Data Article

Dataset for measured viscosity of Polyalpha-Olefin- boron nitride nanofluids

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Abstract

Datasets of measured viscosity of Polyalpha-Olefin- boron nitride (PAO/hBN) nanofluids are reported. An AR-G2 rheometer (from TA Instruments) experimental setup is used for measuring the rheological property of PAO/hBN nanofluids, which is a combined motor and transducer (CMT) instrument. The test fluid sample size is approximately 1.5 ml and the tests were conducted over a temperature range of the tested fluids from −20 °C to 70 °C by a water circulator chamber. The dataset includes measured viscosities as a function of the BN volumetric concentration (ϕ) of 0, 0.6 and 1%. Two sets of viscosity measurements are conducted insuring the thermal equilibrium conditions are reached for all experiments. In set (1), the viscosity is measured at intervals of 10 °C by fixing the temperature at each interval (at −20, −10, 0, 10, 20, 30, 40, 50, 60 and 70 °C), while the shear stress and shear rate are varied. In set (2), the temperature is varied from −20 °C to 70 °C at intervals of 0.5 °C, while the shear stress is fixed and the shear rate is varied accordingly. Set (1) is designed to verify whether the fluids are Newtonian or not and set (2) is designed to derive correlations for the viscosity as a function of temperature. Several characteristics data are recorded including rotational speed of the spindle (RPM), torque, viscosity (Pa-s), shear stress (Pa), shear strain rate (1/s) and temperature (°C). The reuse potential of the dataset includes calculating Reynolds number for further flow studies; heat transfer performance studies of nanofluids; lubrication and lubricants’ development studies and characteristics of Newtonian and

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non-Newtonian fluids. The dataset reported here were used (but not published) in the article published by the author in 
[1] (https://doi.org/10.1016/j.csite.2020.100776).
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### Specifications Table

| Subject                  | Energy (Nanofluids)                                                                 |
|--------------------------|------------------------------------------------------------------------------------|
| Specific subject area    | Nanofluids for heat transfer and lubrication; viscosity measurements                |
| Type of data             | Tables                                                                             |
|                          | Figures                                                                            |
| How data were acquired   | The data were acquired using AR-G2 rheometer (from TA Instruments, 2005) experimental setup for measuring the rheological property of PAO/hBN nanofluids, which is a combined motor and transducer (CMT) instrument. The raw data were exported to Excel spreadsheets. |
| Data format              | Raw and Filtered Data                                                             |
| Parameters for data collection | The two sets of viscosity measurements data are collected at intervals of 10 °C and at intervals of 0.5 °C insuring the thermal equilibrium conditions are reached for all experiments |
| Description of data collection | The data were collected using the measurement method described above. The data were saved and exported to Excel spreadsheets for further organizing. |
| Data source location     | Institution: Qatar University                                                     |
|                          | City/Town/Region: Doha                                                             |
|                          | Country: Qatar                                                                    |
| Data accessibility       | The data are hosted 'With the article'.                                            |
| Related research article | The data article is related to the following research article:                    |
|                          | A.K. Sleiti, Heat transfer measurements of Polyalphaolefin- boron nitride nanofluids for thermal management and lubrication applications, Case Stud. Therm. Eng. 22 (2020) 100,776. https://doi.org/10.1016/j.csite.2020.100776. |

### Value of the Data

- The data are important and useful because the reuse potential of the dataset includes calculating Reynolds number for further flow studies; heat transfer performance studies of nanofluids; lubrication and lubricants’ development studies [2–5] and characteristics of Newtonian and non-Newtonian fluids [6].
- The data can benefit engineers, researchers and scientists working in the fields of energy, thermofluids, power systems, energy storage, materials, cooling, heating and lubrication.
- The data can be used/reused for further insights and development of experiments by extrapolating the data to more ranges of temperature and concentration and testing new sets of PAO based nanofluids.
- The artificial neural networks are high performance predictive tools. The data of the present study can be used for comparative analysis studies of the predictive performance of such artificial neural networks that can be developed using the experimental viscosity results of the nanofluids of the present study.

### 1. Data Description

The data provided in this article are related to the published article in [1]. Fig. 1 shows schematic for the experimental setup used for the viscosity measurements of the pure PAO base fluid and for the PAO/hBN nanofluids. The AR-G2 rheometer from TA Instruments is used. The constraint on the low torque performance of such an instrument is the friction between the
rotating and the stationary components. The temperature of the tested fluids is controlled between −20 °C to 70 °C by a water circulator chamber. Different data were taken including rotational speed of the spindle (RPM), torque, viscosity (Pa-s), shear stress (Pa), shear strain rate (1/s) and temperature (°C).

Shear stress, shear rate, and viscosity data are provided in Tables 1, 3 and 5 (data set (1)) for pure PAO base fluids (ϕ = 0%), for PAO/hBN nanofluids with BN particle concentration, ϕ = 0.6%, and 1.0%, respectively as a function of temperature from negative 20 to 70 °C at intervals of 10 °C. This set of data is used to characterize the fluids in terms of Newtonian or non-Newtonian fluids. Figs. 2, 4 and 6 illustrate the data of Tables 1, 3 and 5, respectively in terms of shear stress versus shear strain for pure PAO base fluids (ϕ = 0%), for PAO/hBN nanofluids with BN particle concentration, ϕ = 0.6%, and 1.0%, respectively over the full temperature range from negative 20 to 70 °C.
Table 1
Raw data for pure PAO base fluids ($\phi = 0$) as a function of temperature at fixed temperature intervals and varied shear and shear rate. This set of data is used to verify whether the fluid is Newtonian or non-Newtonian.

| Shear stress Pa | Shear rate 1/s | Viscosity Pa.s | Temperature ºC |
|----------------|---------------|----------------|---------------|
| 9.995          | 13.44         | 0.7438         | -20           |
| 80.67          | 110.3         | 0.7314         | -20           |
| 151.3          | 208.3         | 0.7266         | -20           |
| 222            | 308.8         | 0.719          | -20           |
| 292.7          | 406           | 0.7209         | -20           |
| 363.4          | 509.5         | 0.7132         | -20           |
| 434.1          | 612.2         | 0.709          | -20           |
| 504.7          | 709.2         | 0.7117         | -20           |
| 575.4          | 816.3         | 0.7049         | -20           |
| 646.1          | 917.7         | 0.704          | -20           |
| 716.8          | 1017          | 0.7046         | -20           |
| 787.4          | 1135          | 0.6939         | -20           |
| 858.1          | 1245          | 0.6893         | -20           |
| 928.8          | 1357          | 0.6847         | -20           |
| 999.4          | 1455          | 0.6867         | -20           |
| 9.988          | 31.49         | 0.3172         | -10           |
| 80.62          | 257.1         | 0.3136         | -10           |
| 151.2          | 487.5         | 0.3102         | -10           |
| 221.9          | 723.8         | 0.3065         | -10           |
| 292.5          | 961.5         | 0.3042         | -10           |
| 363.1          | 1199          | 0.3029         | -10           |
| 433.7          | 1443          | 0.3005         | -10           |
| 504.4          | 1686          | 0.2991         | -10           |
| 575            | 1933          | 0.2975         | -10           |
| 645.6          | 2186          | 0.2954         | -10           |
| 716.2          | 2453          | 0.2922         | -10           |
| 786.8          | 2720          | 0.2893         | -10           |
| 857.4          | 2986          | 0.2872         | -10           |
| 928            | 3268          | 0.284          | -10           |
| 998.6          | 3550          | 0.2813         | -10           |
| 9.976          | 62.7          | 0.1591         | 3.00E-03      |
| 66.27          | 419.1         | 0.1581         | -2.00E-03     |
| 122.6          | 779.3         | 0.1573         | -2.00E-03     |
| 178.9          | 1130          | 0.1582         | 3.00E-03      |
| 235.2          | 1454          | 0.1618         | 3.00E-03      |
| 291.5          | 1805          | 0.1614         | -6.00E-03     |
| 347.7          | 2146          | 0.1621         | 3.00E-03      |
| 404            | 2497          | 0.1618         | 0             |
| 460.3          | 2834          | 0.1624         | 0             |
| 516.6          | 3188          | 0.1621         | -2.00E-03     |
| 572.9          | 3530          | 0.1623         | 0             |
| 629.2          | 3879          | 0.1622         | 0             |
| 685.5          | 4253          | 0.1612         | 3.00E-03      |
| 741.8          | 4646          | 0.1597         | -2.00E-03     |
| 798.1          | 5038          | 0.1584         | -6.00E-03     |
| 9.96           | 103.8         | 0.09593        | 10            |
| 44.82          | 469.6         | 0.09544        | 10            |
| 79.68          | 831.3         | 0.09585        | 10            |
| 114.6          | 1177          | 0.09731        | 10            |
| 149.4          | 1509          | 0.09901        | 10            |
| 184.3          | 1845          | 0.0999        | 10            |
| 219.2          | 2192          | 0.09997        | 10            |
| 254            | 2544          | 0.09987        | 10            |
| 288.9          | 2906          | 0.09942        | 10            |
| 323.8          | 3242          | 0.09986        | 10            |
| 358.6          | 3595          | 0.09975        | 10            |
| 393.5          | 3936          | 0.09998        | 10            |
| 428.4          | 4278          | 0.1001         | 10            |

(continued on next page)
| Shear stress Pa | Shear rate 1/s | Viscosity Pa.s | Temperature °C |
|----------------|----------------|----------------|---------------|
| 463.2          | 4633           | 0.09998        | 10            |
| 498.1          | 4961           | 0.1004         | 10            |
| 9.941          | 155.1          | 0.0641         | 20            |
| 44.73          | 709.3          | 0.06306        | 20            |
| 79.52          | 1264           | 0.06289        | 20            |
| 114.3          | 1806           | 0.06329        | 20            |
| 149.1          | 2357           | 0.06327        | 20            |
| 183.9          | 2903           | 0.06335        | 20            |
| 218.7          | 3461           | 0.06317        | 20            |
| 253.5          | 4025           | 0.06297        | 20            |
| 288.2          | 4581           | 0.06293        | 20            |
| 323            | 5139           | 0.06286        | 20            |
| 357.8          | 5715           | 0.06261        | 20            |
| 9.903          | 253.4          | 0.03908        | 30            |
| 79.93          | 2048           | 0.03902        | 30            |
| 150            | 3865           | 0.0388         | 30            |
| 220            | 5694           | 0.03863        | 30            |
| 290            | 7549           | 0.03841        | 30            |
| 360            | 9465           | 0.03803        | 30            |
| 429.9          | 11,370         | 0.03783        | 30            |
| 499.9          | 13,270         | 0.03768        | 30            |
| 569.9          | 15,180         | 0.03755        | 30            |
| 9.857          | 373.6          | 0.02639        | 40            |
| 44.36          | 1676           | 0.02647        | 40            |
| 78.86          | 2984           | 0.02642        | 40            |
| 113.4          | 4296           | 0.02638        | 40            |
| 147.8          | 5635           | 0.02624        | 40            |
| 182.3          | 6985           | 0.0261         | 40            |
| 216.8          | 8327           | 0.02604        | 40            |
| 251.3          | 9700           | 0.0259         | 40            |
| 285.8          | 11,090         | 0.02577        | 40            |
| 320.2          | 12,470         | 0.02568        | 40            |
| 354.7          | 13,760         | 0.02579        | 40            |
| 9.797          | 530.4          | 0.01847        | 50            |
| 37.09          | 1998           | 0.01856        | 50            |
| 64.39          | 3472           | 0.01854        | 50            |
| 91.67          | 4956           | 0.0185         | 50            |
| 119            | 6463           | 0.01841        | 50            |
| 146.2          | 7969           | 0.01835        | 50            |
| 173.5          | 9532           | 0.0182         | 50            |
| 9.728          | 713.7          | 0.01363        | 60            |
| 24.58          | 1793           | 0.01371        | 60            |
| 39.43          | 2884           | 0.01367        | 60            |
| 54.27          | 3974           | 0.01366        | 60            |
| 69.11          | 5071           | 0.01363        | 60            |
| 83.95          | 6176           | 0.01359        | 60            |
| 98.79          | 7284           | 0.01356        | 60            |
| 113.6          | 8416           | 0.0135         | 60            |
| 128.5          | 9569           | 0.01342        | 60            |
| 143.3          | 10,710         | 0.01338        | 60            |
| 9.647          | 920.2          | 0.01048        | 70            |
| 24.37          | 2330           | 0.01046        | 70            |
| 39.1           | 3734           | 0.01047        | 70            |
| 53.82          | 5156           | 0.01044        | 70            |
| 68.53          | 6601           | 0.01038        | 70            |
| 83.24          | 8057           | 0.01033        | 70            |
| 97.94          | 9514           | 0.01029        | 70            |
| 112.6          | 10,970         | 0.01026        | 70            |
Table 2

Raw data for pure PAO base fluids ($\phi = 0$) as a function of temperature at fixed shear stress and varied temperature at 0.5 °C intervals. This set of data is used to derive correlations for the viscosity as a function of temperature.

| Shear stress Pa | Shear rate 1/s | Viscosity Pa.s | Temperature °C |
|----------------|----------------|----------------|----------------|
| 9.995          | 12.94          | 0.77220        | −19.70         |
| 9.995          | 13.55          | 0.73740        | −19.10         |
| 9.995          | 14.15          | 0.70620        | −18.50         |
| 9.994          | 14.75          | 0.67740        | −18.00         |
| 9.994          | 15.23          | 0.65610        | −17.50         |
| 9.994          | 16.07          | 0.62200        | −17.00         |
| 9.994          | 16.92          | 0.59070        | −16.50         |
| 9.993          | 17.62          | 0.56710        | −16.00         |
| 9.993          | 18.26          | 0.54710        | −15.50         |
| 9.993          | 19.03          | 0.52500        | −15.00         |
| 9.992          | 19.83          | 0.50400        | −14.50         |
| 9.992          | 20.55          | 0.48630        | −14.00         |
| 9.992          | 21.35          | 0.46800        | −13.50         |
| 9.991          | 22.24          | 0.44920        | −13.00         |
| 9.991          | 22.93          | 0.43570        | −12.50         |
| 9.991          | 23.74          | 0.42090        | −12.00         |
| 9.991          | 24.16          | 0.41350        | −11.50         |
| 9.990          | 25.09          | 0.39820        | −11.00         |
| 9.990          | 25.35          | 0.39410        | −10.50         |
| 9.990          | 25.67          | 0.38910        | −10.00         |
| 9.990          | 27.29          | 0.36600        | −9.50          |
| 9.989          | 29.07          | 0.34360        | −9.00          |
| 9.988          | 30.32          | 0.32950        | −8.50          |
| 9.988          | 30.95          | 0.32270        | −8.00          |
| 9.987          | 32.70          | 0.30550        | −7.50          |
| 9.987          | 35.25          | 0.28330        | −7.00          |
| 9.986          | 35.90          | 0.27820        | −6.50          |
| 9.985          | 37.94          | 0.26320        | −6.00          |
| 9.985          | 38.82          | 0.25720        | −5.50          |
| 9.985          | 40.42          | 0.24700        | −5.00          |
| 9.984          | 41.40          | 0.24120        | −4.50          |
| 9.983          | 43.37          | 0.23020        | −4.00          |
| 9.983          | 44.75          | 0.22310        | −3.50          |
| 9.982          | 46.05          | 0.21680        | −3.00          |
| 9.982          | 47.88          | 0.20850        | −2.50          |
| 9.981          | 49.81          | 0.20040        | −2.00          |
| 9.980          | 51.87          | 0.19240        | −1.50          |
| 9.980          | 53.52          | 0.18650        | −1.00          |
| 9.979          | 55.67          | 0.17920        | −0.50          |
| 9.978          | 56.66          | 0.17610        | −0.10          |
| 9.977          | 59.21          | 0.16850        | 0.50           |
| 9.977          | 61.07          | 0.16340        | 1.00           |
| 9.976          | 63.26          | 0.15770        | 1.50           |
| 9.975          | 65.18          | 0.15300        | 2.00           |
| 9.974          | 67.16          | 0.14850        | 2.50           |
| 9.974          | 69.21          | 0.14410        | 3.00           |
| 9.973          | 71.23          | 0.14000        | 3.50           |
| 9.972          | 73.28          | 0.13610        | 4.00           |
| 9.971          | 75.34          | 0.13230        | 4.50           |
| 9.970          | 77.55          | 0.12860        | 5.00           |
| 9.969          | 79.79          | 0.12490        | 5.50           |
| 9.969          | 81.91          | 0.12170        | 6.00           |
| 9.968          | 84.28          | 0.11830        | 6.50           |
| 9.967          | 86.53          | 0.11520        | 7.00           |
| 9.966          | 88.83          | 0.11220        | 7.50           |
| 9.965          | 91.33          | 0.10910        | 8.00           |
| 9.964          | 93.74          | 0.10630        | 8.50           |
| 9.963          | 96.20          | 0.10360        | 9.00           |
| 9.962          | 98.63          | 0.10100        | 9.50           |

(continued on next page)
Table 2 (continued)

| Shear stress Pa | Shear rate 1/s | Viscosity Pa.s | Temperature °C |
|-----------------|----------------|---------------|----------------|
| 9.961           | 101.20         | 0.09844       | 10.00          |
| 9.959           | 103.90         | 0.09588       | 10.50          |
| 9.958           | 106.50         | 0.09354       | 11.00          |
| 9.957           | 109.30         | 0.09113       | 11.50          |
| 9.956           | 112.00         | 0.08889       | 12.00          |
| 9.955           | 114.90         | 0.08668       | 12.50          |
| 9.954           | 117.80         | 0.08454       | 13.00          |
| 9.953           | 120.80         | 0.08242       | 13.50          |
| 9.952           | 123.70         | 0.08046       | 14.00          |
| 9.951           | 126.80         | 0.07849       | 14.50          |
| 9.950           | 129.90         | 0.07662       | 15.00          |
| 9.949           | 133.30         | 0.07466       | 15.50          |
| 9.948           | 136.60         | 0.07283       | 16.00          |
| 9.946           | 139.90         | 0.07110       | 16.50          |
| 9.945           | 143.50         | 0.06931       | 17.00          |
| 9.944           | 147.00         | 0.06767       | 17.50          |
| 9.942           | 150.50         | 0.06605       | 18.00          |
| 9.941           | 154.10         | 0.06453       | 18.50          |
| 9.939           | 157.80         | 0.06301       | 19.00          |
| 9.937           | 161.50         | 0.06153       | 19.50          |
| 9.936           | 165.30         | 0.06011       | 20.00          |
| 9.935           | 169.20         | 0.05871       | 20.50          |
| 9.934           | 173.30         | 0.05732       | 21.00          |
| 9.932           | 177.30         | 0.05602       | 21.50          |
| 9.931           | 181.20         | 0.05481       | 21.90          |
| 9.929           | 185.60         | 0.05349       | 22.50          |
| 9.927           | 189.70         | 0.05234       | 23.00          |
| 9.926           | 194.00         | 0.05116       | 23.50          |
| 9.924           | 198.60         | 0.04997       | 24.00          |
| 9.922           | 203.10         | 0.04886       | 24.50          |
| 9.921           | 207.70         | 0.04775       | 25.00          |
| 9.919           | 212.50         | 0.04669       | 25.50          |
| 9.917           | 216.80         | 0.04575       | 26.00          |
| 9.915           | 221.40         | 0.04478       | 26.50          |
| 9.913           | 226.20         | 0.04383       | 27.00          |
| 9.912           | 231.10         | 0.04290       | 27.50          |
| 9.910           | 236.10         | 0.04197       | 28.00          |
| 9.908           | 241.00         | 0.04111       | 28.50          |
| 9.906           | 246.30         | 0.04023       | 29.00          |
| 9.904           | 251.60         | 0.03936       | 29.50          |
| 9.902           | 256.70         | 0.03858       | 30.00          |
| 9.900           | 262.00         | 0.03778       | 30.50          |
| 9.898           | 266.90         | 0.03709       | 31.00          |
| 9.896           | 272.10         | 0.03637       | 31.50          |
| 9.894           | 277.20         | 0.03569       | 32.00          |
| 9.892           | 282.90         | 0.03496       | 32.50          |
| 9.890           | 288.50         | 0.03428       | 33.00          |
| 9.888           | 294.00         | 0.03363       | 33.50          |
| 9.885           | 300.00         | 0.03295       | 34.00          |
| 9.883           | 305.80         | 0.03232       | 34.50          |
| 9.881           | 311.90         | 0.03168       | 35.00          |
| 9.878           | 317.90         | 0.03108       | 35.50          |
| 9.876           | 323.80         | 0.03050       | 36.00          |
| 9.874           | 330.00         | 0.02992       | 36.50          |
| 9.871           | 336.20         | 0.02936       | 37.00          |
| 9.869           | 342.50         | 0.02881       | 37.50          |
| 9.866           | 348.90         | 0.02828       | 38.00          |
| 9.864           | 355.30         | 0.02776       | 38.50          |
| 9.862           | 362.00         | 0.02724       | 39.00          |
| 9.859           | 368.70         | 0.02674       | 39.50          |

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| Shear stress (Pa) | Shear rate (1/s) | Viscosity (Pa.s) | Temperature (°C) |
|------------------|-----------------|-----------------|-----------------|
| 9.856            | 375.10          | 0.02628         | 40.00           |
| 9.854            | 382.40          | 0.02577         | 40.50           |
| 9.851            | 388.50          | 0.02535         | 41.00           |
| 9.849            | 395.80          | 0.02488         | 41.50           |
| 9.846            | 402.90          | 0.02444         | 42.00           |
| 9.843            | 409.80          | 0.02402         | 42.50           |
| 9.840            | 417.30          | 0.02358         | 43.00           |
| 9.838            | 424.30          | 0.02318         | 43.50           |
| 9.835            | 431.50          | 0.02279         | 44.00           |
| 9.832            | 438.80          | 0.02240         | 44.50           |
| 9.829            | 446.40          | 0.02202         | 45.00           |
| 9.826            | 454.00          | 0.02164         | 45.50           |
| 9.824            | 461.10          | 0.02130         | 46.00           |
| 9.821            | 468.80          | 0.02095         | 46.50           |
| 9.817            | 477.20          | 0.02057         | 47.00           |
| 9.815            | 484.70          | 0.02025         | 47.50           |
| 9.812            | 492.50          | 0.01992         | 48.00           |
| 9.808            | 500.60          | 0.01959         | 48.50           |
| 9.805            | 508.80          | 0.01927         | 49.00           |
| 9.802            | 516.70          | 0.01897         | 49.50           |
| 9.799            | 524.70          | 0.01868         | 50.00           |
| 9.796            | 533.00          | 0.01838         | 50.50           |
| 9.793            | 540.70          | 0.01811         | 51.00           |
| 9.790            | 549.40          | 0.01782         | 51.50           |
| 9.787            | 557.60          | 0.01755         | 52.00           |
| 9.784            | 564.60          | 0.01733         | 52.50           |
| 9.780            | 573.80          | 0.01704         | 53.00           |
| 9.777            | 581.70          | 0.01681         | 53.50           |
| 9.774            | 590.60          | 0.01655         | 54.00           |
| 9.771            | 598.60          | 0.01632         | 54.50           |
| 9.768            | 606.60          | 0.01610         | 55.00           |
| 9.765            | 615.00          | 0.01588         | 55.50           |
| 9.761            | 623.80          | 0.01565         | 56.00           |
| 9.758            | 631.30          | 0.01546         | 56.50           |
| 9.755            | 641.40          | 0.01521         | 57.00           |
| 9.752            | 649.00          | 0.01502         | 57.50           |
| 9.749            | 657.00          | 0.01484         | 58.00           |
| 9.746            | 663.90          | 0.01468         | 58.50           |
| 9.743            | 670.90          | 0.01452         | 59.00           |
| 9.739            | 681.90          | 0.01428         | 59.50           |
| 9.736            | 690.50          | 0.01410         | 60.00           |
| 9.734            | 695.10          | 0.01400         | 60.50           |
| 9.733            | 698.80          | 0.01393         | 61.00           |
| 9.729            | 709.30          | 0.01372         | 61.50           |
| 9.687            | 817.10          | 0.01186         | 62.00           |
| 9.683            | 827.50          | 0.01170         | 62.50           |
| 9.680            | 837.40          | 0.01156         | 63.00           |
| 9.675            | 848.60          | 0.01140         | 63.50           |
| 9.671            | 858.80          | 0.01126         | 64.00           |
| 9.667            | 869.10          | 0.01112         | 64.50           |
| 9.663            | 880.70          | 0.01097         | 65.00           |
| 9.659            | 891.60          | 0.01083         | 65.50           |
| 9.655            | 902.20          | 0.01070         | 66.00           |
| 9.650            | 913.60          | 0.01056         | 66.50           |
| 9.646            | 924.70          | 0.01043         | 67.00           |
| 9.642            | 935.60          | 0.01031         | 67.50           |
| 9.637            | 948.00          | 0.01017         | 68.00           |
| 9.633            | 958.80          | 0.01005         | 68.50           |
| 9.628            | 971.30          | 0.00991         | 69.00           |
| 9.624            | 982.70          | 0.00979         | 69.50           |
| 9.620            | 994.50          | 0.00967         | 70.00           |
Fig. 3. Viscosity versus temperature for pure PAO base fluid over a temperature range from negative 20 to 70 °C.

Tables 2, 4 and 6 (data set (2)) provide the raw data for pure PAO base fluid (φ = 0), for PAO/hBN nanofluids with BN particle concentration, φ = 0.6% and φ = 1.0%, respectively as a function of temperature at fixed shear stress and varied temperature at 0.5 °C intervals. This set of data is used to derive correlations for the viscosity as a function of temperature. Figs. 3, 5 and 7 illustrate the data of Tables 2, 4 and 6, respectively in terms of viscosity versus temperature for pure PAO base fluids (φ = 0%), for PAO/hBN nanofluids with BN particle concentration, φ = 0.6%, and 1.0%, respectively over the full temperature range from negative 20 to 70 °C.

Fig. 2 shows a plot of Table 1 data of the shear stress versus shear rate for the base fluid (pure PAO) over the full range of temperatures from negative 20 to 70 °C. The linear behaviour of the results confirms that the pure PAO is Newtonian fluid.

Fig. 3 illustrates data from Table 2 of the dependence of viscosity on temperature for the base fluid (pure PAO) over a temperature range from negative 20 to 70 °C.

Fig. 4 shows a plot of the data presented in Table 3 of the shear stress versus shear rate for PAO/hBN nanofluid with BN particle concentration, φ = 0.6% over the full range of temperatures from negative 20 to 70 °C.

Fig. 5 illustrates data from Table 4 of the dependence of viscosity on temperature for PAO/hBN nanofluid with BN particle concentration, φ = 0.6% over a temperature range from negative 20 to 70 °C.

Fig. 6 shows a plot of the data presented in Table 5 of the shear stress versus shear rate for PAO/hBN nanofluid with BN particle concentration, φ = 1.0% over the full range of temperatures from negative 20 to 70 °C.

Fig. 7 illustrates data from Table 6 of the dependence of viscosity on temperature for PAO/hBN nanofluid with BN particle concentration, φ = 1.0% over a temperature range from negative 20 to 68.5 °C.

2. Experimental Design, Materials and Methods

The BN used in this study is the Hexagonal Boron Nitride (hBN) Powder 99.5% pure purchased from M K Impex Canada and the PAO is DURASYN_ 166 purchased from Chemcentral (Chicago, IL, USA). The average particles size of the BN is 70 nm and the density of the BN powder is 2.26 gm/cm3. Nanofluid samples with BN particle volumetric concentrations of 0.6% and 1% were prepared by adding the exact amount of Boron nitride to the PAO. For preparing the 1% by
Table 3
Raw data for PAO/hBN nanofluid for BN particle concentration, φ = 0.6% as a function of temperature at fixed temperature intervals and varied shear and shear rate. This set of data is used to verify whether the fluid is Newtonian or non-Newtonian.

| Shear stress Pa | Shear rate 1/s | Viscosity Pa.s | Temperature °C |
|-----------------|----------------|---------------|----------------|
| 9.996           | 11.74          | 0.8513        | −20            |
| 80.68           | 95.4           | 0.8457        | −20            |
| 151.4           | 180.6          | 0.8379        | −20            |
| 222             | 267.1          | 0.8314        | −20            |
| 292.7           | 354.7          | 0.8253        | −20            |
| 363.4           | 445.1          | 0.8164        | −20            |
| 434.1           | 534            | 0.8128        | −20            |
| 504.8           | 622.2          | 0.8113        | −20            |
| 575.4           | 711.3          | 0.809         | −20            |
| 646.1           | 801.3          | 0.8064        | −20            |
| 716.8           | 893.9          | 0.8019        | −20            |
| 787.5           | 988.1          | 0.7969        | −20            |
| 858.2           | 1087           | 0.7893        | −20            |
| 928.8           | 1182           | 0.7856        | −20            |
| 999.5           | 1278           | 0.7823        | −20            |
| 9.989           | 27.57          | 0.3623        | −10            |
| 62.04           | 172.5          | 0.3597        | −10            |
| 114.1           | 319.6          | 0.3569        | −10            |
| 166.1           | 470.2          | 0.3533        | −10            |
| 218.2           | 618.6          | 0.3527        | −10            |
| 270.2           | 771.9          | 0.3501        | −10            |
| 322.3           | 924.7          | 0.3485        | −10            |
| 374.3           | 1077           | 0.347         | −10            |
| 426.4           | 1229           | 0.3469        | −10            |
| 478.4           | 1385           | 0.3455        | −10            |
| 530.5           | 1539           | 0.3446        | −10            |
| 582.5           | 1700           | 0.3426        | −10            |
| 634.6           | 1859           | 0.3413        | −10            |
| 686.6           | 2016           | 0.3405        | −10            |
| 738.6           | 2192           | 0.337         | −10            |
| 790.7           | 2364           | 0.3344        | −10            |
| 842.7           | 2541           | 0.3316        | −10            |
| 894.8           | 2710           | 0.3302        | −10            |
| 946.8           | 2885           | 0.3282        | −10            |
| 998.8           | 3068           | 0.3256        | −10            |
| 9.98           | 51.63          | 0.1933        | 0              |
| 61.98           | 328.8          | 0.1885        | 0              |
| 114             | 609.9          | 0.1869        | 3.00E-03       |
| 166             | 888.9          | 0.1867        | 3.00E-03       |
| 218             | 1168           | 0.1867        | 7.00E-03       |
| 270             | 1448           | 0.1864        | 3.00E-03       |
| 322             | 1726           | 0.1866        | 3.00E-03       |
| 374             | 2000           | 0.187         | 7.00E-03       |
| 426             | 2279           | 0.1869        | −2.00E-03      |
| 478             | 2558           | 0.1868        | 0              |
| 530             | 2836           | 0.1869        | −0.01          |
| 582             | 3100           | 0.1878        | −6.00E-03      |
| 634             | 3384           | 0.1874        | −2.00E-03      |
| 686             | 3674           | 0.1867        | 0              |
| 738             | 3971           | 0.1859        | 3.00E-03       |
| 789.9           | 4270           | 0.185         | −2.00E-03      |
| 841.9           | 4559           | 0.1847        | 7.00E-03       |
| 893.9           | 4861           | 0.1839        | −6.00E-03      |
| 945.9           | 5161           | 0.1833        | −0.01          |
| 997.9           | 5475           | 0.1823        | 0              |
| 9.964           | 93.13          | 0.107         | 10             |
| 61.88           | 589.6          | 0.1049        | 10             |

(continued on next page)
| Shear stress Pa | Shear rate 1/s | Viscosity Pa.s | Temperature °C |
|----------------|---------------|----------------|----------------|
| 113.8          | 1089          | 0.1045         | 10             |
| 165.7          | 1595          | 0.1039         | 10             |
| 217.6          | 2107          | 0.1033         | 10             |
| 269.5          | 2628          | 0.1025         | 10             |
| 321.4          | 3178          | 0.1011         | 10             |
| 373.3          | 3721          | 0.1003         | 10             |
| 425.2          | 4314          | 0.09856        | 10             |
| 9.941          | 154.2         | 0.06447        | 20             |
| 61.74          | 959.1         | 0.06437        | 20             |
| 113.5          | 1770          | 0.06414        | 20             |
| 165.3          | 2591          | 0.06381        | 20             |
| 217.1          | 3427          | 0.06336        | 20             |
| 268.9          | 4253          | 0.06323        | 20             |
| 320.7          | 5069          | 0.06326        | 20             |
| 372.5          | 5901          | 0.06312        | 20             |
| 424.3          | 6760          | 0.06276        | 20             |
| 9.912          | 230           | 0.0431         | 30             |
| 44.61          | 1032          | 0.04323        | 30             |
| 79.3           | 1836          | 0.0432         | 30             |
| 114            | 2660          | 0.04286        | 30             |
| 148.7          | 3459          | 0.04298        | 30             |
| 183.4          | 4296          | 0.04268        | 30             |
| 218            | 5092          | 0.04282        | 30             |
| 252.7          | 5929          | 0.04263        | 30             |
| 287.4          | 6772          | 0.04244        | 30             |
| 322.1          | 7636          | 0.04218        | 30             |
| 9.87           | 341.5         | 0.0289         | 40             |
| 44.41          | 1539          | 0.02886        | 40             |
| 78.95          | 2742          | 0.0288         | 40             |
| 113.5          | 3947          | 0.02876        | 40             |
| 148            | 5161          | 0.02868        | 40             |
| 182.6          | 6390          | 0.02857        | 40             |
| 217.1          | 7649          | 0.02838        | 40             |
| 251.6          | 8915          | 0.02822        | 40             |
| 286.1          | 10,170        | 0.02813        | 40             |
| 9.817          | 478.4         | 0.02052        | 50             |
| 30.15          | 1482          | 0.02034        | 50             |
| 50.48          | 2485          | 0.02031        | 50             |
| 70.81          | 3492          | 0.02027        | 50             |
| 91.14          | 4509          | 0.02021        | 50             |
| 111.5          | 5530          | 0.02016        | 50             |
| 131.8          | 6537          | 0.02016        | 50             |
| 152.1          | 7579          | 0.02007        | 50             |
| 172.4          | 8636          | 0.01996        | 50             |
| 192.7          | 9725          | 0.01982        | 50             |
| 9.832          | 427.6         | 0.02299        | 60             |
| 29.99          | 1881          | 0.01595        | 60             |
| 50.19          | 3233          | 0.01552        | 60             |
| 70.39          | 4578          | 0.01538        | 60             |
| 90.58          | 5964          | 0.01519        | 60             |
| 110.7          | 7378          | 0.01501        | 60             |
| 130.9          | 8752          | 0.01496        | 60             |
| 151.1          | 10,130        | 0.01492        | 60             |
| 171.3          | 11,610        | 0.01476        | 60             |
| 10             | 5.06E-06      | 1.98E+06       | 70             |
| 29.93          | 2041          | 0.01467        | 70             |
| 49.96          | 3841          | 0.01301        | 70             |
| 70.05          | 5469          | 0.01281        | 70             |
| 90.18          | 7016          | 0.01285        | 70             |
| 110.1          | 9034          | 0.01219        | 70             |
| 130.1          | 10,970        | 0.01186        | 70             |
Table 4
Raw data for PAO/hBN nanofluid with BN particle concentration, \( \phi = 0.6\% \) as a function of temperature at fixed shear stress and varied temperature at 0.5 °C intervals. This set of data is used to derive correlations for the viscosity as a function of temperature.

| Shear stress Pa | Shear rate 1/s | Viscosity Pa.s | Temperature °C |
|-----------------|---------------|----------------|----------------|
| 9.996           | 10.99         | 0.90920        | −19.70         |
| 9.996           | 11.43         | 0.87420        | −19.10         |
| 9.995           | 11.89         | 0.84070        | −18.60         |
| 9.995           | 12.40         | 0.80590        | −18.00         |
| 9.995           | 12.88         | 0.77630        | −17.50         |
| 9.995           | 13.42         | 0.74460        | −17.00         |
| 9.995           | 14.01         | 0.71340        | −16.50         |
| 9.994           | 14.56         | 0.68640        | −16.00         |
| 9.994           | 15.13         | 0.66060        | −15.60         |
| 9.994           | 15.68         | 0.63730        | −15.00         |
| 9.994           | 16.20         | 0.61680        | −14.50         |
| 9.994           | 16.82         | 0.59410        | −14.00         |
| 9.993           | 17.54         | 0.56980        | −13.50         |
| 9.993           | 18.24         | 0.54780        | −13.00         |
| 9.993           | 18.69         | 0.53470        | −12.50         |
| 9.993           | 19.45         | 0.51360        | −12.00         |
| 9.992           | 19.95         | 0.50090        | −11.50         |
| 9.992           | 20.95         | 0.47690        | −11.00         |
| 9.992           | 21.97         | 0.45470        | −10.50         |
| 9.991           | 22.87         | 0.43690        | −10.00         |
| 9.991           | 23.48         | 0.42550        | −9.50          |
| 9.991           | 24.25         | 0.41200        | −9.00          |
| 9.990           | 25.37         | 0.39380        | −8.50          |
| 9.990           | 25.70         | 0.38880        | −8.00          |
| 9.990           | 27.15         | 0.36800        | −7.50          |
| 9.989           | 28.16         | 0.35470        | −7.00          |
| 9.989           | 29.09         | 0.34340        | −6.50          |
| 9.988           | 30.10         | 0.33190        | −6.00          |
| 9.988           | 31.14         | 0.32080        | −5.50          |
| 9.988           | 32.42         | 0.30810        | −5.00          |
| 9.987           | 33.63         | 0.29700        | −4.50          |
| 9.987           | 34.62         | 0.28840        | −4.00          |
| 9.986           | 36.19         | 0.27590        | −3.50          |
| 9.986           | 37.07         | 0.26930        | −3.00          |
| 9.985           | 38.70         | 0.25800        | −2.50          |
| 9.985           | 40.25         | 0.24810        | −2.00          |
| 9.984           | 41.40         | 0.24120        | −1.50          |
| 9.983           | 43.54         | 0.22930        | −1.00          |
| 9.983           | 45.30         | 0.20300        | −0.50          |
| 9.983           | 44.76         | 0.23080        | 0.00           |
| 9.982           | 48.01         | 0.20790        | 0.50           |
| 9.981           | 49.51         | 0.20160        | 1.00           |
| 9.980           | 51.50         | 0.19380        | 1.50           |
| 9.980           | 53.33         | 0.18710        | 2.00           |
| 9.979           | 55.01         | 0.18140        | 2.50           |
| 9.978           | 56.81         | 0.17560        | 3.00           |
| 9.978           | 58.64         | 0.17010        | 3.50           |
| 9.977           | 60.41         | 0.16520        | 4.00           |
| 9.976           | 62.21         | 0.16040        | 4.50           |
| 9.975           | 64.28         | 0.15520        | 5.00           |
| 9.975           | 66.07         | 0.15100        | 5.50           |
| 9.974           | 68.02         | 0.14660        | 6.00           |
| 9.973           | 70.19         | 0.14210        | 6.50           |
| 9.972           | 72.28         | 0.13800        | 7.00           |
| 9.972           | 74.21         | 0.13440        | 7.50           |
| 9.971           | 76.54         | 0.13030        | 8.00           |
| 9.970           | 78.62         | 0.12680        | 8.50           |
| 9.969           | 81.08         | 0.12300        | 9.00           |
| 9.968           | 83.44         | 0.11950        | 9.50           |

(continued on next page)
| Shear stress (Pa) | Shear rate (1/s) | Viscosity (Pa.s) | Temperature (°C) |
|------------------|-----------------|-----------------|-----------------|
| 9.967            | 85.84           | 0.11610         | 10.00           |
| 9.966            | 88.41           | 0.11270         | 10.50           |
| 9.965            | 90.72           | 0.10980         | 11.00           |
| 9.964            | 93.21           | 0.10690         | 11.50           |
| 9.963            | 95.74           | 0.10410         | 12.00           |
| 9.962            | 98.32           | 0.10130         | 12.50           |
| 9.961            | 101.00          | 0.09858         | 13.00           |
| 9.960            | 103.70          | 0.09602         | 13.50           |
| 9.959            | 106.60          | 0.09338         | 14.00           |
| 9.958            | 109.40          | 0.09102         | 14.50           |
| 9.957            | 112.40          | 0.08862         | 15.00           |
| 9.956            | 115.50          | 0.08619         | 15.50           |
| 9.955            | 118.30          | 0.08412         | 16.00           |
| 9.953            | 121.70          | 0.08182         | 16.50           |
| 9.952            | 124.50          | 0.07994         | 17.00           |
| 9.951            | 128.00          | 0.07773         | 17.50           |
| 9.950            | 131.00          | 0.07596         | 18.00           |
| 9.948            | 134.80          | 0.07380         | 18.50           |
| 9.947            | 138.00          | 0.07209         | 19.00           |
| 9.946            | 141.30          | 0.07040         | 19.50           |
| 9.944            | 145.20          | 0.06850         | 20.00           |
| 9.943            | 148.20          | 0.06708         | 20.50           |
| 9.942            | 152.30          | 0.06529         | 21.00           |
| 9.940            | 155.80          | 0.06381         | 21.50           |
| 9.939            | 159.50          | 0.06231         | 22.00           |
| 9.937            | 163.80          | 0.06069         | 22.50           |
| 9.936            | 167.70          | 0.05924         | 23.00           |
| 9.934            | 171.60          | 0.05789         | 23.50           |
| 9.933            | 175.90          | 0.05646         | 24.00           |
| 9.931            | 179.70          | 0.05525         | 24.50           |
| 9.930            | 183.90          | 0.05400         | 25.00           |
| 9.927            | 190.60          | 0.05207         | 25.40           |
| 9.926            | 194.60          | 0.05101         | 26.00           |
| 9.924            | 198.40          | 0.05002         | 26.50           |
| 9.922            | 202.70          | 0.04895         | 27.00           |
| 9.921            | 207.20          | 0.04789         | 27.50           |
| 9.919            | 211.80          | 0.04682         | 28.00           |
| 9.917            | 216.80          | 0.04573         | 28.50           |
| 9.915            | 221.20          | 0.04482         | 29.00           |
| 9.914            | 225.80          | 0.04390         | 29.50           |
| 9.912            | 231.20          | 0.04286         | 30.00           |
| 9.910            | 235.60          | 0.04206         | 30.50           |
| 9.908            | 241.00          | 0.04111         | 31.00           |
| 9.906            | 246.30          | 0.04021         | 31.50           |
| 9.904            | 251.30          | 0.03941         | 32.00           |
| 9.902            | 256.80          | 0.03856         | 32.50           |
| 9.900            | 262.30          | 0.03774         | 33.00           |
| 9.898            | 267.70          | 0.03697         | 33.50           |
| 9.896            | 272.70          | 0.03629         | 34.00           |
| 9.893            | 278.80          | 0.03548         | 34.50           |
| 9.891            | 284.60          | 0.03476         | 35.00           |
| 9.889            | 290.00          | 0.03411         | 35.50           |
| 9.887            | 296.40          | 0.03335         | 36.00           |
| 9.884            | 302.10          | 0.03272         | 36.50           |
| 9.882            | 307.70          | 0.03211         | 37.00           |
| 9.880            | 313.60          | 0.03150         | 37.50           |
| 9.878            | 320.10          | 0.03086         | 38.00           |
| 9.875            | 326.00          | 0.03029         | 38.50           |
| 9.873            | 332.50          | 0.02969         | 39.00           |
| 9.870            | 338.90          | 0.02913         | 39.50           |
| 9.868            | 345.20          | 0.02858         | 40.00           |
| 9.866            | 351.40          | 0.02807         | 40.50           |
| Shear stress (Pa) | Shear rate (1/s) | Viscosity (Pa.s) | Temperature (°C) |
|------------------|-----------------|-----------------|-----------------|
| 9.863            | 358.40          | 0.02752         | 41.00           |
| 9.860            | 365.00          | 0.02702         | 41.50           |
| 9.858            | 371.90          | 0.02650         | 42.00           |
| 9.855            | 378.80          | 0.02602         | 42.50           |
| 9.853            | 385.10          | 0.02559         | 43.00           |
| 9.850            | 392.40          | 0.02510         | 43.50           |
| 9.847            | 399.70          | 0.02464         | 44.00           |
| 9.844            | 406.50          | 0.02422         | 44.50           |
| 9.842            | 413.80          | 0.02378         | 45.00           |
| 9.839            | 421.30          | 0.02336         | 45.50           |
| 9.836            | 429.00          | 0.02293         | 46.00           |
| 9.833            | 435.90          | 0.02256         | 46.50           |
| 9.830            | 443.20          | 0.02218         | 47.00           |
| 9.828            | 450.90          | 0.02180         | 47.50           |
| 9.824            | 459.10          | 0.02140         | 48.00           |
| 9.822            | 466.10          | 0.02107         | 48.50           |
| 9.819            | 474.40          | 0.02070         | 49.00           |
| 9.816            | 482.00          | 0.02037         | 49.50           |
| 9.813            | 489.70          | 0.02004         | 50.00           |
| 9.809            | 498.30          | 0.01968         | 50.50           |
| 9.806            | 506.00          | 0.01938         | 51.00           |
| 9.803            | 514.20          | 0.01907         | 51.50           |
| 9.800            | 522.70          | 0.01875         | 52.00           |
| 9.797            | 530.60          | 0.01846         | 52.50           |
| 9.794            | 539.40          | 0.01816         | 53.00           |
| 9.790            | 548.00          | 0.01787         | 53.50           |
| 9.787            | 556.40          | 0.01759         | 54.00           |
| 9.784            | 565.10          | 0.01731         | 54.50           |
| 9.780            | 573.80          | 0.01705         | 55.00           |
| 9.777            | 582.40          | 0.01679         | 55.50           |
| 9.774            | 591.50          | 0.01652         | 56.00           |
| 9.770            | 600.40          | 0.01627         | 56.50           |
| 9.767            | 609.00          | 0.01604         | 57.00           |
| 9.764            | 617.90          | 0.01580         | 57.50           |
| 9.760            | 627.80          | 0.01555         | 58.00           |
| 9.757            | 636.40          | 0.01533         | 58.50           |
| 9.753            | 646.30          | 0.01509         | 59.00           |
| 9.749            | 655.20          | 0.01488         | 59.50           |
| 9.746            | 664.60          | 0.01466         | 60.00           |
| 9.742            | 674.20          | 0.01445         | 60.50           |
| 9.738            | 684.00          | 0.01424         | 61.00           |
| 9.735            | 693.80          | 0.01403         | 61.50           |
| 9.731            | 702.30          | 0.01386         | 62.00           |
| 9.727            | 712.50          | 0.01365         | 62.50           |
| 9.723            | 723.20          | 0.01345         | 63.00           |
| 9.720            | 732.30          | 0.01327         | 63.50           |
| 9.716            | 741.60          | 0.01310         | 64.00           |
| 9.712            | 752.30          | 0.01291         | 64.50           |
| 9.709            | 760.20          | 0.01277         | 65.00           |
| 9.705            | 770.40          | 0.01260         | 65.50           |
| 9.702            | 779.70          | 0.01244         | 66.00           |
| 9.698            | 789.50          | 0.01228         | 66.50           |
| 9.694            | 799.40          | 0.01213         | 67.00           |
| 9.691            | 808.70          | 0.01198         | 67.50           |
| 9.686            | 820.00          | 0.01181         | 68.00           |
| 9.683            | 828.80          | 0.01168         | 68.50           |
| 9.679            | 838.00          | 0.01155         | 69.00           |
| 9.675            | 849.80          | 0.01139         | 69.50           |
| 9.672            | 857.50          | 0.01128         | 70.00           |
Table 5

Raw data for PAO/hBN nanofluid for BN particle concentration, $\phi = 1.0\%$ as a function of temperature at fixed temperature intervals and varied shear and shear rate. This set of data is used to verify whether the fluid is Newtonian or non-Newtonian.

| Shear stress (Pa) | Shear rate (1/s) | Viscosity (Pa.s) | Temperature (°C) |
|------------------|------------------|------------------|-----------------|
| 9.998            | 5.864            | 1.705            | −20             |
| 11.66            | 6.873            | 1.696            | −20             |
| 13.59            | 8.021            | 1.694            | −20             |
| 15.85            | 9.343            | 1.696            | −20             |
| 18.47            | 10.92            | 1.692            | −20             |
| 21.54            | 12.71            | 1.694            | −20             |
| 25.11            | 14.91            | 1.684            | −20             |
| 29.28            | 17.41            | 1.682            | −20             |
| 34.14            | 20.27            | 1.684            | −20             |
| 39.8             | 23.65            | 1.683            | −20             |
| 46.41            | 27.63            | 1.679            | −20             |
| 54.1             | 32.36            | 1.672            | −20             |
| 63.08            | 37.72            | 1.672            | −20             |
| 73.55            | 44.18            | 1.665            | −20             |
| 85.75            | 51.5             | 1.665            | −20             |
| 9.995            | 14.09            | 0.7096           | −10             |
| 12.58            | 17.79            | 0.7072           | −10             |
| 15.84            | 22.46            | 0.7053           | −10             |
| 19.94            | 28.31            | 0.7044           | −10             |
| 25.11            | 35.62            | 0.7047           | −10             |
| 31.61            | 45.07            | 0.7012           | −10             |
| 39.79            | 57.09            | 0.6969           | −10             |
| 50.09            | 72.18            | 0.694            | −10             |
| 63.06            | 91.57            | 0.6887           | −10             |
| 79.39            | 115.7            | 0.686            | −10             |
| 99.94            | 146              | 0.6843           | −10             |
| 125.8            | 184.3            | 0.6827           | −10             |
| 158.4            | 232.6            | 0.681            | −10             |
| 199.4            | 295.8            | 0.6741           | −10             |
| 251              | 372.9            | 0.6731           | −10             |
| 316              | 471.8            | 0.6699           | −10             |
| 397.9            | 597.8            | 0.6656           | −10             |
| 500.9            | 755.4            | 0.6631           | −10             |
| 630.6            | 950.1            | 0.6637           | −10             |
| 793.9            | 1208             | 0.657            | −10             |
| 999.4            | 1541             | 0.6485           | −10             |
| 1099             | 1705             | 0.6447           | −10             |
| 9.988            | 31.07            | 0.3215           | 7.00E-03        |
| 12.9             | 40.3             | 0.3201           | −2.00E-03       |
| 16.66            | 52.14            | 0.3195           | −2.00E-03       |
| 21.52            | 67.52            | 0.3187           | −2.00E-03       |
| 27.79            | 87.8             | 0.3165           | 0               |
| 35.89            | 113.6            | 0.3158           | 0               |
| 46.36            | 147.4            | 0.3145           | −6.00E-03       |
| 59.88            | 190.6            | 0.3142           | 3.00E-03        |
| 77.33            | 243.9            | 0.3171           | 7.00E-03        |
| 99.88            | 314.2            | 0.3179           | −0.01           |
| 129              | 406.3            | 0.3175           | −2.00E-03       |
| 166.6            | 525.1            | 0.3173           | 3.00E-03        |
| 215.2            | 680.1            | 0.3164           | −6.00E-03       |
| 277.9            | 876.9            | 0.3169           | 3.00E-03        |
| 358.9            | 1130             | 0.3175           | −6.00E-03       |
| 463.6            | 1476             | 0.3142           | 7.00E-03        |
| 598.8            | 1895             | 0.316            | 3.00E-03        |
| 773.3            | 2456             | 0.3148           | 0               |
| 998.9            | 3017             | 0.3311           | 0               |
| 1099             | 3203             | 0.343            | −2.00E-03       |

(continued on next page)
Table 5 (continued)

| Shear stress Pa | Shear rate 1/s | Viscosity Pa.s | Temperature °C |
|-----------------|---------------|----------------|----------------|
| 9.981           | 49.21         | 0.2028         | 10             |
| 75.85           | 385.8         | 0.1966         | 10             |
| 141.7           | 727.5         | 0.1948         | 10             |
| 207.6           | 1077          | 0.1928         | 10             |
| 273.5           | 1434          | 0.1907         | 10             |
| 339.3           | 1790          | 0.1896         | 10             |
| 405.2           | 2157          | 0.1879         | 10             |
| 471             | 2519          | 0.187          | 10             |
| 536.9           | 2874          | 0.1868         | 10             |
| 602.8           | 3241          | 0.186          | 10             |
| 668.6           | 3599          | 0.1858         | 10             |
| 734.5           | 3973          | 0.1849         | 10             |
| 800.3           | 4363          | 0.1834         | 10             |
| 866.2           | 4724          | 0.1834         | 10             |
| 932.1           | 5098          | 0.1828         | 10             |
| 997.9           | 5471          | 0.1824         | 10             |
| 9.961           | 103.5         | 0.09625        | 20             |
| 61.86           | 639.9         | 0.09668        | 20             |
| 113.8           | 1178          | 0.09655        | 20             |
| 165.7           | 1724          | 0.09609        | 20             |
| 217.6           | 2267          | 0.09595        | 20             |
| 269.4           | 2828          | 0.09527        | 20             |
| 321.3           | 3385          | 0.09493        | 20             |
| 373.2           | 3945          | 0.0946         | 20             |
| 425.1           | 4521          | 0.09404        | 20             |
| 477             | 5085          | 0.09381        | 20             |
| 528.9           | 5689          | 0.09297        | 20             |
| 580.8           | 6292          | 0.0923         | 20             |
| 632.6           | 6883          | 0.09191        | 20             |
| 684.5           | 7503          | 0.09123        | 20             |
| 736.4           | 8132          | 0.09055        | 20             |
| 788.2           | 8776          | 0.08981        | 20             |
| 840.1           | 9412          | 0.08926        | 20             |
| 891.9           | 10,110        | 0.08822        | 20             |
| 943.8           | 10,750        | 0.08781        | 20             |
| 995.6           | 11,400        | 0.08733        | 20             |
| 9.936           | 168.6         | 0.05893        | 30             |
| 61.7            | 1048          | 0.0589         | 30             |
| 113.5           | 1938          | 0.05854        | 30             |
| 165.2           | 2831          | 0.05836        | 30             |
| 217             | 3735          | 0.05809        | 30             |
| 268.7           | 4661          | 0.05766        | 30             |
| 320.5           | 5593          | 0.05731        | 30             |
| 372.2           | 6553          | 0.05681        | 30             |
| 424             | 7484          | 0.05665        | 30             |
| 475.7           | 8444          | 0.05634        | 30             |
| 527.4           | 9424          | 0.05597        | 30             |
| 579.2           | 10,440        | 0.0555         | 30             |
| 630.9           | 11,440        | 0.05517        | 30             |
| 682.6           | 12,430        | 0.05492        | 30             |
| 734.4           | 13,380        | 0.05488        | 30             |
| 786.1           | 14,300        | 0.05497        | 30             |
| 837.9           | 15,270        | 0.05488        | 30             |
| 889.6           | 16,070        | 0.05535        | 30             |
| 9.896           | 271.2         | 0.03649        | 40             |
| 51.05           | 1396          | 0.03657        | 40             |
| 92.19           | 2528          | 0.03647        | 40             |
| 133.3           | 3648          | 0.03655        | 40             |
| 174.5           | 4809          | 0.03628        | 40             |
| 215.6           | 5972          | 0.0361         | 40             |

(continued on next page)
Table 5 (continued)

| Shear stress (Pa) | Shear rate (1/s) | Viscosity (Pa.s) | Temperature (°C) |
|-------------------|------------------|-----------------|-----------------|
| 256.7             | 7172             | 0.0358          | 40              |
| 297.9             | 8346             | 0.03569         | 40              |
| 339               | 9528             | 0.03558         | 40              |
| 380.1             | 10,760           | 0.03532         | 40              |
| 421.2             | 11,980           | 0.03516         | 40              |
| 462.3             | 13,170           | 0.03511         | 40              |
| 503.4             | 14,350           | 0.03507         | 40              |
| 9.848             | 396.4            | 0.02484         | 50              |
| 35.25             | 1420             | 0.02482         | 50              |
| 60.64             | 2443             | 0.02482         | 50              |
| 86.04             | 3471             | 0.02479         | 50              |
| 111.4             | 4495             | 0.02479         | 50              |
| 136.8             | 5551             | 0.02465         | 50              |
| 162.2             | 6598             | 0.02458         | 50              |
| 187.6             | 7664             | 0.02448         | 50              |
| 213               | 8733             | 0.02439         | 50              |
| 238.4             | 9824             | 0.02426         | 50              |
| 263.7             | 10,880           | 0.02423         | 50              |
| 289.1             | 11,950           | 0.02419         | 50              |
| 9.785             | 560              | 0.01747         | 60              |
| 35.02             | 2002             | 0.01749         | 60              |
| 60.26             | 3447             | 0.01748         | 60              |
| 85.5              | 4894             | 0.01747         | 60              |
| 110.7             | 6344             | 0.01745         | 60              |
| 136               | 7830             | 0.01736         | 60              |
| 161.2             | 9339             | 0.01726         | 60              |
| 186.4             | 10,780           | 0.01728         | 60              |
| 211.6             | 12,280           | 0.01724         | 60              |
| 9.714             | 747.5            | 0.01299         | 70              |
| 34.77             | 2663             | 0.01306         | 70              |
| 59.82             | 4584             | 0.01305         | 70              |
| 84.87             | 6548             | 0.01296         | 70              |
| 109.9             | 8525             | 0.01289         | 70              |
| 134.9             | 10,480           | 0.01288         | 70              |

Fig. 4. Shear stress versus shear strain for PAO/hBN nanofluid with BN particle concentration, \( \phi = 0.6\% \) over a temperature range from negative 20 to 70 °C.
Table 6
Raw data for PAO/hBN nanofluid with BN particle concentration, $\phi = 1.0\%$ as a function of temperature at fixed shear stress and varied temperature at 0.5 °C intervals. This set of data is used to derive correlations for the viscosity as a function of temperature.

| Shear stress Pa | Shear rate 1/s | Viscosity Pa.s | Temperature °C |
|----------------|---------------|----------------|----------------|
| 9.998          | 6.42          | 1.55700        | −19.70         |
| 9.997          | 6.69          | 1.49400        | −19.10         |
| 9.997          | 7.00          | 1.42800        | −18.50         |
| 9.997          | 7.33          | 1.36400        | −18.00         |
| 9.997          | 7.65          | 1.30700        | −17.50         |
| 9.997          | 8.00          | 1.25000        | −17.00         |
| 9.997          | 8.36          | 1.19600        | −16.50         |
| 9.997          | 8.72          | 1.14700        | −16.00         |
| 9.997          | 9.14          | 1.09400        | −15.50         |
| 9.996          | 9.53          | 1.04900        | −15.00         |
| 9.996          | 9.93          | 1.00700        | −14.50         |
| 9.996          | 10.33         | 0.96800        | −14.00         |
| 9.996          | 10.74         | 0.93080        | −13.50         |
| 9.996          | 11.13         | 0.89820        | −13.00         |
| 9.996          | 11.59         | 0.86220        | −12.50         |
| 9.995          | 12.06         | 0.82890        | −12.00         |
| 9.995          | 12.53         | 0.79740        | −11.50         |
| 9.995          | 13.08         | 0.76420        | −11.00         |
| 9.995          | 13.50         | 0.74050        | −10.50         |
| 9.995          | 14.14         | 0.70690        | −10.00         |
| 9.994          | 14.78         | 0.67640        | −9.50          |
| 9.994          | 15.54         | 0.64330        | −9.00          |
| 9.994          | 15.81         | 0.63200        | −8.50          |
| 9.994          | 16.64         | 0.60050        | −8.00          |
| 9.993          | 17.38         | 0.57510        | −7.50          |
| 9.993          | 18.23         | 0.54820        | −7.00          |
| 9.993          | 18.65         | 0.52580        | −6.50          |
| 9.993          | 19.18         | 0.50290        | −6.00          |
| 9.992          | 19.94         | 0.49010        | −5.50          |
| 9.992          | 20.84         | 0.47950        | −5.00          |
| 9.992          | 21.96         | 0.45490        | −4.50          |
| 9.991          | 22.71         | 0.43990        | −4.00          |
| 9.991          | 23.55         | 0.42420        | −3.50          |
| 9.991          | 24.63         | 0.40570        | −3.00          |
| 9.990          | 25.06         | 0.39860        | −2.50          |
| 9.990          | 26.29         | 0.38000        | −2.00          |
| 9.990          | 27.22         | 0.36700        | −1.50          |
| 9.990          | 26.10         | 0.35820        | −1.00          |
| 9.989          | 29.34         | 0.34040        | −0.50          |
| 9.989          | 27.97         | 0.35710        | −0.10          |
| 9.989          | 29.70         | 0.33630        | 0.50           |
| 9.988          | 32.52         | 0.30710        | 1.00           |
| 9.987          | 33.89         | 0.29470        | 1.50           |
| 9.987          | 35.22         | 0.28360        | 2.00           |
| 9.986          | 36.37         | 0.27460        | 2.50           |
| 9.986          | 37.62         | 0.26540        | 3.00           |
| 9.985          | 38.92         | 0.25660        | 3.50           |
| 9.985          | 40.15         | 0.24870        | 4.00           |
| 9.984          | 41.76         | 0.23910        | 4.50           |
| 9.984          | 43.07         | 0.23180        | 4.90           |
| 9.983          | 44.54         | 0.22410        | 5.50           |
| 9.982          | 45.92         | 0.21740        | 6.00           |
| 9.982          | 47.36         | 0.21080        | 6.50           |
| 9.981          | 48.86         | 0.20430        | 7.00           |
| 9.981          | 50.47         | 0.19780        | 7.50           |
| 9.980          | 52.08         | 0.19160        | 8.00           |
| 9.979          | 53.72         | 0.18580        | 8.50           |

(continued on next page)
| Shear stress Pa | Shear rate 1/s | Viscosity Pa.s | Temperature °C |
|----------------|---------------|----------------|----------------|
| 9.979          | 55.34         | 0.18030        | 9.00           |
| 9.978          | 57.07         | 0.17490        | 9.50           |
| 9.977          | 58.86         | 0.16950        | 10.00          |
| 9.977          | 60.63         | 0.16460        | 10.50          |
| 9.976          | 62.56         | 0.15950        | 11.00          |
| 9.975          | 64.36         | 0.15500        | 11.50          |
| 9.975          | 66.31         | 0.15040        | 12.00          |
| 9.974          | 68.25         | 0.14610        | 12.50          |
| 9.973          | 70.13         | 0.14220        | 12.90          |
| 9.972          | 72.30         | 0.13790        | 13.50          |
| 9.972          | 74.41         | 0.13400        | 14.00          |
| 9.971          | 76.49         | 0.13030        | 14.50          |
| 9.970          | 78.77         | 0.12660        | 15.00          |
| 9.969          | 80.91         | 0.12320        | 15.50          |
| 9.968          | 83.29         | 0.11970        | 16.00          |
| 9.967          | 85.64         | 0.11640        | 16.50          |
| 9.966          | 87.99         | 0.11330        | 17.00          |
| 9.965          | 90.72         | 0.10990        | 17.50          |
| 9.964          | 93.07         | 0.10710        | 18.00          |
| 9.963          | 95.49         | 0.10430        | 18.50          |
| 9.962          | 98.29         | 0.10140        | 19.00          |
| 9.961          | 100.80        | 0.09880        | 19.50          |
| 9.960          | 103.30        | 0.09639        | 19.90          |
| 9.959          | 106.30        | 0.09370        | 20.50          |
| 9.958          | 109.00        | 0.09138        | 21.00          |
| 9.957          | 111.80        | 0.08907        | 21.50          |
| 9.956          | 114.80        | 0.08669        | 22.00          |
| 9.955          | 117.90        | 0.08444        | 22.50          |
| 9.954          | 120.80        | 0.08240        | 23.00          |
| 9.953          | 123.90        | 0.08033        | 23.50          |
| 9.951          | 127.00        | 0.07834        | 24.00          |
| 9.950          | 130.30        | 0.07636        | 24.50          |
| 9.949          | 133.60        | 0.07445        | 25.00          |
| 9.947          | 139.40        | 0.07137        | 25.40          |
| 9.945          | 142.50        | 0.06978        | 26.00          |
| 9.944          | 145.60        | 0.06830        | 26.50          |
| 9.943          | 149.20        | 0.06664        | 27.00          |
| 9.942          | 152.80        | 0.06507        | 27.50          |
| 9.940          | 156.40        | 0.06358        | 28.00          |
| 9.939          | 160.00        | 0.06211        | 28.50          |
| 9.937          | 163.80        | 0.06065        | 29.00          |
| 9.936          | 167.60        | 0.05927        | 29.50          |
| 9.934          | 171.90        | 0.05780        | 30.00          |
| 9.933          | 175.50        | 0.05661        | 30.50          |
| 9.931          | 179.50        | 0.05532        | 31.00          |
| 9.930          | 184.00        | 0.05396        | 31.50          |
| 9.928          | 188.30        | 0.05272        | 32.00          |
| 9.926          | 192.30        | 0.05162        | 32.50          |
| 9.925          | 196.90        | 0.05040        | 33.00          |
| 9.923          | 201.40        | 0.04926        | 33.50          |
| 9.921          | 205.80        | 0.04820        | 34.00          |
| 9.920          | 210.20        | 0.04720        | 34.50          |
| 9.918          | 214.70        | 0.04619        | 35.00          |
| 9.916          | 219.50        | 0.04517        | 35.50          |
| 9.914          | 224.20        | 0.04422        | 36.00          |
| 9.912          | 229.10        | 0.04327        | 36.50          |
| 9.911          | 233.90        | 0.04237        | 37.00          |
| 9.909          | 238.80        | 0.04149        | 37.50          |
| 9.907          | 244.10        | 0.04058        | 38.00          |
| 9.905          | 249.00        | 0.03977        | 38.50          |
| Shear stress Pa | Shear rate 1/s | Viscosity Pa.s | Temperature °C |
|----------------|---------------|----------------|----------------|
| 9.903          | 254.00        | 0.03899        | 39.00          |
| 9.901          | 259.70        | 0.03812        | 39.50          |
| 9.899          | 264.60        | 0.03741        | 40.00          |
| 9.897          | 270.30        | 0.03661        | 40.50          |
| 9.894          | 275.90        | 0.03586        | 41.00          |
| 9.892          | 281.00        | 0.03520        | 41.50          |
| 9.890          | 287.20        | 0.03444        | 42.00          |
| 9.888          | 292.40        | 0.03382        | 42.50          |
| 9.886          | 298.30        | 0.03314        | 43.00          |
| 9.884          | 304.10        | 0.03250        | 43.50          |
| 9.881          | 310.40        | 0.03184        | 44.00          |
| 9.879          | 315.80        | 0.03128        | 44.50          |
| 9.877          | 321.60        | 0.03071        | 45.00          |
| 9.875          | 328.00        | 0.03011        | 45.50          |
| 9.872          | 333.90        | 0.02956        | 46.00          |
| 9.870          | 340.30        | 0.02900        | 46.50          |
| 9.867          | 346.70        | 0.02846        | 47.00          |
| 9.865          | 352.90        | 0.02796        | 47.50          |
| 9.862          | 359.50        | 0.02743        | 48.00          |
| 9.860          | 366.10        | 0.02694        | 48.50          |
| 9.857          | 372.60        | 0.02645        | 49.00          |
| 9.855          | 379.50        | 0.02597        | 49.50          |
| 9.852          | 386.50        | 0.02549        | 50.00          |
| 9.849          | 393.40        | 0.02504        | 50.50          |
| 9.847          | 399.90        | 0.02462        | 51.00          |
| 9.844          | 407.00        | 0.02419        | 51.50          |
| 9.842          | 414.20        | 0.02376        | 52.00          |
| 9.839          | 421.50        | 0.02334        | 52.50          |
| 9.836          | 428.10        | 0.02298        | 52.90          |
| 9.833          | 435.50        | 0.02258        | 53.50          |
| 9.830          | 443.10        | 0.02218        | 54.00          |
| 9.828          | 450.10        | 0.02184        | 54.50          |
| 9.825          | 458.00        | 0.02145        | 55.00          |
| 9.822          | 464.90        | 0.02113        | 55.50          |
| 9.819          | 472.80        | 0.02077        | 56.00          |
| 9.816          | 480.10        | 0.02045        | 56.50          |
| 9.813          | 488.10        | 0.02010        | 57.00          |
| 9.810          | 496.50        | 0.01976        | 57.50          |
| 9.807          | 503.80        | 0.01947        | 58.00          |
| 9.804          | 511.50        | 0.01917        | 58.50          |
| 9.801          | 520.00        | 0.01885        | 59.00          |
| 9.798          | 527.80        | 0.01856        | 59.50          |
| 9.795          | 535.90        | 0.01828        | 60.00          |
| 9.792          | 543.60        | 0.01801        | 60.50          |
| 9.789          | 552.20        | 0.01773        | 61.00          |
| 9.786          | 560.10        | 0.01747        | 61.50          |
| 9.782          | 568.90        | 0.01720        | 62.00          |
| 9.779          | 577.40        | 0.01694        | 62.50          |
| 9.776          | 585.50        | 0.01670        | 63.00          |
| 9.773          | 594.00        | 0.01645        | 63.50          |
| 9.770          | 600.80        | 0.01626        | 64.00          |
| 9.767          | 607.90        | 0.01607        | 64.50          |
| 9.765          | 614.10        | 0.01590        | 65.00          |
| 9.764          | 617.00        | 0.01582        | 65.50          |
| 9.763          | 619.50        | 0.01576        | 66.00          |
| 9.767          | 609.90        | 0.01571        | 66.50          |
| 9.775          | 587.00        | 0.01566        | 67.00          |
| 9.807          | 504.90        | 0.01561        | 67.50          |
| 9.852          | 385.80        | 0.01556        | 68.00          |
| 9.851          | 212.00        | 0.01551        | 68.50          |
volume sample, a surfactant (oleic acid) was added in the amount of 50% by volume of BN particles. After that, the sample was placed on a magnetic stirrer for more than 30 min and then in ultrasonic agitator (Branson Digital Sonifier, model 450) for 360 min for the 0.6% samples and for 420 min for the 1% samples to ensure uniform dispersion of the nanoparticles.

Fig. 1 shows schematic of the experimental setup that was used to measure the rheological property of the pure PAO and the PAO/hBN nanofluids. The setup is an AR-G2 rheometer from TA Instruments, New Castle, Delaware. It is a combined motor and transducer (CMT) instrument. The lower component of the measuring system is fixed, while the upper component is attached to a shaft, that can be rotated by a torque produced by an induction motor. The constraint on the low torque performance of the instrument is the friction between the rotating and the stationary components. Standard 1° cone plate was used to measure the viscosity, shear stress and shear strain rate for the samples of the fluids. Measurements can be made at torques from 0.01 N.m to
Viscosity versus temperature for PAO/hBN nanofluid with BN particle concentration, $\phi = 1.0\%$ over a temperature range from negative 20 to 68.5 °C.

200 mN-m. The fluid samples with 1.5 ml volume, is placed on the bottom fixed plate, then the upper movable part, which consists of cone assembly is moved to bottom. The distance between the two plates is about 26 μm. The desired shear stress range is produced by moving the cone plate over the fluid. To control the temperature of the test fluid from −20 °C to 70 °C, a water circulator chamber is used. The measure data include rotational speed of the spindle (RPM), torque, viscosity (Pa.s), shear stress (Pa), shear strain rate (1/s) and temperature (°C).

Each viscosity measurement was conducted under thermal equilibrium by insuring that sufficient time (at least 3 min) is given between measurements to allow the temperature to stabilize.

**Ethics Statement**

The work did not involve the use of human subjects nor animal experiments. The work does not involve data collected from social media platforms.

**CRediT Author Statement**

Ahmad K. Sleiti: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Visualization, Investigation, Validation, Writing- Reviewing and Editing.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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