# EXPERIMENTAL STUDY CONCERNING THE CONTRIBUTION OF THE RADIATIVE COMPONENT TO THE EFFECTIVE THERMAL CONDUCTIVITY OF TOLUENE

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The coaxial-cylinders method was used in an experimental study concerning the contribution of the radiative component to the effective thermal conductivity of toluene. It has been found that this contribution becomes quite significant at high temperatures.

The widely used relative methods of measuring the thermal conductivity (λ) of liquids and gases require that the thermal conductivity of standard reference substances be known exactly and over a sufficiently wide range of state variables. Toluene is one such substance, by virtue of its very favorable physicochemical properties. Recommendations pertaining to the use of toluene as a standard reference liquid have been made in [1-4].

Many studies concerning the thermal conductivity of toluene are surveyed and discussed in [3, 4]. The values of λ obtained by various authors often differ from one another, especially at high temperatures, by an amount much larger than the overall error in each case, making it difficult to generalize all the published data and to recommend the correct values. One source of these discrepancies is the radiative component of heat transmission through fluids which are semitranslucent to infrared radiation.

It is to be noted that the effective thermal conductivity, which one measures for plane layers [5-7] or cylindrical layers [8] of the test fluid, depends rather intricately on both the physical and the optical properties as well as on the geometry of both the fluid layer and the boundary surfaces. Special tests performed by the plane-layer method [6] and the hot-wire method [9] in the appropriate apparatus have yielded relations between the radiative component of the effective thermal conductivity and the thickness of the fluid test layer. Nevertheless, the information available today is quite scarce and the problem requires a further thorough experimental as well as theoretical analysis.

In view of this, the authors have made an experimental study concerning the relation between the effective thermal conductivity of toluene and the width of the test gap, over the temperature range from −40 to +200°C, in an apparatus designed for the coaxial-cylinders method of measurement. A set of six interchangeable cylinders with different diameters 17.728, 17.203, 16.799, 16.191, 15.610, 14.799 ± 0.003 mm made it possible to vary the thickness of the test layer from 0.1 to 1.6 mm. The dimensions of these cylinders were inspected under a model UIM-21 microscope with a ±0.002 mm precision. The inside diameter of the outer cylinder was 17.944 ± 0.005 mm, as measured with a special dial indicator at 40 locations along its height and around its circumference, with an error not exceeding ±0.002 mm. All cylinders had been made of refined copper, with their active surfaces carefully polished and subsequently chrome plated.

The construction of our test cell is shown in Fig. 1. An inner cylinder 4 is centered relative to the outer cylinder 3 by means of porcelain pins mounted into micrometer screws. The eccentricity is measured with a set of special feeler gages and under the model UIM-21 microscope, before and after a test. The test gap is hermetically closed at both ends of the cell by means of 0.3 mm thick Teflon inserts 2,

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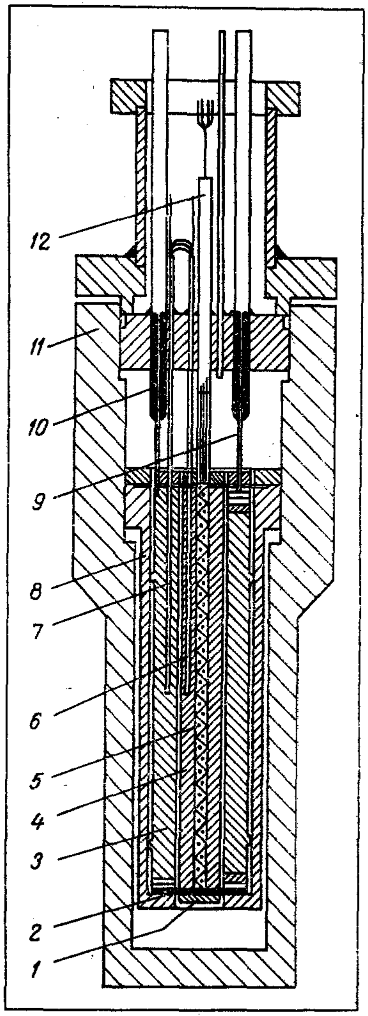


Fig. 1. Construction of the test cell.

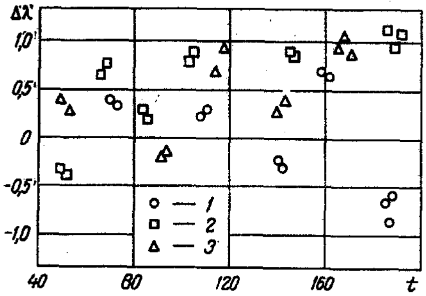


Fig. 2. Departure (%) of test values for the thermal conductivity of water from those values recommended by the authors of [4], at a gap width: 1) 0.371 mm; 2) 1.167 mm; 3) 1.573 mm.

sealed with tight flanges 1 of stainless steel. Into an axial 4 mm (diameter) hole drilled in each inner cylinder is inserted the electric heater 5 bifilarly wound on a porcelain tube and insulated from the cylinder wall by a heat-resistant varnish and a Teflon coating. Current and potential leads to the heater are brought out from the test zone through a capillary tube 12. The temperature drop across the layer and the reference temperature of the thermal conductivity measurement are determined with a three-junction differential thermocouple and an absolute copper–constantan thermocouple, both precalibrated and embedded in respective sheaths 6 and 7 of stainless steel. The gap is filled with the test fluid, poured in under vacuum along capillaries 9 and 10 through holes specially drilled in the outer cylinder.

The test cell was placed in a brass beaker 8, all inside an autoclave 11. The test pressure was produced with compressed nitrogen through a distributor vessel connected to the autoclave chamber, so that rather thin Teflon inserts sufficed for hermetically sealing the test gap and reducing the heat leakage from an inner cylinder.

The test cell was thermostaticized in a liquid thermostat with white spirit and grade PMS-100 silicone fluid. Temperature fluctuations inside the thermostat did not exceed ±0.005°C and there were no sensible temperature variations at the surface of the outer cylinder. The axial temperature gradient was $5 \cdot 10^{-5}$ deg/mm at the maximum test temperature.

The heater in the test cell was energized from a model U-1199 stable direct-current source. Direct-current potentiometers, model R37-1 class 0.01 and model R-348 class 0.002, were used in measurements of the heater power and the temperature.

The effective thermal conductivity of toluene was measured at gap widths 0.108, 0.371, 0.573, 0.877, 1.167, and 1.573 mm over the temperature range from −40 to +200°C, yielding more than 170 test points. In order to eliminate heat convection, the tests were performed at two to four different temperature drops across the layer and as many different values of the product $Gr \cdot Pr < 1200$. The results were then numerically corrected for heat leakage at the cylinder end-faces, for the thermocouple mountings, for the eccentricity between cylinders, and for thermally produced variations in the dimensions of the test cell, all together not exceeding 2.5%. An error analysis has shown that the maximum relative error of these test data is ±1.5% (the measurement error with a gap $\delta = 0.108$ mm wide was ±2.5 to ±3.0%). The results of thermal conductivity measurements for toluene are shown in Table 1. For gap widths $\delta = 0.371$, 1.167, and 1.573 mm are also shown data pertaining to the thermal conductivity of water over the 40-180°C temperature range. The departure of the test values for water from those recommended in [4] is shown in Fig. 2.

An analysis of the test data has shown that the effective thermal conductivity of toluene has different values when measured in gaps of different widths; also that these differences become larger at higher

TABLE 1. Test Values of the Thermal Conductivity of Toluene, $\lambda \cdot 10^4$ (W/m·deg)

| t | λ | t | λ | t | λ | t | λ | t | λ | t | λ | t | λ | t | λ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| δ=0,108 mm | | 152,1 | 974 | 104,6 | 1101 | 53,4 | 1238 | 30,3 | 1302 | −6,3 | 1418 | 153,2 | 1039 | 99,3 | 1148 |
| −36,1 | 1488 | 152,6 | 964 | 106,5 | 1107 | 54,9 | 1247 | 31,5 | 1313 | 4,8 | 1379 | 154,1 | 1030 | 99,8 | 1163 |
| −35,6 | 1476 | 169,8 | 923 | 124,2 | 1059 | 85,8 | 1164 | 52,2 | 1258 | 5,2 | 1392 | 182,1 | 982 | 100,1 | 1157 |
| −8,2 | 1406 | 170,5 | 931 | 124,8 | 1050 | 86,6 | 1152 | 53,8 | 1249 | 30,9 | 1325 | 183,0 | 974 | 110,6 | 1128 |
| −7,5 | 1413 | 175,9 | 918 | 149,5 | 998 | 108,5 | 1089 | 77,6 | 1194 | 40,3 | 1283 | 191,3 | 969 | 111,4 | 1137 |
| 19,8 | 1319 | 176,7 | 909 | 150,4 | 991 | 109,4 | 1101 | 78,2 | 1183 | 42,1 | 1295 | 191,5 | 963 | 123,2 | 1112 |
| 20,6 | 1306 | 197,4 | 875 | 151,2 | 996 | 131,9 | 1046 | 110,5 | 1104 | 43,0 | 1286 | 191,6 | 966 | 124,0 | 1104 |
| 21,1 | 1314 | 198,1 | 879 | 185,7 | 922 | 132,6 | 1037 | 112,0 | 1112 | 55,1 | 1237 | δ=1,573 mm | | 124,6 | 1103 |
| 29,5 | 1284 | 198,7 | 871 | 186,4 | 927 | 133,5 | 1044 | 113,8 | 1097 | 65,6 | 1226 | −19,8 | 1457 | 147,2 | 1056 |
| 30,7 | 1293 | 199,2 | 864 | 199,2 | 899 | 176,8 | 955 | 144,3 | 1035 | 67,5 | 1232 | −19,0 | 1448 | 148,1 | 1064 |
| 45,0 | 1239 | δ=0,371 mm | | 199,6 | 889 | 177,0 | 947 | 145,2 | 1026 | 87,0 | 1184 | 13,2 | 1375 | 148,4 | 1059 |
| 45,8 | 1249 | −37,4 | 1493 | 200,3 | 894 | 177,2 | 943 | 166,1 | 991 | 88,4 | 1172 | 14,7 | 1361 | 157,1 | 1042 |
| 73,3 | 1178 | −36,8 | 1480 | 200,8 | 895 | 177,6 | 950 | 166,7 | 983 | 88,5 | 1170 | 17,8 | 1352 | 157,9 | 1049 |
| 74,2 | 1167 | −6,3 | 1399 | 208,9 | 876 | 195,2 | 924 | 199,0 | 936 | 100,7 | 1146 | 31,2 | 1317 | 158,3 | 1046 |
| 102,7 | 1094 | −4,7 | 1391 | 209,1 | 883 | 195,6 | 918 | 199,2 | 926 | 101,4 | 1137 | 32,5 | 1324 | 172,6 | 1018 |
| 103,6 | 1082 | 27,2 | 1302 | δ=0,573 mm | | 196,1 | 911 | 199,5 | 930 | 109,2 | 1124 | 60,1 | 1257 | 172,8 | 1012 |
| 105,8 | 1085 | 29,0 | 1313 | −32,6 | 1476 | 196,4 | 907 | 199,6 | 926 | 110,1 | 1129 | 60,3 | 1244 | 184,4 | 1006 |
| 107,1 | 1084 | 42,5 | 1255 | −30,3 | 1490 | δ=0,877 mm | | δ=1,167 mm | | 120,8 | 1098 | 61,2 | 1252 | 185,7 | 994 |
| 127,6 | 1013 | 45,8 | 1264 | −16,1 | 1425 | −29,8 | 1469 | −31,2 | 1465 | 123,4 | 1086 | 81,2 | 1209 | 185,9 | 1001 |
| 127,7 | 1017 | 46,4 | 1248 | −15,4 | 1437 | −29,1 | 1474 | −28,6 | 1477 | 124,5 | 1090 | 82,8 | 1201 | 186,0 | 998 |
| 129,0 | 1028 | 71,5 | 1197 | 9,2 | 1356 | −15,2 | 1422 | −7,1 | 1406 | 150,8 | 1032 | | | | |
| 140,3 | 988 | 73,6 | 1189 | 10,5 | 1369 | −14,0 | 1435 | | | | | | | | |
| 141,2 | 982 | 71,5 | 1181 | 25,9 | 1323 | 17,7 | 1354 | | | | | | | | |
| 141,8 | 985 | 103,3 | 1112 | 27,1 | 1314 | 18,5 | 1346 | | | | | | | | |

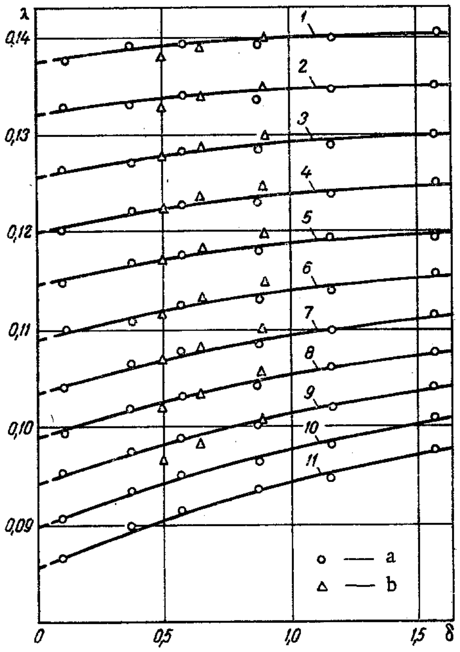


Fig. 3. Effective thermal conductivity λ (W/m · deg) of toluene, as a function of the gap width δ (mm): a) coaxial-cylinders method; b) hot-wire method at a temperature of (°C): 1) 0; 2) 20; 3) 40; 4) 60; 5) 80; 6) 100; 7) 120; 8) 140; 9) 160; 10) 180; 11) 200.

temperatures. On the other hand, the thermal conductivity of water (whose thermal absorptivity is rather high) remains the same, within test accuracy, over the entire range of test temperatures and regardless of the gap width, while in satisfactory agreement with recommended values [4].

The said differences in test values for the thermal conductivity of toluene can, obviously, be only due to heat radiation. Since the radiation characteristics of the liquid and of the active cylinder surfaces were identical here, hence these data on the effective thermal conductivity of toluene should be regarded as reflecting a dependence on the gap width. In order to eliminate the effect of the radiative component, we have plotted in Fig. 3 isotherms of the effective thermal conductivity for toluene, as a function of the gap width, and have extrapolated them to a zero layer thickness so as to establish what, evidently, should be regarded as the true "molecular" thermal conductivity. The values of thermal conductivity thus found over the temperature range from −40 to +200°C, within a ±0.5% accuracy, may be approximated by the following equation:

$$\lambda_0 = 0.1373 - 0.03062\,(t/100) + 0.00232\,(t/100)^2. \tag{1}$$

The thermal conductivity of toluene was also measured by the hot-wire method over the 0-160°C temperature range and in gaps δ = 0.5, 0.675, and 0.90 mm wide, as shown in Fig. 3 [9]. An analysis has revealed that the values of thermal conductivity obtained by the hot-wire method and by the coaxial-cylinders method with the same gap widths differ respectively by an amount not exceeding the overall errors of both methods.

On the basis of the data thus obtained, an equation has been derived describing the effective thermal conductivity of toluene as a function of the gap width:

$$\lambda_\delta = \lambda_0 + [0.0037 + 0.0031\,(t/100) - 0.0003\,(t/100)^2]\,\delta - 0.001\delta^2. \tag{2}$$

An extrapolation of the test curves to a zero gap width has made it possible to estimate the radiative component in the effective thermal conductivity of toluene. Thus, at the maximum test temperature of 200°C and at the gap width δ = 1.573 mm this component contributed approximately 14%. Therefore, the effect of radiation appears quite substantial and must be taken into account in any study concerning the thermal conductivity of fluids semitranslucent to infrared radiation.

## NOTATION

λ is the thermal conductivity;
t is the temperature;
Gr is the Grashof number;
Pr is the Prandtl number;

$\delta$ is the layer thickness;

$\Delta\lambda$ is the deviation;

$\lambda_0$ is the thermal conductivity in a gap $\delta = 0$;

$\lambda_\delta$ is the effective thermal conductivity.

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