuum treatment (12 mm Hg) was selected on the basis of the condition of preventing intense evaporation of the intermediate heat carrier (TCD) selected to 130-142°C and the removal of its vapor into the vacuum-pump system. A very important practical result of the experimental process was the establishment of the fact that, as direct measurements showed, removal of the vapor of the intermediate heat carrier (TCD) from the drying chamber in

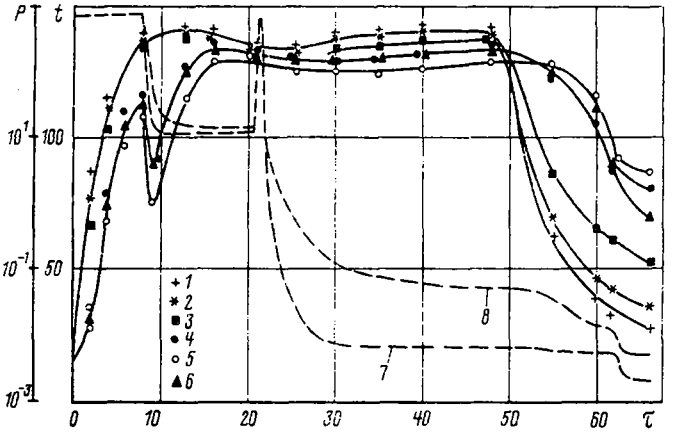

Fig. 2. Curves of the kinetics of changes in temperature and residual pressure at the control points: 1, 2, 3, 4, 5, 6) temperature recorded by thermocouples 22, 16, 15, 14, 12, 10, respectively; 7, 8) pressure in the casing of the control capacitor and internal pressure in the central zone of the center control section of the stack, respectively. P, mm Hg; t, °C; τ, h.

the course of 21 h of atmospheric heating and preliminary vacuum drying was small and did not exceed 1-2 liters (the estimate was made on the basis of the amount of condensate in the trap, and also of the change in the level of heat carrier in the drying chamber). These data confirmed experimentally that the investigated drying method is technically substantiated and that TCD is an efficient intermediate heat carrier. After atmospheric air was admitted to the system, the liquid intermediate heat carrier had been removed from the drying chamber, and the trap emptied, the chamber was again evacuated, and the stage of final drying of the capacitors in deep vacuum began. After 30 h of heat treatment, the residual pressure in the drying chamber was maintained stably at the level of 0.007 mm Hg until the cooling stage began, after which the residual pressure dropped to 0.005 mm Hg. The temperature level of the process was maintained at 140°C; the temperature of the capacitor dielectric in different zones of the control capacitor was practically stabilized during the last 18 h of final vacuum drying and amounted to 129-133°C. As regards one of the principal criteria of terminating the process of vacuum drying of capacitors, viz., the residual internal local pressure in the dielectric, the recommended permissible level of this parameter (on the order of magnitude 0.1 mm Hg [7]) was already attained after 35-40 h of heat treatment of the capacitors, and during the last 5 hours this pressure remained unchanged and equal to 0.05 mm Hg. The total duration of atmospheric heating and vacuum drying of capacitors in this experimental process (including temporary interruption of the process for admitting atmospheric air to the drying chamber to remove the liquid intermediate heat carrier from it and to empty the trap) was 48 hours. Potting and impregnation of the capacitors were carried out at 66-53°C. After the experimental process was finished, three capacitors were checked for airtightness and sent for electrical testing in accordance with GOST 1282-72. The test results confirmed the good quality of the drying. In addition to the evaluation of the quality of the drying, the data of the electrical tests of the capacitors were also used to determine the depth of thermal aging of the capacitor dielectric from the magnitude of the relative degrees of polymerization (SP/SP_0) of paper specimens taken from two sections of the control capacitor after drying. These analyses showed that the degree of depolymerization of the capacitor dielectric in the investigated experimental process did not exceed 12%.

Thus, the experimental process carried out under experimental conditions with ordinary capacitors confirmed the correctness of the principal foundations and the technical feasibility of the suggested simplified variant of the highly efficient method of drying unsealed power capacitors with heat supplied by a liquid intermediate heat carrier that is technologically compatible with the dielectric of the capacitor and the impregnant.

This new technology can be introduced on the basis of existing vacuum dryers which have to be somewhat modified and provided with a system of supplementary heating and circulation of liquid intermediate heat carrier.

LITERATURE CITED

1. I. F. Pikus and N. A. Gudko, Izv. Akad. Nauk BSSR, Ser. Fiz. Energ. Nauk, No. 2 (1978).
2. I. F. Pikus and N. A. Gudko, Inventor's Certificate No. 593260, Byull. Izobret., No. 6 (1978).
3. N. A. Gudko, I. F. Pikus, et al., Inventor's Certificate No. 658611. Byull. Izobret., No. 15 (1979).
4. Yu. I. Dmitrenko et al., Electrotekh. Prom. Elektrotekh. Mater., No. 10 (1977).
5. N. A. Andrianov and V. V. Skipetrov, Synthetic Liquid Dielectrics [in Russian], Gosénergoizdat, Moscow–Leningrad (1962).
6. I. F. Pikus, N. A. Gudko, A. N. Tarasov, and Ya. S. Raptunovich, Elektrotekh. Prom. Ser. VVA, No. 3 (1977).
7. I. F. Pikus, N. A. Gudko, A. G. Voskhodov, and S. I. Zhukov, Elektrotekh. Prom. Ser. VVA, No. 8 (1977).

NONEQUILIBRIUM THERMODYNAMICS OF MONODISPERSE SUSPENSIONS

G. P. Yasnikov

UDC 536.70+532.135

The internal-energy and entropy balance equations of monodisperse suspensions are averaged over the statistical ensemble of possible spatial configurations of solid spherical particles.

The present work is based on the method of statistical averaging of the balance equations, valid for a liquid and at the level of individual particles, developed in [1, 2].

For the local physical quantities $G(t, \vec{r}, C_N)$ appearing in these equations, which depend on hydrodynamic – $\vec{r}$ – and phase – $C_N(\vec{r}^{(1)}, \ldots, \vec{r}^{(N)})$ – variables (N is the number of particles), the average over the distribution function $\Phi(t/C_N)$ is introduced.

The commutation properties of the averaging operator constructed in this way allow equations describing the behavior (on average) of continua which model the phases of a suspension to be obtained.

The account below is based on the matrix formalism introduced in [3]. The explicit form of the matrices and the operations involving them which are used in the present work are given in the Appendix. As in [3], consideration is restricted to a mixture of a liquid with solid spherical particles without diffusion, chemical reactions, or phase transitions. The phase materials are assumed to be incompressible and rotation of the particles insignificant.

"Microscopic" balance equations for the mechanical and total energy valid in the liquid and inside the particles may be written in the form [4]

$$D\frac{d}{dt}\left(\frac{1}{2}V^2+\psi\right)=-\vec{\nabla}\cdot(\Sigma\cdot\vec{V})+\Sigma:\vec{\nabla}\vec{V}, \tag{1}$$

$$D\frac{de}{dt}=-\vec{\nabla}\cdot(\Sigma\cdot\vec{V})-\vec{\nabla}\cdot\vec{J}_q. \tag{2}$$

After multiplying Eqs. (1) and (2) by Θ – Eq. (A.1) – and averaging, the following relations are obtained:

$$\langle \Theta D\frac{d}{dt}\left(\frac{1}{2}V^2+\psi\right)\rangle=-\langle \Theta\vec{\nabla}\cdot(\Sigma\cdot\vec{V})\rangle+\langle \Sigma:(\vec{\nabla}\vec{V})\,\Theta\rangle, \tag{3}$$

$$\langle \Theta D\frac{de}{dt}\rangle=-\langle \Theta\vec{\nabla}\cdot(\Sigma\cdot\vec{V})\rangle-\langle \Theta\vec{\nabla}\cdot\vec{J}_q\rangle. \tag{4}$$

S. M. Kirov Ural Polytechnic Institute, Sverdlovsk.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 38, No. 1, pp. 78-84, January, 1980. Original article submitted March 5, 1979.

0022-0841/80/3801-0053$07.50