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TRANSPORT COEFFICIENTS OF DECOMPOSITION PRODUCTS OF THE BTS TRANSFORMER OIL[1]

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The paper presents the computed values of electrical conductivity, thermal conductivity and viscosity of products of the BTS transformer oil decomposed by electric arc at temperatures from 1000 to 20 000 K and at pressures from 0.1 to 3 MPa. Some important input data are also presented. The discussion of the calculated results follows.

КОЭФФИЦИЕНТЫ ПЕРЕНОСА ДЛЯ ПРОДУКТОВ РАСПАДА ТРАНСФОРМАТОРНОГО МАСЛА BTS

В работе приведены рассчитанные значения электропроводности, теплопроводности и вязкости продуктов, полученных разложением трансформаторного масла при помощи электрической дуги при температурах от 1000 до 20 000 К и давлениях от 0,1 до 3 МПа. Приводятся также некоторые важные входные данные и сделан анализ результатов вычислений.

I. INTRODUCTION

The performance of reliable oil circuit breakers demands the knowledge of the transport properties of the gaseous medium in which the switching arc glows. The calculated composition of the oil gaseous arc decomposition products dependent on temperature and pressure has been already presented in [1]. Now, transport coefficients, i. e. electrical conductivity, thermal conductivity and viscosity must be also introduced. The calculation method of the transport coefficients has been described, e. g., in [2], [3] and the calculation program in the 3rd approximation of the Enskog-Chapman method has been worked out [4]. The transport coefficients have been computed at temperatures from 1000 to 4000 K with the temperature step 500 K and with pressures 0.1, 0.5, 1.2 and 3 MPa and at the temperatures from 5000 to 20 000 K with the temperature step 1000 K and with pressures 0.1, 0.175, 0.25, 0.35, 0.5, 0.75, 1.5 and 3 MPa. The calculated values are arranged into tables and graphs. The discussion concerning the physical processes which occur in the partially ionized oil decomposition products is based on the calculated results.

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Table 1

Rigid sphere diameters σ [10^{-10} m]

	σ [10^{-10} m]		σ [10^{-10} m]
C	3.38	C_2H	4.00
H	2.71	C_2H_2	4.03
O	3.05	C_2H_3	4.10
N	3.30	C_2H_4	4.16
S	3.84	C_2H_6	4.44
CH	3.37	H_2	2.83
CH_3	3.70	N_2	3.80
CH_4	3.76	CO	3.69

II. INPUT DATA

The mixture composition, given by the molar fractions of the 21 components, has been taken from [5]. The components dealt with are C, H, O, N, S, CH_4, CH_3,

Table 2

Electron-neutral effective collision cross sections Q_{ea} [10^{-20} m^2]

T[K]	C	H	O	N	CH	C_2H	H_2	N_2	CO
5 000	6.1	27.2	—	2.1	8.9	12.6	15.5	13.5	15.6
6 000	11.8	25.8	—	2.3	8.9	12.6	15.9	—	16.2
7 000	7.7	24.5	4.5	2.5	8.9	—	16.2	—	17.2
8 000	7.5	25.3	4.4	2.7	—	—	16.7	—	—
9 000	7.8	22.4	4.5	2.8	—	—	16.5	—	—
10 000	8.7	22.9	4.9	2.9	—	—	—	—	—
11 000	9.0	20.8	5.1	3.0	—	—	—	—	—
12 000	9.5	20.8	5.4	3.1	—	—	—	—	—
13 000	9.8	19.6	5.5	3.2	—	—	—	—	—
14 000	10.1	19.0	5.7	3.3	—	—	—	—	—
15 000	10.4	18.5	5.9	3.3	—	—	—	—	—
16 000	10.7	17.5	—	3.4	—	—	—	—	—
17 000	10.9	16.5	—	3.4	—	—	—	—	—
18 000	11.0	15.5	—	—	—	—	—	—	—
19 000	11.2	15.0	—	—	—	—	—	—	—
20 000	11.4	14.7	—	—	—	—	—	—	—

Table 3a

Total thermal conductivity λ [W m⁻¹ K⁻¹] from 1000 to 4000 K

T [K]	p [MPa] 0.1	0.5	1.0	2.0	3.0
1000	1.900 − 1*)	1.692 − 1	1.625 − 1	1.563 − 1	1.528 − 1
1500	5.856 − 1	6.137 − 1	6.094 − 1	4.600 − 1	4.131 − 1
2000	2.710 − 1	3.055 − 1	3.464 − 1	4.051 − 1	4.404 − 1
2500	4.876 − 1	3.782 − 1	3.553 − 1	3.442 − 1	3.422 − 1
3000	1.302 + 0	7.812 − 1	6.499 − 1	5.560 − 1	5.146 − 1
3500	2.756 + 0	1.689 + 0	1.343 + 0	1.075 + 0	9.500 − 1
4000	2.497 + 0	1.533 + 0	1.225 + 0	9.963 − 1	8.929 − 1

*) 1.900 − 1 denotes 1.900×10^{-1}

Table 3b

Viscosity η [kg m⁻¹ s⁻¹] from 1000 to 4000 K

T [K]	p [MPa] 0.1	0.5	1.0	2.0	3.0
1000	2.617 − 5	2.622 − 5	2.624 − 5	2.625 − 5	2.626 − 5
1500	3.119 − 5	3.159 − 5	3.172 − 5	3.181 − 5	3.186 − 5
2000	3.544 − 5	3.553 − 5	3.561 − 5	3.575 − 5	3.599 − 5
2500	3.954 − 5	3.959 − 5	3.961 − 5	3.964 − 5	3.969 − 5
3000	4.289 − 5	4.316 − 5	4.323 − 5	4.329 − 5	4.331 − 5
3500	4.471 − 5	4.584 − 5	4.613 − 5	4.635 − 5	4.644 − 5
4000	4.492 − 5	4.715 − 5	4.789 − 5	4.848 − 5	4.870 − 5

C_2H_4, C_2H_3, C_2H_2, C_2H, H_2, N_2, CO, CH, e, C^+, N^+, H^+, O^+. At each temperature and pressure point only the components with molar fractions greater than 10^{-5} are taken into consideration.

The effective collision cross sections of electrons with neutral particles have been obtained by interpolation of the values given in [6]. The assumption of the local thermodynamic equilibrium allows us to transfer the values of energy in [6] into the values of temperature. The effective cross sections used in our work are introduced in Table 1.

The effective collision cross sections of the mutual collisions of neutral particles and of the collisions of neutral particles with positive ions have been determined from the rigid sphere diameters. They have been taken from [7]. Some complicated molecules have been dealt with by applying empirical combination rules. The values of rigid sphere diameters used in the present work are in Table 2.

Table 4a

Electrical conductivity σ [Sm⁻¹]

T[K]	p [MPa] 0.1	0.175	0.250	0.350	0.500	0.750	1.500	3.000
5 000	8.918 + 0	6.601 + 0	5.328 + 0	4.265 + 0	3.285 + 0	2.393 + 0	1.357 + 0	8.038 − 1
6 000	7.447 + 1	5.853 + 1	5.002 + 1	4.303 + 1	3.656 + 1	3.024 + 1	2.140 + 1	2.435 + 1
7 000	4.383 + 2	3.861 + 2	3.569 + 2	3.318 + 2	3.071 + 2	2.810 + 2	2.387 + 2	1.983 + 2
8 000	1.289 + 3	1.089 + 3	9.704 + 2	8.665 + 2	7.648 + 2	6.606 + 2	5.089 + 2	3.877 + 2
9 000	2.544 + 3	2.264 + 3	2.080 + 3	1.906 + 3	1.725 + 3	1.527 + 3	1.219 + 3	9.555 + 2
10 000	2.673 + 3	2.477 + 3	2.334 + 3	2.191 + 3	2.029 + 3	1.842 + 3	1.599 + 3	1.231 + 3
11 000	3.751 + 3	3.610 + 3	3.488 + 3	3.352 + 3	3.185 + 3	2.975 + 3	2.570 + 3	2.161 + 3
12 000	4.733 + 3	4.673 + 3	4.595 + 3	4.491 + 3	4.349 + 3	4.146 + 3	3.727 + 3	3.226 + 3
13 000	5.722 + 3	5.772 + 3	5.762 + 3	5.718 + 3	5.633 + 3	5.486 + 3	5.101 + 3	4.581 + 3
14 000	6.643 + 3	6.804 + 3	6.869 + 3	6.896 + 3	6.885 + 3	6.810 + 3	6.526 + 3	6.040 + 3
15 000	7.509 + 3	7.783 + 3	7.927 + 3	8.030 + 3	8.103 + 3	8.121 + 3	7.977 + 3	7.584 + 3
16 000	8.314 + 3	8.714 + 3	8.944 + 3	9.136 + 3	9.304 + 3	9.439 + 3	0.900 + 3	9.259 + 3
17 000	8.596 + 3	9.559 + 3	9.879 + 3	1.016 + 4	1.043 + 4	1.070 + 4	1.097 + 4	1.095 + 4
18 000	1.624 + 4	4.107 + 3	4.429 + 3	4.754 + 3	5.162 + 3	5.637 + 3	6.443 + 3	7.096 + 3
19 000	1.031 + 4	1.101 + 4	1.148 + 4	1.193 + 4	1.240 + 4	1.292 + 4	1.369 + 4	1.420 + 4
20 000	1.090 + 4	1.166 + 4	1.217 + 4	1.268 + 4	1.324 + 4	1.386 + 4	1.487 + 4	1.566 + 4

Table 4b

Total thermal conductivity λ [W m⁻¹ K⁻¹] from 5000 to 20 000K

	p [MPa]							
T[K]	0.1	0.175	0.250	0.350	0.500	0.750	1.500	3.000
5 000	3.463 + 0	5.689 + 0	7.670 + 0	9.875 + 0	1.246 + 1	1.557 + 1	2.082 + 1	3.642 + 1
6 000	8.284 − 1	1.079 + 0	1.331 + 0	1.665 + 0	2.162 + 0	2.973 + 0	5.240 + 0	8.783 + 0
7 000	6.599 − 1	7.006 − 1	7.480 − 1	8.146 − 1	9.165 − 1	1.096 + 0	1.583 + 0	2.509 + 0
8 000	8.621 − 1	8.125 − 1	7.948 − 1	7.894 − 1	7.973 − 1	8.289 − 1	9.598 − 1	1.251 − 0
9 000	1.299 + 0	1.160 + 0	1.088 + 0	1.032 + 0	9.846 − 1	9.476 − 1	9.319 − 1	9.985 − 1
10 000	1.955 + 0	1.716 + 0	1.582 + 0	1.469 + 0	1.361 + 0	1.253 + 0	1.107 + 0	9.804 − 1
11 000	2.735 + 0	2.433 + 0	2.250 + 0	2.088 + 0	1.928 + 0	1.763 + 0	1.528 + 0	1.321 + 0
12 000	3.458 + 0	3.175 + 0	2.979 + 0	2.792 + 0	2.598 + 0	2.384 + 0	2.052 + 0	1.765 + 0
13 000	4.008 + 0	3.832 + 0	2.679 + 0	3.511 + 0	3.317 + 0	3.089 + 0	2.696 + 0	2.331 + 0
14 000	4.337 + 0	4.319 + 0	4.247 + 0	4.140 + 0	3.993 + 0	3.790 + 0	3.395 + 0	2.980 + 0
15 000	4.438 + 0	4.611 + 0	4.647 + 0	4.631 + 0	4.565 + 0	4.432 + 0	4.100 + 0	3.684 + 0
16 000	4.303 + 0	4.685 + 0	4.854 + 0	4.954 + 0	4.999 + 0	4.976 + 0	4.778 + 0	4.425 + 0
17 000	4.010 + 0	4.561 + 0	4.858 + 0	5.087 + 0	5.264 + 0	5.382 + 0	5.378 + 0	5.151 + 0
18 000	4.194 + 0	4.896 + 0	5.311 + 0	5.667 + 0	6.022 + 0	6.336 + 0	6.645 + 0	6.655 + 0
19 000	3.474 + 0	4.072 + 0	4.482 + 0	4.872 + 0	5.271 + 0	5.676 + 0	6.179 + 0	6.380 + 0
20 000	3.351 + 0	3.901 + 0	4.302 + 0	4.707 + 0	5.150 + 0	5.646 + 0	6.378 + 0	6.838 + 0

Table 4c

Viscosity η [kg m⁻¹ s⁻¹] from 5000 to 20 000 K

	p MPa							
T [K]	0.1	0.175	0.250	0.350	0.500	0.750	1.500	3.000
5 000	4.596 − 5	4.624 − 5	4.654 − 5	4.690 − 5	4.734 − 5	4.785 − 5	4.856 − 5	4.898 − 5
6 000	5.007 − 5	5.010 − 5	5.013 − 5	5.017 − 5	5.023 − 5	5.034 − 5	5.072 − 5	5.146 − 5
7 000	5.399 − 5	5.403 − 5	5.405 − 5	5.407 − 5	5.410 − 5	5.413 − 5	5.419 − 5	5.425 − 5
8 000	5.733 − 5	5.750 − 5	5.757 − 5	5.763 − 5	5.770 − 5	5.770 − 5	5.775 − 5	5.777 − 5
9 000	5.941 − 5	6.004 − 5	6.034 − 5	6.056 − 5	6.075 − 5	6.091 − 5	6.109 − 5	6.119 − 5
10 000	5.926 − 5	6.088 − 5	6.168 − 5	6.231 − 5	6.284 − 5	6.333 − 5	6.391 − 5	6.425 − 5
11 000	5.614 − 5	5.927 − 5	6.092 − 5	6.223 − 5	6.341 − 5	6.449 − 5	6.583 − 5	6.670 − 5
12 000	5.008 − 5	5.491 − 5	5.761 − 5	5.987 − 5	6.195 − 5	6.396 − 5	6.656 − 5	6.832 − 5
13 000	4.217 − 5	4.835 − 5	5.201 − 5	5.525 − 5	5.837 − 5	6.149 − 5	6.579 − 5	6.886 − 5
14 000	3.385 − 5	4.062 − 5	4.494 − 5	4.894 − 5	5.294 − 5	5.720 − 5	6.340 − 5	6.813 − 5
15 000	2.606 − 5	3.284 − 5	3.738 − 5	4.178 − 5	4.639 − 5	5.152 − 5	5.951 − 5	6.608 − 5
16 000	1.953 − 5	2.571 − 5	3.012 − 5	3.455 − 5	3.943 − 5	4.506 − 5	5.443 − 5	6.275 − 5
17 000	1.478 − 5	1.991 − 5	2.386 − 5	2.801 − 5	3.278 − 5	3.852 − 5	4.871 − 5	5.847 − 5
18 000	1.177 − 5	1.573 − 5	1.897 − 5	2.686 − 5	3.235 − 5	4.272 − 5	5.346 − 5	
19 000	1.016 − 5	1.312 − 5	1.565 − 5	1.856 − 5	2.226 − 5	2.716 − 5	3.712 − 5	4.830 − 5
20 000	9.452 − 6	1.168 − 5	1.362 − 5	1.592 − 5	1.892 − 5	2.312 − 5	3.221 − 5	4.327 − 5

The values of the reaction heats necessary for the reaction component of thermal conductivity have been computed with the help of stoichiometric coefficients of independent reactions and from the heats of formation. Their values are the same as those used in the composition calculations [5].

The "frozen" specific heats necessary for the Eucken correction of thermal conductivity have been taken from [8].

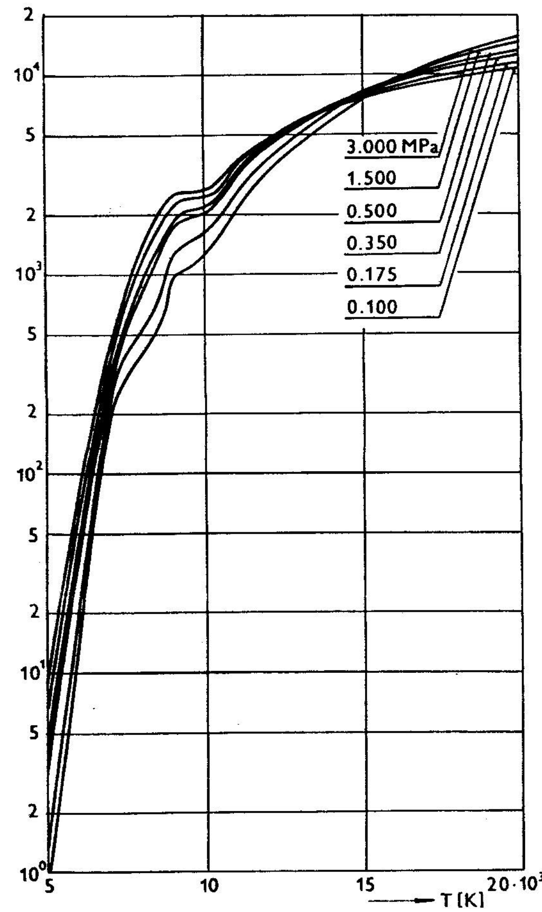

Fig. 1a.

III. DISCUSSION OF CALCULATED VALUES

The calculated values of electrical conductivity, total thermal conductivity and viscosity for the given temperatures and pressures are presented in Tables 3a, b and

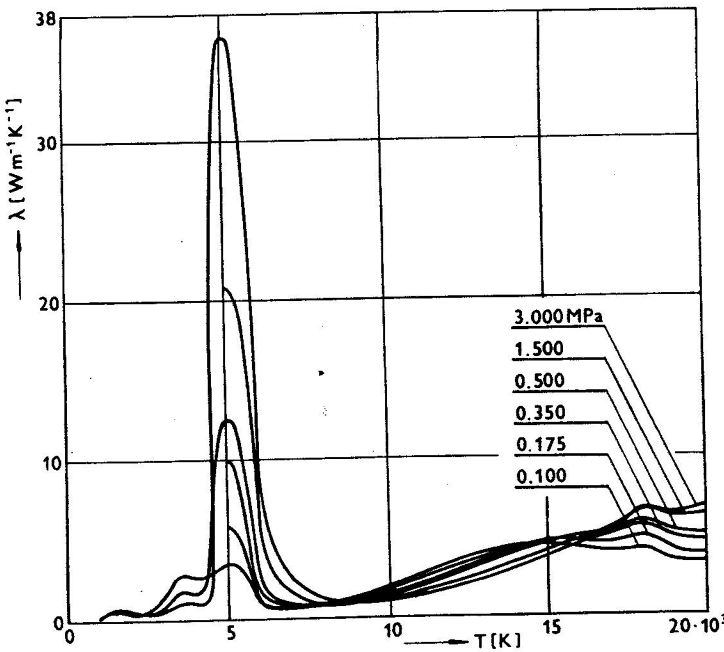

Fig. 1b.

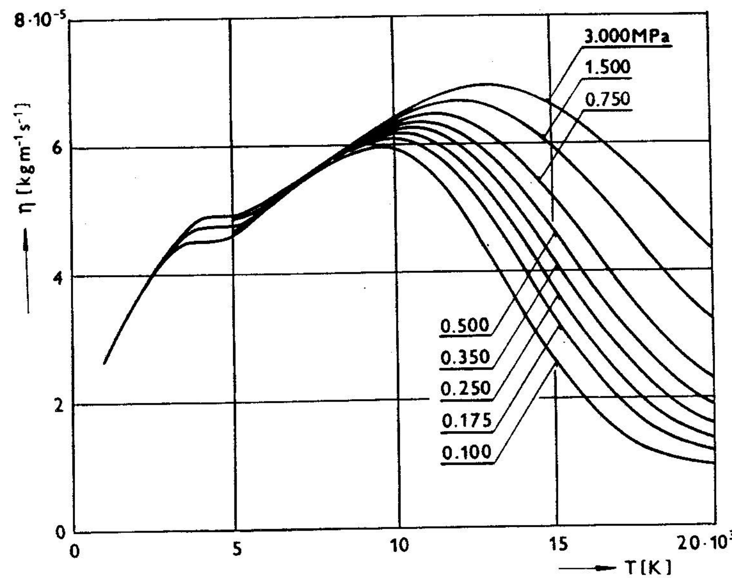

Fig. 1c.

4a—c. They are also demonstrated in Figs. 1a—c. In the temperature dependence of electrical conductivity in Fig. 1a a sattle between 9000 and 10 000 K at all pressure values can be observed. In this temperature region the influence of electron-neutral atom collisions slows down and the influence of Coulomb collisions begins to prevail. At temperatures greater than 10 000 K only Coulomb collisions are important and the temperature dependence of electrical conductivity approaches the dependence $T^{3/2}$. The pressure dependence of electrical conductivity approaches at lower temperatures the well known $1/\sqrt{p}$ dependence. In the temperature region from 15 000 to 16 000 K electrical conductivity does not depend on pressure at all. At higher temperatures it rises with pressure as it acquires the qualities of a fully ionized gas.

The total thermal conductivity (see Fig. 1b) has the great dissociation maximum at 5000 K caused by the dissociation of the molecular hydrogen H_2 and the molecule C_2H. The maximum rises and shifts to higher temperatures with pressure. A further dissociation maximum appears at 3500 K. The ionization maximum caused by the ionization of carbon and hydrogen occurs at 13 000—14 000 K at lower pressures. At higher pressures only a small maximum at 18 000 K occurs. It is caused by the ionization of a relatively small amount of nitrogen.

The entire course of the temperature dependence of viscosity (see Fig. 1c) has, as usual, a great maximum which rises and shifts to higher temperatures with pressure. The maximum is caused by a gradual prevailing of the Coulomb interactions over the neutral particle interactions of lower temperatures. The sattle in the temperature range 4000—5000 K is caused by the dissociation, because the dissociated gas has a smaller viscosity than the mixture of complex molecules.

From all three temperature and pressure dependences it can be concluded that their courses have the usual forms of other partially ionized gases. But the presented concrete results for the BTS oil decomposition products cannot be compared with works of other authors because we do not know if such works exist.

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