

Supplementary Materials

# Experimental Investigation of the Melt Shear Viscosity, Specific Volume and Thermal Conductivity of Low-Density Polyethylene/Multi-Walled Carbon Nanotube Composites Using Capillary Flow

Nicoleta-Violeta Stanciu, Felicia Stan \* and Catalin Fetecau

Center of Excellence Polymer Processing, Dunarea de Jos University of Galati, 47 Domneasca, 800 008, Galati, Romania;

\* Correspondence: felicia.stan@ugal.ro

Received: date; Accepted: date; Published: date

Table S1. Parameters of the power-law model.

| MWCNTs<br>(wt.%) | Temperature<br>(°C) | K<br>(Pa·s <sup>n</sup> ) | n     | R <sup>2</sup> |
|------------------|---------------------|---------------------------|-------|----------------|
| 0.1              | 110                 | 2392.76                   | 0.549 | 0.994          |
|                  | 120                 | 1523.35                   | 0.585 | 0.996          |
|                  | 130                 | 1021.41                   | 0.617 | 0.995          |
|                  | 140                 | 661.45                    | 0.653 | 0.994          |
| 0.3              | 110                 | 2703.96                   | 0.534 | 0.996          |
|                  | 120                 | 1749.85                   | 0.570 | 0.996          |
|                  | 130                 | 1132.40                   | 0.605 | 0.996          |
|                  | 140                 | 704.69                    | 0.646 | 0.994          |
| 0.5              | 110                 | 2870.78                   | 0.527 | 0.995          |
|                  | 120                 | 1845.44                   | 0.563 | 0.996          |
|                  | 130                 | 1226.03                   | 0.596 | 0.996          |
|                  | 140                 | 768.42                    | 0.636 | 0.994          |
| 1                | 110                 | 3553.04                   | 0.504 | 0.995          |
|                  | 120                 | 2519.42                   | 0.526 | 0.998          |
|                  | 130                 | 1674.94                   | 0.560 | 0.996          |
|                  | 140                 | 1125.64                   | 0.591 | 0.996          |
| 3                | 110                 | 4806.18                   | 0.482 | 0.992          |
|                  | 120                 | 3479.37                   | 0.502 | 0.996          |
|                  | 130                 | 2502.07                   | 0.525 | 0.996          |
|                  | 140                 | 1786.08                   | 0.549 | 0.996          |
| 5                | 110                 | 9086.57                   | 0.419 | 0.996          |
|                  | 120                 | 6327.03                   | 0.446 | 0.997          |
|                  | 130                 | 4721.72                   | 0.467 | 0.998          |
|                  | 140                 | 3669.44                   | 0.483 | 0.999          |

**Table S2.** Analysis of variance for the consistency index  $K$ .

| Source           | DF | Seq SS   | Adj SS   | Adj MS   | F     | P     | C (%) |
|------------------|----|----------|----------|----------|-------|-------|-------|
| MWCNT (wt.%)     | 5  | 59984628 | 59984628 | 11996926 | 33.66 | 0.000 | 65    |
| Temperature (°C) | 3  | 26266799 | 26266799 | 8755600  | 24.57 | 0.000 | 29    |
| Residual Error   | 15 | 5346112  | 5346112  | 356407   |       |       |       |
| Total            | 23 | 91597539 |          |          |       |       |       |

**Table S3.** Analysis of variance for the power-law index  $n$ .

| Source           | DF | Seq SS   | Adj SS   | Adj MS   | F      | P     | C (%) |
|------------------|----|----------|----------|----------|--------|-------|-------|
| MWCNT (wt.%)     | 5  | 0.062143 | 0.062143 | 0.012429 | 145.86 | 0.000 | 69    |
| Temperature (°C) | 3  | 0.027216 | 0.027216 | 0.009072 | 106.47 | 0.000 | 30    |
| Residual Error   | 15 | 0.001278 | 0.001278 | 0.000085 |        |       |       |
| Total            | 23 | 0.090637 |          |          |        |       |       |

**Table S4.** Flow activation energy.

| MWCNTs<br>(wt.%) | App. shear rate<br>(s <sup>-1</sup> ) | $E_{\dot{\gamma}}$<br>(kJ/mol) | $R^2$ |
|------------------|---------------------------------------|--------------------------------|-------|
| 0.1              | 500                                   | 23.16                          | 0.999 |
|                  | 1000                                  | 21.51                          | 0.994 |
|                  | 3000                                  | 15.30                          | 0.999 |
|                  | 4000                                  | 13.49                          | 0.995 |
| 0.3              | 500                                   | 22.42                          | 0.999 |
|                  | 1000                                  | 20.08                          | 0.999 |
|                  | 3000                                  | 15.92                          | 1.00  |
|                  | 4000                                  | 14.26                          | 0.998 |
| 0.5              | 500                                   | 22.73                          | 0.999 |
|                  | 1000                                  | 20.10                          | 0.999 |
|                  | 3000                                  | 15.65                          | 0.993 |
|                  | 4000                                  | 14.32                          | 0.974 |
| 1                | 500                                   | 23.40                          | 0.973 |
|                  | 1000                                  | 20.66                          | 0.995 |
|                  | 3000                                  | 15.03                          | 0.963 |
|                  | 4000                                  | 13.64                          | 0.935 |
| 3                | 500                                   | 22.03                          | 0.984 |
|                  | 1000                                  | 20.77                          | 0.990 |
|                  | 3000                                  | 15.36                          | 0.943 |
|                  | 4000                                  | 13.91                          | 0.908 |
| 5                | 500                                   | 19.10                          | 0.992 |
|                  | 1000                                  | 15.72                          | 0.999 |
|                  | 3000                                  | 9.21                           | 0.953 |
|                  | 4000                                  | 7.83                           | 0.920 |

**Table S5.** Analysis of variance for the flow activation energy (kJ/mol).

| Source                | DF | Seq SS  | Adj SS  | Adj MS  | F      | P     | %  |
|-----------------------|----|---------|---------|---------|--------|-------|----|
| MWCNTs (wt.%)         | 5  | 91.141  | 91.141  | 18.228  | 39.01  | 0.000 | 21 |
| App. shear rate (1/s) | 3  | 344.022 | 344.022 | 114.674 | 245.41 | 0.000 | 78 |
| Residual Error        | 15 | 7.009   | 7.009   | 0.467   |        |       |    |
| Total                 | 23 | 442.173 |         |         |        |       |    |

**Table S6.** Parameters of the linear model  $\eta = \alpha + \beta \cdot \phi$  and the goodness of fit.

| Melt temperature<br>(°C) | App. shear rate<br>(s <sup>-1</sup> ) | $\alpha$<br>(Pa·s) | $\beta$<br>(Pa·s/wt.%) | $R^2$ |
|--------------------------|---------------------------------------|--------------------|------------------------|-------|
| 110                      | 250                                   | 205.25             | 32.11                  | 0.984 |
|                          | 500                                   | 151.36             | 19.68                  | 0.984 |
|                          | 1000                                  | 114.11             | 11.54                  | 0.986 |
|                          | 3000                                  | 63.51              | 4.52                   | 0.996 |
|                          | 4000                                  | 52.65              | 3.64                   | 0.991 |
| 120                      | 250                                   | 205.25             | 32.11                  | 0.983 |
|                          | 500                                   | 122.53             | 15.97                  | 0.975 |
|                          | 1000                                  | 91.59              | 10.00                  | 0.987 |
|                          | 3000                                  | 53.64              | 4.14                   | 0.993 |
|                          | 4000                                  | 45.62              | 3.24                   | 0.998 |
| 130                      | 250                                   | 130.31             | 23.49                  | 0.985 |
|                          | 500                                   | 100.38             | 14.60                  | 0.974 |
|                          | 1000                                  | 73.75              | 12.56                  | 0.983 |
|                          | 3000                                  | 45.91              | 3.87                   | 0.986 |
|                          | 4000                                  | 39.29              | 3.11                   | 0.981 |
| 140                      | 250                                   | 102.84             | 20.93                  | 0.963 |
|                          | 500                                   | 81.69              | 12.89                  | 0.984 |
|                          | 1000                                  | 63.56              | 8.17                   | 0.984 |
|                          | 3000                                  | 37.59              | 4.13                   | 0.983 |
|                          | 4000                                  | 33.91              | 2.94                   | 0.974 |

<sup>1</sup>  $\eta$  - apparent melt shear viscosity,  $\phi$  - MWCNT wt.%,  $\alpha$ ,  $\beta$  - model parameters.

**Table S7.** Parameters of the Tait model for the LDPE/MWCNT composites.

| Parameters                        | MWCNTs (wt.%)           |                         |                         |                         |                         |                         |
|-----------------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
|                                   | 0.1                     | 0.3                     | 0.5                     | 1                       | 3                       | 5                       |
| $b_{1s}$ (mm <sup>3</sup> /g)     | 1.1018×10 <sup>3</sup>  | 1.0968×10 <sup>3</sup>  | 1.0975×10 <sup>3</sup>  | 1.0940×10 <sup>3</sup>  | 1.0815×10 <sup>3</sup>  | 1.0060×10 <sup>3</sup>  |
| $b_{2s}$ (mm <sup>3</sup> /kg °C) | 7.8597×10 <sup>-1</sup> | 7.6150×10 <sup>-1</sup> | 6.2898×10 <sup>-1</sup> | 7.1563×10 <sup>-1</sup> | 5.3723×10 <sup>-1</sup> | 1.0166×10 <sup>-1</sup> |
| $b_{3s}$ (bar)                    | 1.0294×10 <sup>3</sup>  | 1.0945×10 <sup>3</sup>  | 1.0742×10 <sup>3</sup>  | 1.1483×10 <sup>3</sup>  | 1.1377×10 <sup>3</sup>  | 1.8648×10 <sup>3</sup>  |
| $b_{4s}$ (1/°C)                   | 1.1966×10 <sup>-2</sup> | 1.0896×10 <sup>-2</sup> | 1.2118×10 <sup>-2</sup> | 1.0081×10 <sup>-2</sup> | 1.1757×10 <sup>-2</sup> | 1.0488×10 <sup>-2</sup> |
| $b_{1m}$ (mm <sup>3</sup> /g)     | 1.1863×10 <sup>3</sup>  | 1.1782×10 <sup>3</sup>  | 1.2029×10 <sup>3</sup>  | 1.1844 ×10 <sup>3</sup> | 1.1900×10 <sup>3</sup>  | 1.1739×10 <sup>3</sup>  |
| $b_{2m}$ (mm <sup>3</sup> /kg °C) | 1.2794                  | 1.3516                  | 1.1170                  | 1.2138                  | 1.0137                  | 9.3332×10 <sup>-1</sup> |
| $b_{3m}$ (bar)                    | 7.1798×10 <sup>2</sup>  | 7.2243×10 <sup>2</sup>  | 7.5580×10 <sup>2</sup>  | 8.3479×10 <sup>2</sup>  | 8.6149×10 <sup>2</sup>  | 8.5314×10 <sup>2</sup>  |
| $b_{4m}$ (1/°C)                   | 5.0292×10 <sup>-4</sup> | 4.8950×10 <sup>-4</sup> | 1.6284×10 <sup>-3</sup> | 3.5456×10 <sup>-5</sup> | 3.7832×10 <sup>-4</sup> | 3.1927×10 <sup>-3</sup> |
| $b_5$ (°C)                        | 102.51                  | 101.55                  | 102.40                  | 102.51                  | 102.83                  | 102.72                  |
| $b_6$ (°C/bar)                    | 2.0395×10 <sup>-2</sup> | 2.1096×10 <sup>-2</sup> | 2.0329×10 <sup>-2</sup> | 2.2039×10 <sup>-2</sup> | 1.9518×10 <sup>-2</sup> | 1.9167×10 <sup>-2</sup> |
| $b_7$ (mm <sup>3</sup> /g)        | 7.1139×10 <sup>1</sup>  | 6.6160×10 <sup>1</sup>  | 9.0432×10 <sup>1</sup>  | 7.3962×10 <sup>1</sup>  | 9.2788×10 <sup>1</sup>  | 1.5111×10 <sup>2</sup>  |
| $b_8$ (1/°C)                      | 3.3673×10 <sup>-2</sup> | 3.5145×10 <sup>-2</sup> | 2.6435×10 <sup>-2</sup> | 2.6435×10 <sup>-2</sup> | 2.6558×10 <sup>-2</sup> | 1.6866×10 <sup>-2</sup> |
| $b_9$ (1/bar)                     | 5.6669×10 <sup>-4</sup> | 5.8702×10 <sup>-4</sup> | 4.4469×10 <sup>-4</sup> | 4.7290×10 <sup>-4</sup> | 4.4272×10 <sup>-4</sup> | 3.8001×10 <sup>-4</sup> |

**Table S8.** Thermal conductivity (W/m·K) of the LDPE/MWCNT composites.

| Pressure<br>(bar) | Temperature<br>(°C) | MWCNTs (wt.%) |       |       |       |       |
|-------------------|---------------------|---------------|-------|-------|-------|-------|
|                   |                     | 0.1           | 0.3   | 1     | 3     | 5     |
| 100               | 70                  | 0.272         | 0.272 | 0.280 | 0.312 | 0.343 |
|                   | 90                  | 0.240         | 0.238 | 0.243 | 0.269 | 0.300 |
|                   | 110-140             | 0.223         | 0.222 | 0.226 | 0.251 | 0.282 |
| 250               | 70                  | 0.276         | 0.274 | 0.282 | 0.311 | 0.354 |
|                   | 90                  | 0.254         | 0.252 | 0.258 | 0.287 | 0.321 |
|                   | 110-140             | 0.229         | 0.228 | 0.233 | 0.258 | 0.293 |
| 500               | 70                  | 0.279         | 0.274 | 0.287 | 0.311 | 0.354 |
|                   | 90                  | 0.276         | 0.275 | 0.283 | 0.316 | 0.351 |
|                   | 100                 | 0.252         | 0.252 | 0.257 | 0.287 | 0.324 |
|                   | 110-140             | 0.239         | 0.238 | 0.244 | 0.272 | 0.310 |