# Thermophysical Properties of Vespel™ SP1

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## ABSTRACT

Vespel™[1] is one of the commonly used thermal conductivity reference materials, due to its consistent thermophysical properties. There is, however, very little data available describing its thermal diffusivity and specific heat capacity.

This work presents new data for thermal diffusivity and specific heat capacity obtained using the flash method, with the latter also being determined using a differential scanning calorimeter. Additional thermal conductivity data, obtained using a steady state method, is also presented and compared to the values derived from the transient data.



## INTRODUCTION

Vespel™ SP1 (referred to as Vespel™ for the rest of this work) is a polyimide manufactured as an unfilled resin with ultra high purity and durability. Due to its consistent and stable characteristics, Vespel™ has evolved to be a reliable industry accepted thermal conductivity reference for testing low conductive materials. As a reference, it has been confirmed to be stable, unaltered by thermal cycling, and consistent with lot-to-lot production. Vespel™ is also one of the rare polymeric materials that can be heated up to 300 °C and still maintain its thermal and mechanical properties unaltered. Even with these exceptional characteristics there are few publications available on its thermal conductivity and even fewer on its thermal expansion, thermal diffusivity and specific heat capacity. This work presents experiments characterizing these properties.

The new data was obtained for thermal diffusivity and specific heat capacity using the flash technique and a differential scanning calorimeter (DSC). The results of these measurements, along with derived density values were used to calculate the thermal conductivity. Additionally, steady state thermal conductivity tests were

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[1] Trademark of DuPont du Nemours and Company, Wilmington, DE

performed to verify these calculated values. Push-rod dilatometry was used for the thermal expansion measurements.

## THERMAL EXPANSION

The material's thermal expansion was studied using a fused silica push-rod type dilatometer, Unitherm™ Model 1091 (Anter Corporation), according to the specifications of ASTM E228-95 test method.

The sample was machined to form a specimen 50.8 mm long, 6.35 mm square cross section, with the ends flat and parallel. Three experiments were performed from 20 °C to 300 °C in air atmosphere with a heating rate of 1 °C/minute. The values of percent expansion versus temperature, shown in Table I, were obtained by fitting fourth order polynomial curves to the experimental data. In addition to the results of the three runs performed, Table I shows results obtained in a previous study [1] carried on in the same manner, but on samples from a different lot. The average of all three sets of test results is shown and the relative standard deviation between the individual runs is calculated.

It is important to notice that the maximum value of the relative standard deviation at all temperatures is only 0.67 %. Since the instrument used for testing has been thoroughly characterized in a separate study [2] and has been proven to be very repeatable, the very small relative standard deviation values obtained show that the material's thermal expansion characteristic is very repeatable.



TABLE I. THERMAL EXPANSION OF VESPEL™

| **Temperature (°C)** | **Thermal Expansion: (%)** | | | | | **Relative Standard Deviation (%)** |
|---|---|---|---|---|---|---|
| | **Previous Run** | **Run 1** | **Run 2** | **Run 3** | **Average (1, 2, 3)** | |
| 25 | 0.024 | 0.022 | 0.022 | 0.022 | 0.022 | 0.00 |
| 50 | 0.146 | 0.136 | 0.134 | 0.137 | 0.136 | 0.67 |
| 75 | 0.270 | 0.253 | 0.251 | 0.255 | 0.253 | 0.46 |
| 100 | 0.396 | 0.374 | 0.372 | 0.378 | 0.375 | 0.47 |
| 125 | 0.525 | 0.500 | 0.498 | 0.505 | 0.501 | 0.42 |
| 150 | 0.656 | 0.631 | 0.629 | 0.636 | 0.632 | 0.33 |
| 175 | 0.790 | 0.768 | 0.765 | 0.772 | 0.768 | 0.27 |
| 200 | 0.927 | 0.909 | 0.907 | 0.912 | 0.909 | 0.16 |
| 225 | 1.068 | 1.056 | 1.054 | 1.057 | 1.056 | 0.09 |
| 250 | 1.214 | 1.209 | 1.206 | 1.208 | 1.208 | 0.08 |
| 275 | 1.367 | 1.367 | 1.364 | 1.365 | 1.365 | 0.07 |
| 300 | 1.527 | 1.532 | 1.527 | 1.528 | 1.529 | 0.10 |

## THERMAL DIFFUSIVITY

Three thermal diffusivity tests were performed on a Vespel™ sample, having 12.7 mm diameter, 2.032 mm thickness and flat and parallel faces. The measurements were performed with a FlashLine™ 3000 (Anter Corporation) instrument using the flash technique, according to the specifications of ASTM E1461-01 test method. The results were again compared with previous data obtained in the same fashion, but on samples from a different lot [1]. Table II shows a comparison between the current data and the previous one, with the relative standard deviation calculated for the three sets of measurements performed in this study.

TABLE II. THERMAL DIFFUSIVITY OF VESPEL™

| Temperature (°C) | Thermal Diffusivity ($cm^2s^{-1}$) | | | | | Relative Standard Deviation (%) |
|---|---|---|---|---|---|---|
| | Previous Run | Run 1 | Run 2 | Run 3 | Average (1, 2, 3) | |
| 25 | 0.0026 | 0.00255 | 0.00259 | 0.00260 | 0.00258 | 0.59 |
| 50 | 0.0025 | 0.00249 | 0.00250 | 0.00251 | 0.00250 | 0.23 |
| 75 | 0.0024 | 0.00232 | 0.00234 | 0.00229 | 0.00232 | 0.63 |
| 100 | 0.0022 | 0.00227 | 0.00226 | 0.00228 | 0.00227 | 0.25 |
| 125 | 0.0022 | 0.00215 | 0.00218 | 0.00214 | 0.00216 | 0.56 |
| 150 | 0.0021 | 0.00209 | 0.00211 | 0.00206 | 0.00209 | 0.70 |
| 175 | 0.0020 | 0.00206 | 0.00206 | 0.00204 | 0.00205 | 0.32 |
| 200 | 0.0020 | 0.00201 | 0.00200 | 0.00198 | 0.00200 | 0.44 |
| 225 | 0.0019 | 0.00194 | 0.00194 | 0.00196 | 0.00195 | 0.34 |
| 250 | 0.0019 | 0.00190 | 0.00189 | 0.00193 | 0.00191 | 0.63 |
| 275 | 0.0019 | 0.00190 | 0.00190 | 0.00180 | 0.00187 | 1.79 |
| 300 | 0.0018 | 0.00179 | 0.00178 | 0.00177 | 0.00178 | 0.32 |



It is visible that the results obtained in this study are very close to those previously obtained [1], proving lot-to-lot consistency regarding the material's thermal diffusivity. The instrument used for these measurements was thoroughly characterized in a separate study [3] and was proven to be very repeatable. The small values of the relative standard deviations obtained here show that the thermal diffusivity characteristic of the Vespel™ material is very repeatable. Figure 1 illustrates the thermal diffusivity data obtained for the three different runs, showing the thermal diffusivity's dependency on temperature.

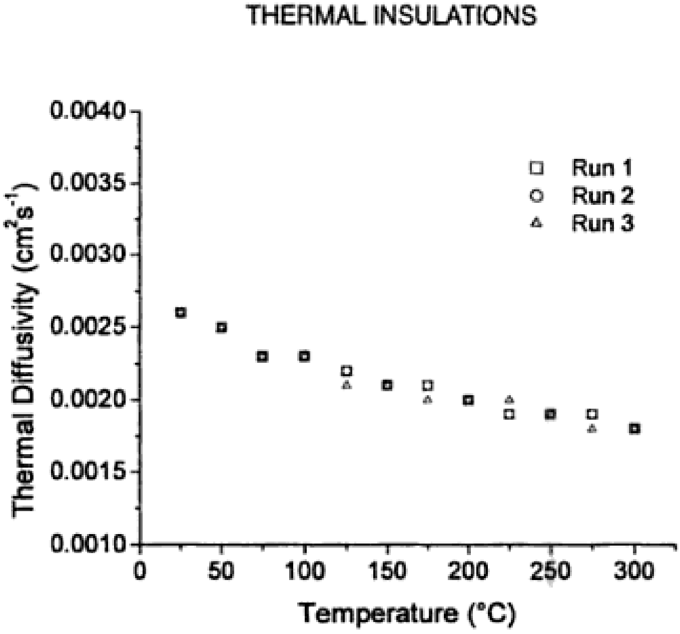


Figure 1. Thermal Diffusivity of Vespel™

All three sets of measurements were performed in air atmosphere, using the same test parameters and data analysis.



## SPECIFIC HEAT CAPACITY

Two different methods were used to measure the specific heat capacity of the material: the flash technique and differential scanning calorimetry, being performed according to specifications of ASTM test methods E1461-01 and E1269-95, respectively. For the flash technique, three separate measurements were performed on the same instrument and using the same sample as in the thermal diffusivity measurements, taking advantage of the multi-sample testing capability of the equipment. Due to the concurrent testing of a reference material and of the Vespel™ specimen, these tests yielded very accurate and repeatable results, generated in a truly differential fashion.

Table III shows the specific heat capacity data obtained using both test methods. The results obtained during the three independent runs on the flash instrument are individually shown, and the relative standard deviation is calculated for each test temperature. The last column in Table III represents the relative difference between the specific heat capacity values obtained through the two test methods involved in this study.

TABLE III. SPECIFIC HEAT CAPACITY OF VESPEL™

| Temperature (°C) | Specific Heat Capacity ($Jkg^{-1}K^{-1}$) | | | | | | Relative Difference (%) |
|---|---|---|---|---|---|---|---|
| | Run 1 | Run 2 | Run 3 | Average (1, 2, 3) | Relative Standard Deviation (%) | DSC | |
| 25 | 1008.6 | 994.3 | 1011.4 | 1004.8 | 0.53 | ----- | ------ |
| 50 | 1083.5 | 1081.7 | 1103.6 | 1089.6 | 0.65 | 1068.8 | 1.19 |
| 75 | 1133.6 | 1168.7 | 1160.9 | 1154.4 | 0.92 | 1155.7 | 0.12 |
| 100 | 1261.3 | 1216.1 | 1240.9 | 1239.4 | 1.06 | 1237.7 | 0.14 |
| 125 | 1283.5 | 1286.0 | 1274.7 | 1281.4 | 0.27 | 1315.4 | 2.65 |
| 150 | 1348.6 | 1353.3 | 1361.0 | 1354.3 | 0.27 | 1389.4 | 2.59 |
| 175 | 1436.4 | 1449.8 | 1452.8 | 1446.4 | 0.35 | 1460.4 | 0.97 |
| 200 | 1513.5 | 1490.9 | 1521.3 | 1508.6 | 0.60 | 1529.2 | 1.36 |
| 225 | 1567.3 | 1584.6 | 1556.1 | 1569.3 | 0.53 | 1596.3 | 1.72 |
| 250 | 1611.4 | 1608.6 | 1590.8 | 1603.6 | 0.40 | 1662.6 | 3.68 |
| 275 | 1676.1 | 1699.9 | 1689.7 | 1688.5 | 0.41 | 1728.5 | 2.37 |
| 300 | 1777.0 | 1772.9 | 1735.1 | 1761.7 | 0.76 | 1795.0 | 1.89 |



The differential scanning calorimeter used was a Setaram DSC instrument, Model 96. The results of all the specific heat capacity measurements obtained are shown in Figure 2 for the entire temperature range.

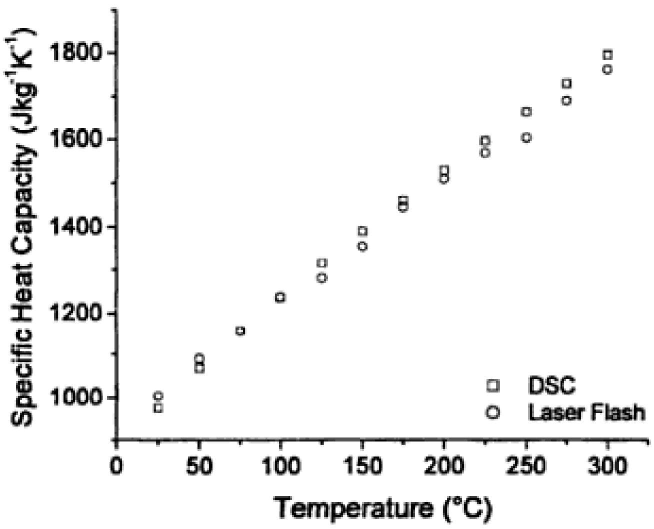


Figure 2. Specific heat capacity of Vespel™

It is important to note that at all test temperatures, the relative difference between the results generated by the two methods is less than 3.7 %, which was considered to be very good.

## THERMAL CONDUCTIVITY

The steady state thermal conductivity measurements were performed using a guarded heat flow meter device, Unitherm™ Model 2022 (Anter Corporation), operating according to ASTM E1530-99 test method. The size of the tested sample was 50.8 mm diameter, 6.35 mm thick with the faces flat and parallel. A thin layer of highly conductive paste was used on both faces of the sample to minimize the contact resistance. The sample was held under constant pressure of approximately 20 psi at each temperature for approximately 60 minutes to ensure thermal equilibrium. Thermocouples were used to measure the temperature difference between the two faces of the sample.

Table IV compares the results of the direct measurements obtained from 25 °C to 300 °C to the known thermal conductivity values for Vespel™, generally accepted by industry [1].



TABLE IV. THERMAL CONDUCTIVITY OF VESPEL™

| Temperature (°C) | Thermal Conductivity ($W{\cdot}m^{-1}{\cdot}K^{-1}$) Direct Measurement | Book Values | Relative Difference (%) |
|---|---|---|---|
| 25 | 0.377 | 0.379 | 0.53 |
| 50 | 0.381 | 0.384 | 0.78 |
| 75 | 0.386 | 0.389 | 0.77 |
| 100 | 0.391 | 0.394 | 0.76 |
| 125 | 0.396 | 0.399 | 0.75 |
| 150 | 0.402 | 0.404 | 0.50 |
| 175 | 0.407 | 0.409 | 0.49 |
| 200 | 0.413 | 0.414 | 0.24 |
| 225 | 0.419 | 0.419 | 0.00 |
| 250 | 0.425 | 0.424 | 0.24 |
| 275 | 0.430 | 0.429 | 0.23 |
| 300 | 0.436 | 0.434 | 0.46 |

Since the guarded heat flow meter method is expected to generate thermal conductivity results within a ± 3 % band, and since all the values obtained for relative thermal conductivity difference are smaller than 1 %, at all test temperatures, it was concluded that the thermal conductivity values generated by the current study are of high quality.

In addition to the direct measurements of thermal conductivity, the other results obtained in the current study were used to generate thermal conductivity values, which were compared with the set of results generated through direct measurements.

Considering that the Vespel™ material is isotropic and homogeneous, thermal conductivity ($\lambda$) was calculated from the results of thermal diffusivity ($\alpha$), specific heat capacity ($C_p$) and thermal expansion measurements at each temperature using the following equation.

$$\lambda = \alpha \cdot C_p \cdot \rho \qquad (1)$$

The thermal expansion determinations were used to calculate the material's density ($\rho$) over the entire temperature range.

Table V shows the results for the thermal diffusivity and specific heat capacity measurements along with the values of derived thermal conductivity.

TABLE V. THERMAL CONDUCTIVITY OF VESPEL™

| Temperature (°C) | Thermal Diffusivity ($cm^2s^{-1}$) | Specific Heat Capacity ($J \cdot kg^{-1}K^{-1}$) | Density ($kg \cdot m^{-3}$) | Derived Thermal Conductivity ($W \cdot m^{-1}K^{-1}$) | Measured Thermal Conductivity ($W \cdot m^{-1}K^{-1}$) | Relative Difference (%) |
|---|---|---|---|---|---|---|
| 25 | 0.0026 | 1004.8 | 1433.59 | 0.372 | 0.377 | 1.45 |
| 50 | 0.0025 | 1089.6 | 1428.70 | 0.389 | 0.381 | 2.06 |
| 75 | 0.0023 | 1154.4 | 1423.71 | 0.381 | 0.386 | 1.34 |
| 100 | 0.0023 | 1239.4 | 1418.52 | 0.399 | 0.391 | 2.08 |
| 125 | 0.0022 | 1281.4 | 1413.19 | 0.391 | 0.396 | 1.41 |
| 150 | 0.0021 | 1354.3 | 1407.68 | 0.398 | 0.402 | 0.96 |
| 175 | 0.0021 | 1446.4 | 1401.99 | 0.416 | 0.407 | 2.14 |
| 200 | 0.0020 | 1508.6 | 1396.12 | 0.421 | 0.413 | 1.74 |
| 225 | 0.0020 | 1569.3 | 1390.04 | 0.425 | 0.419 | 1.30 |
| 250 | 0.0019 | 1603.6 | 1383.78 | 0.423 | 0.425 | 0.43 |
| 275 | 0.0018 | 1688.5 | 1377.36 | 0.428 | 0.430 | 0.58 |
| 300 | 0.0018 | 1761.7 | 1370.70 | 0.430 | 0.436 | 1.33 |



Table V also shows the thermal conductivity results obtained from direct measurements performed using the guarded heat flow meter method, and the relative difference between the two sets of results.

Figure 3 shows a comparison between the known thermal conductivity values for Vespel™ and the thermal conductivity results obtained using the two approaches.

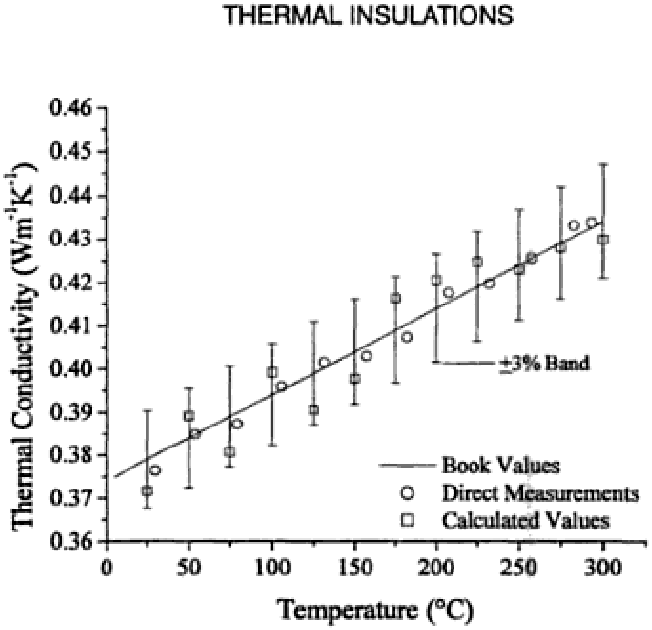


Figure 3. Thermal Conductivity of Vespel™

It is visible that all the thermal conductivity values obtained are well within the ± 3 % band associated with the known values, proving that not only the thermal conductivity values of this material are reliable, but also the thermal expansion, thermal diffusivity and the specific heat capacity values that lead to the end result.

## CONCLUSION

This work proves that Vespel™ in its pure form is a reliable reference material for thermal expansion, thermal conductivity, thermal diffusivity and specific heat capacity within the temperature range of 25 °C to 300 °C. The repeatable results obtained while measuring all these thermophysical properties also demonstrate the material's lot-to-lot repeatability.

## REFERENCES

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