and constant-pressure specific heats, respectively, of the mixture referred to volume; τ_{qk}, τ_{fk}, temperature and velocity relaxation times, respectively, of the k-th group of solid particles; t, times; ω, frequency in the Fourier series expansion; $i = \sqrt{-1}$; α_h, differential Joule–Thompson coefficient (adiabatic throttle effect); N, number of groups of particles in the mixture.

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TEMPERATURE–DENSITY PARAMETERS OF FREON-13 ON THE SATURATION LINE

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Experimental data of a high degree of accuracy are presented on the temperature–density parameters of Freon-13 on the saturation line in the density range of $(0.08246\text{–}1.6061)\cdot 10\ \mathrm{kg/m^3}$.

The investigation of the temperature–density parameters of argon [1], Freon-23 [2], and Freon-13B1 [3] on the saturation line by the method of quasistatic thermograms has established the possibility of using this method to study the vapor and liquid branches of the saturation line in a wide region of temperatures, including those in the vicinity of the critical point. Investigations of Freon-13 were made on the same installation to obtain more precise data on the saturation line and to test the linear diameter rule and the possibility of describing the temperature–density parameters following the hypothesis of scale similarity.

The limiting error of the density data on the saturation line is from 0.03% for $\rho \approx 1.6\ \mathrm{g/cm^3}$ to 0.07% for the critical density on the liquid branch and from 0.07% for the critical density to 0.10% for the lowest densities on the vapor branch. The temperature of the phase transition is determined from the scale of the MPTSh-68 with an error of ±0.01°K, while its reproducibility is no worse than ±0.002°K.

The purity of the Freon-13 investigated was 99.99%, so that the sample was not subjected to any additional purification.

The experimentally obtained data on the temperature–density parameters of Freon-13 are presented in Tables 1 and 2.

The values of the critical temperature T_c and critical density ρ_c, which are presented in Table 3 in a comparison with data on the critical parameters obtained in the work of other authors, were determined by graphic analysis of the tip of the saturation line.

When a device with one container is used to investigate the temperature–density parameters on the saturation line it is impossible to determine the densities of the liquid and vapor at the same temperature; thus, to test the dependence of the average density $\bar{\rho}$ on the

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TABLE 1. Vapor Branch of Saturation Line

T, °K	$\rho''\cdot 10^{-3}$, kgf/m³	$v''\cdot 10^{3}$, m³/kgf	T, °K	$\rho''\cdot 10^{-3}$, kgf/m³	$v''\cdot 10^{3}$, m³/kgf
255,95	0,08246	12,13	$300,71_2$	0,4144	2,413
270,06	0,1246	8,026	$301,27_0$	0,4438	2,253
292,70	0,2635	3,795	$301,83_8$	0,5022	1,9912
$297,68_5$	0,3326	3,007	$301,95_3$	0,5675	1,7621
$299,63_8$	0,3774	2,650	$301,97_4$	0,5682	1,7599

TABLE 2. Liquid Branch of Saturation Line

T, °K	$\rho'\cdot 10^{-3}$, kgf/m³	$v'\cdot 10^{3}$, m³/kgf	T, °K	$\rho'\cdot 10^{-3}$, kgf/m³	$v'\cdot 10^{3}$, m³/kgf
167,66	1,6061	0,6226	295,63	0,8827	1,1329
192,50	1,5150	0,6601	297,95	0,8363	1,1957
212,38	1,4369	0,6959	$299,52_4$	0,7953	1,2574
232,68	1,3485	0,7416	$300,56_0$	0,7584	1,3186
252,78	1,2477	0,8015	$301,19_8$	0,7250	1,3793
273,17	1,1196	0,8932	$301,72_1$	0,6789	1,4730
280,38	1,0637	0,9401	$301,92_1$	0,6387	1,5657
287,68	0,9886	1,0115	$301,97_3$	0,5987	1,6703
292,56	0,9303	1,0749			

TABLE 3. Values of Critical Temperature and Density of Freon-13

T_c, °K	ρ_c, g/cm³	Lit. source	T_c, °K	ρ_c, g/cm³	Lit. source
301,93	0,581	[4]	301,93	0,5811	[8]
301,97	0,5820	[5]	301,99	0,5530	[9]
302,00	0,5782	[6]	$301,97_4$	0,5810	Present work
302,35	0,5709	[7]			

temperature (diameter) we used the values of $\bar{\rho}$ determined from a smoothed curve (both graphically and analytically). The error in determining the average density does not exceed 0.15% in the entire region of ρ' and ρ'' investigated. The linear dependence on the temperature (linear diameter)

$$\bar{\rho} = 0.5810 + 0.4980\,\tau \tag{1}$$

is satisfied within the limits of this error in the entire investigated region of temperatures of the vapor branch of the saturation line, including the vicinity of the critical point down to $T \leqslant T_c - 0.005$°K.

Taking into account the linear dependence of the average density on the temperature, the densities of the liquid and vapor were found from the equation

$$\bar{\rho} = \rho_c + b\tau + a\tau^{\beta}, \tag{2}$$

which, following the hypothesis of scale similarity [10], can be represented in the form

$$\tilde{\rho} = a\tau^{\beta}\,. \tag{3}$$

The exponent β is determined by graphic analysis of experimental data in the coordinates of $\log\tilde{\rho}$ from $\log\tau$. For $\tau > 0.165$, β equals 0.313 ± 0.003, while for $10^{-4} < \tau < 0.165$ it equals 0.340 ± 0.005. Considering this difference in the values of the exponent, the analytical expressions for describing the two branches of the liquid and vapor saturation line were chosen separately for each region of τ.

For $\tau > 0.165$ the experimental data are described by Eq. (3) with an error not exceeding 0.08%, with $a = 1.03512$ for the liquid:

$$\rho' = 0.5810 + 0.4980\,\tau + 1.03512\,\tau^{0.313}\,. \tag{4}$$

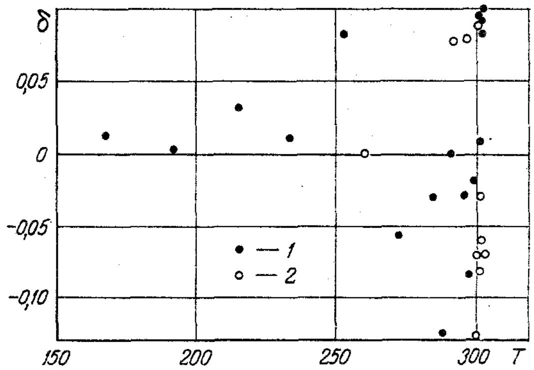

Fig. 1. Departure of calculated values of liquid and vapor densities on saturation line from experimental data (1: liquid; 2: vapor). T, °K; $\delta = [(\rho_{calc} - \rho_{exp})/\rho_{calc}]\cdot 100$, %.

TABLE 4. Density of Freon-13 on the Saturation Line

t, °C	T, °K	$\rho'\cdot 10^{-3}$, kgf/m³	$\rho''\cdot 10^{-3}$, kgf/m³	Deviations in percent from data of [8]	
				δ′	δ″
—106	167,15	1,6076		—0,46	
—102	171,15	1,5934		—0,45	
—98	175,15	1,5791		—0,44	
—94	179,15	1,5647		—0,42	
—90	183,15	1,5500		—0,41	
—86	187,15	1,5352		—0,38	
—82	191,15	1,5201		—0,37	
—78	195,15	1,5049		—0,35	
—74	199,15	1,4894		—0,33	
—70	203,15	1,4737		—0,30	
—66	207,15	1,4577		—0,28	
—62	201,15	1,4415		—0,25	
—58	215,15	1,4249		—0,22	
—54	219,15	1,4081		—0,19	
—50	223,15	1,3909		—0,15	
—46	227,15	1,3733		—0,12	
—42	231,15	1,3553		—0,07	
—38	235,15	1,3368		—0,04	
—34	239,15	1,3179		—0,01	
—30	243,15	1,2984		0,06	
—26	247,15	1,2782		0,12	
—22	251,15	1,2574		0,17	
—18	255,15	1,2358	0,08063	0,24	3,06
—14	259,15	1,2133	0,08995	0,31	1,81
—10	263,15	1,1887	0,10067	0,31	0,94
—6	267,15	1,1620	0,1141	0,24	1,31
—2	271,15	1,1339	0,1290	0,18	1,47
6	275,15	1,1038	0,1459	0,10	1,51
2	279,15	1,0713	0,1651	0,03	1,39
10	283,15	1,0356	0,1876	—0,05	1,28
14	287,15	0,9956	0,2144	—0,13	1,07
18	291,15	0,9490	0,2477	—0,21	0,93
22	295,15	0,8911	0,2925	—0,29	0,99
26	299,15	0,8066	0,3639	—0,31	1,48
28	301,15	0,7273	0,4367	—0,12	2,11

In the region $10^{-4} < \tau < 0.0165$, an equation of the type of (3) gives large deviations from the experimental data. Corrections to the asymptotic equation (3) in the form

$$\tilde{\rho} = a\tau^{\beta} + c\tau^{\beta+\Delta}, \qquad (5)$$

where Δ is a calculated quantity, have been obtained in recent years in a number of reports [11-15] to describe the saturation line.

Equation (5) with Δ = 0.315 (from [13]) best describes the experimental results: The maximum deviation of the calculated from the experimental data does not exceed 0.12% for both the liquid and the vapor branches of the saturation line (Fig. 1). In this case

$$\rho' = 0.5810 + 0.4980\,\tau + 1.07347\,\tau^{0.340} + 0.03530\,\tau^{0.655}, \tag{6}$$

$$\rho'' = 0.5810 + 0.4980\,\tau - 1.07945\,\tau^{0.340} - 0.02660\,\tau^{0.655}. \tag{7}$$

The rms deviation of the values calculated from Eqs. (4), (6), and (7) from the experimental values for the liquid and vapor branches of the saturation line is 0.08%.

When the liquid density is calculated using the coefficients a and c for the vapor the maximum deviation of the calculated results from the experimental ones grows but does not exceed 0.22%. (In the calculations the value of the critical temperature was taken as equal to 301.974°K.)

The values of the temperature–density parameters of Freon-13 on the saturation line, calculated from Eqs. (4), (6), and (7), and their deviations from the calculated values of [8] are given every four degrees in Table 4.

NOTATION

T, absolute temperature of phase transition from two-phase to one-phase state (or vice versa); T_c, critical temperature; ρ', ρ'', densities of liquid and vapor, respectively, on saturation line; ρ_c, density at critical points; $\bar{\rho} = (\rho' + \rho'')/2$, average density; $\tau = (T_c - T)/2$, reduced temperature; $\tilde{\rho}$, parameter of order, equal to $\rho' - \rho_c - b\tau$ for the liquid phase and $\rho_c + b\tau - \rho''$ for the vapor phase.

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