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Density, viscosity and specific heat capacity of diesel blends with rapeseed and soybean oil methyl ester

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Abstract

This paper reports measurements of the density, viscosity and specific heat capacity of diesel blends with rapeseed and soybean oil methyl ester for temperatures in the range of (0 and 60) °C and pressures up to 300 MPa. Density and viscosity values were obtained by direct experimental measurements while heat capacity values have been calculated using density results and speed of sound data measured previously. At ambient pressure the uncertainty in density measurements was between 0.005 and 0.01 % ($k = 2$) and for viscosity measurements it was between 0.2 and 1.3 % ($k = 2$). At elevated pressures the uncertainty in density measurements was 0.08 % ($k = 2$) while for viscosity and heat capacity it was 2 % ($k = 2$). The work was undertaken by four European National Metrology Institutes as part of a project entitled ‘Metrology for Biofuels’ within Euramet’s European Metrology Research Programme.

Keywords: density, viscosity, specific heat capacity, biofuel, high pressure

1 Introduction

Europe has defined ambitious targets for the development of biofuels with the aim of improving domestic energy security, improving the overall CO₂ balance and sustaining European competitiveness. The development of innovative biofuel technologies, supported by thermophysical and chemical characterization, will help to pursue these objectives. In particular, European Directive 2009/28/EC on the promotion of the use of energy from renewable sources endorsed, in Article 3, a mandatory target of a 20 % share of energy from renewable sources in overall European Community energy consumption by 2020 and a target of at least 10 % of the final consumption of energy in transport.

In this context, thermophysical properties, such as density, viscosity and heat capacity of fuels and biofuel blends are important material parameters for legal purposes, for ensuring proper trade, enabling process control, ensuring proper operation and in developing new automotive applications. For example, liquid fuels are dispensed by volume for ease of daily use. Legal metrology considers density and its temperature dependence as crucial quantities to convert the measured volumes to a standard volume at 15 °C in order to ensure fair trade.

In particular, density, viscosity, vapour pressure, surface tension, thermal conductivity, specific heat, sorption energy, and calorific value are input quantities needed to determine the process efficiency of injection, atomisation, ignition, and combustion of fuel in the engine. A deep and precise knowledge of these parameters

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is, therefore, necessary for the optimisation, and the improvement, of the combustion process to achieve a reduction in fuel consumption, pollutant emission, and noise.

However, the thermophysical properties of biofuels and blends are significantly different from those of fossil fuels. Characterisation parameters known for fossil fuels which are used for volume measurement (for legal purposes) and for process control in engines (for industrial purposes) cannot be readily transferred to biofuels. Specifically, the temperature and pressure dependence of key properties such as density and viscosity can be appreciably different from those of conventional hydrocarbon-based fuels.

In recognition of the knowledge gaps within the metrology framework required for the successful introduction of biofuels and biofuel blends, the European Union funded the project entitled 'Metrology for Biofuels' within Euramet's European Metrology Research Programme (EMRP). This project, led by the Laboratoire national de métrologie et d'essais (LNE, France), brought together 14 participants from 9 countries, including the largest European National Metrology Institutes (NMIs) with experience and expertise in physical and chemical metrology.

Within the project, work package 2, led by the Physikalisch-Technische Bundesanstalt (PTB, Germany), focused on the development of high quality metrology reference methods suitable for biofuels. A key part of this work package involved the measurement of thermophysical properties of biofuels and their blends at ambient and non-ambient conditions. This paper presents an overview of the work undertaken by the four partners (PTB, LNE, INRiM and NEL) and a summary of results.

2 Experimental

2.1 Material

Pure mineral diesel (summer quality) was provided by Shell Deutschland Oil GmbH, Hamburg, Germany while biodiesels rapeseed oil methyl ester (RME) and soybean oil methyl ester (SME) were provided by ADM Research GmbH, Hamburg, Germany. These components were used to prepare blends denoted in the usual way by Bx-RME or Bx-SME (where x represents the percentage volume fraction of the biofuel in the blend on the base of 15 °C). In addition to the pure B100-RME, B100-SME and B0 (summer diesel), the investigation covered the blends B5-RME, B5-SME, B10-RME, B10-SME, B15-RME and B15-SME. The blends were prepared gravimetrically at PTB and then sent to the partners at NEL, INRiM and LNE-CNAM. One SME tank showed precipitates in the liquid. It was therefore filtered before further usage.

For the pure soybean and rapeseed oil methyl esters, together with blends B5, B10 and B15, the University of Rostock determined, by means of Karl-Fischer titration, that the water content did not exceed 0.024 wt%. Selected physical and chemical properties of the neat fuels are listed in Table 1.

2.2 Ambient pressure density measurements

PTB, LNE-CNAM and NEL made measurements of the density of the samples at ambient pressure. Comparisons were carried out in the temperature range between 0 °C and 50 °C.

At PTB, measurements of the density were carried out using an Anton Paar DMA 5000 oscillatory densitometer. The thermal insulation of the measuring cell of this densitometer was modified to enable measurements across an extended temperature range between -20 °C and +50 °C. Viscosity correction was considered negligible for the biofuels under study, since their viscosities were found generally to be below 10 mPa s. The samples were injected into the measuring cell by using glass syringes with steel needles. The volume of the syringes (12 ml) was chosen to be about 5 times larger than that of the measuring cell in order to

- i. be able to repeat the measurement and
- ii. rinse the cell from parts of the samples which had been in contact with air at the opening of the needle during transfer from stock bottle to the densitometer.

Since fatty acid ester components of biofuels are capable of dissolving and penetrating plastic materials, the operating procedure generally excluded contact of the samples with plastics on the input side. The exit of the measuring cell was connected via a hose (about 0.5 m in length) with a bottle to collect used samples. A hole of 0.5 mm diameter was bored into the cover of this bottle for pressure relief during temperature changes while the input side was closed by the syringe. This arrangement ensured that evaporation losses of the sample could not affect the measurement results. Calibration of the densitometer was carried out using pure water and the reference materials *n*-nonane and EF164 as provided by PTB. After injection of the sample, a temperature run was started at 50 °C. At each temperature step of 5 K down to 0 °C, the sample was allowed to thermally equilibrate for approximately 3 minutes before data were recorded. The absolute expanded uncertainty ($k = 2$) of density measurements that can be obtained with this device and procedure was estimated to be 0.05 kg m⁻³.

At NEL, measurements of the density were also carried out using an Anton Paar DMA 5000 oscillatory densitometer. The device was calibrated and used in accordance with the manufacturer's instructions. This device forms part of UK National Flow Measurement Standard Facilities and is traceably calibrated using air, pure water and reference standards provided by H&D Fitzgerald Ltd. For use as part of the Flow Measurement Standard Facilities, the expanded uncertainty of density measurement is 0.011 % (at $k = 2$), based on the use of an acceptance criterion of 0.01 % for agreement with the reference standard densities. However, over the duration of this project, observed deviations between the densities recorded by the DMA 5000 and the reference fluids never exceeded 0.005 % confirming that across the temperature range studied (5 to 90 °C) in this project, the estimated expanded uncertainty would not exceed 0.01 % ($k = 2$).

At LNE, measurements of density were carried out using two, independent, pycnometers, each of 100 ml volume. Temperature was controlled by means of thermostatic baths, containing either ethanol or water, depending on the temperature range required. Special precautions were taken at low temperatures (below 10 °C) to avoid condensation affecting the weights of the pycnometers. The expanded uncertainty of the densities determined by this method is estimated at 0.005 % ($k = 2$).

2.3 Ambient pressure viscosity measurements

At PTB, measurements of the dynamic viscosity were carried out using an Anton Paar SVM 3000 viscometer. The viscometer was calibrated using four different viscosity reference materials (2A, 10A, 100A and *n*-nonane) as provided by PTB. Sample handling was performed with syringes in the same way as described in Section 2.2 for density measurements. After injection of the sample a temperature run was started at 50 °C. At each temperature step of 5 K down to 0 °C, the sample was allowed to thermally equilibrate for approximately 3 min before viscosity data were recorded. The relative expanded uncertainty of viscosity measurements that can be obtained with this device and procedure was estimated to be 1 % ($k = 2$).

For comparison, additional measurements of the kinematic viscosity were carried out for B100-RME at 20 °C and 40 °C by using an Ubbelohde-type capillary viscometer. The relative expanded uncertainties of these measurements were 0.2 % ($k = 2$).

At NEL, measurements of the dynamic viscosity were also carried out using an Anton Paar SVM 3000 viscometer. The device was calibrated and used in accordance with the manufacturer's instructions. This device forms part of UK National Flow Measurement Standard Facilities and is traceably calibrated using reference standards provided by Poulten, Selfe and Lee Ltd. Across the temperature range studied (0 to 100°C) the estimated expanded uncertainty of viscosity measurement is 1.3 % ($k = 2$).

At LNE, measurements of kinematic viscosity were carried out using Ubbelohde-type capillary viscometers. For temperatures of 20 °C and above, two independent primary viscometers were used, with temperature control provided by a water bath. At lower temperatures, two independent secondary viscometers were used, with temperature control provided by an ethanol bath. The relative expanded uncertainties of the measurements never exceeded 1.0 % ($k = 2$) and were typically between 0.2 and 0.3 % at temperatures of 20 °C and above.

2.4 Elevated pressure density measurements

NEL obtained density data at elevated pressures using a Micro-pVT apparatus, based on the piston-in-a-bottle design [1]. The basic principle of the method consists of forcing a metal rod through a seal into a closed cylinder

containing the liquid. The pressure on the fluid is determined from the load on the rod and the volume change is determined from its displacement. Temperature control is provided by a jacket around the pressure vessel through which a temperature control medium can be circulated. The density $\rho_{t,p}$ of the fluid sample in the pressure vessel at temperature t and pressure p is given by

$$\rho_{t,p} = \rho_{t,p_0} \frac{V_{t,p_0}}{V_{t,p}} \quad (1)$$

where the subscript 0 refers to ambient pressure. For this work ambient pressure densities for each fluid were derived from the data obtained from the measurements made with the Anton Paar DMA 5000 densitometer. In principle the device can be used in an absolute mode, if the dimensions of the rod and cylinder are known with sufficient accuracy and suitable correction terms can be derived to account for pressure- and temperature-induced dimensional changes. In practice, however, it is calibrated using one or more fluids whose density is known sufficiently accurately as a function of pressure. Prior to use, the system was calibrated using iso-octane (Sigma Aldrich 2,2,4-trimethylpentane, anhydrous, product number: 360066-1L, stated minimum purity 99.8 %). Considering the method and the expanded uncertainty of the reference data, the expanded uncertainty of the high pressure density data is estimated to be 0.08 % ($k = 2$).

2.5 Elevated pressure viscosity measurements

NEL obtained viscosity data at elevated pressures using a falling sinker high-pressure viscometer [2].

The basic principle of the method is that the viscosity of a fluid can be determined from the time taken for a cylindrical sinker to descend down a vertical tube containing the sample liquid. By containing the entire tube within a high pressure vessel and providing a means of controlling the temperature, it is possible to make viscosity measurements at elevated temperatures and pressures. In principle the device can be used in an absolute mode, if the dimensions of the sinker and cylinder are known with sufficient accuracy and suitable correction terms can be derived to account for pressure- and temperature-induced dimensional changes. In practice, however, it is calibrated using one or more fluids whose viscosity is known sufficiently accurately at ambient pressure and which cover the expected viscosity range at elevated pressure. Prior to use, the system was calibrated using iso-octane, n-dodecane and di-(2ethylhexyl)sebacate (all supplied by Sigma-Aldrich). Taking account of the method and the expanded uncertainty of the reference data, the expanded uncertainty of the high pressure viscosity data is estimated to be 2.0 % ($k = 2$).

2.6 Elevated pressure specific heat capacity measurements

INRiM obtained constant pressure heat capacity data at elevated pressures from accurate speed of sound measured using a double pulse-echo technique.

Speed of sound is a physical quantity intrinsically related to the thermodynamic properties of a fluid and can be calculated, either from a specific equation of state for the fluid, or from the appropriate combination of physical parameters it depends on. The high accuracy available in the determination of the speed of sound of pure fluids and fluid mixtures even at elevated pressures therefore offers the possibility of obtaining thermophysical property data at elevated pressures for other parameters. In particular, the constant pressure heat capacity c_p at temperature T and pressure p is related to the speed of sound w and density ρ by

$$c_p = \frac{T \frac{1}{\rho^2} \left(\frac{\partial \rho}{\partial T} \right)_p^2}{\left(\frac{\partial \rho}{\partial p} \right)_T - \frac{1}{w^2}} \quad (2)$$

INRiM optimized a dedicated numerical calculation method [7], allowing the determination of c_p starting only from density and speed-of-sound experimental values, as input data.

Unlike the fundamental equations explicit in the Helmholtz free energy, this numerical method has only a local validity, but nevertheless is a useful instrument for the indirect determination of thermodynamical properties which are particularly difficult to obtain, such as heat capacity, especially at high pressure conditions.

This method is a variant of the well characterized Recursive Equation Method (*REM*) [3-5] and enables the implementation of empirical equations of state for single phase fluids. For pure fluids, for example in pure water or *n*-nonane, it has been shown that the method can be successfully applied. However, in the case of samples with a more complex thermodynamic behaviour (such as biofuels), the algorithm exhibits limitations [6]. For this reason, it has not been possible to determine the specific heat capacity for all measured samples and the results here reported should be considered as indicative and not as reference values.

3 Results

3.1 Density at ambient pressure

All density data that had been measured for a specified blend at atmospheric pressure between 0 °C and 50 °C (the common temperature range) with three different devices at three different institutes deviated from each other by no more than 0.02 %, except for the data from NEL for the B0 sample. The data (excluding NEL's data for the B0 sample) were fitted to a third-order polynomial in temperature

$$\rho_{\text{fit}}(t) = \rho_0 \{1 + \gamma(t - t_0)\} = \rho_0 \left\{ 1 + [a_1 + a_2(t - t_0) + a_3(t - t_0)^2](t - t_0) \right\} \quad (3)$$

where ρ_0 is the reference density at $t_0 = 15$ °C as used for conversion purposes. The coefficients a_1 , a_2 and a_3 describe the temperature dependence of the thermal expansion coefficient γ . The parameters are summarized in Table 2. The reference densities ρ_0 at $t_0 = 15$ °C of the Bx-RME and Bx-SME biofuel blends show an almost linear dependence on the composition range under study (cf. Table 2). Figures 1 to 5 show the relative deviations of the measured densities from the respective fitted means for B0, B5-RME, B5-SME, B100-RME and B100-SME. The data agree within their stated relative uncertainties ($k = 2$) at temperatures above 10 °C. Deviations slightly greater than the respective uncertainties can be observed at temperatures from 10 °C down to 0 °C. Combining these observations, the estimated overall relative uncertainty of the densities of the biofuels between 0 °C and 50 °C is 0.02 % ($k = 2$).

The densities measured at PTB (circles in Figures 1 to 5) are generally slightly lower than the ones measured at the other NMIs. Since the blends had been prepared at PTB, it is possible that volatile components escaped from the samples during transportation across Europe, thereby changing their composition. Density measurements below 0 °C indicate the start of solidification processes for B100-RME (Figure 6) and B100-SME. Furthermore, the formation of precipitates, which occurred in B100-SME even at ambient temperatures and is most pronounced at lower temperatures, can also contribute to the deviations in the measured densities below 10 °C.

For the B100-RME and B100-SME samples, densities calculated using Eq. 3 at 15 °C are 883.1 kg m⁻³ and 885.2 kg m⁻³ respectively. The corresponding values from Table 1 are 883.4 kg m⁻³ and 885.3 kg m⁻³, i.e. differences of 0.03 % and 0.01 % respectively. In the time frame of the measurement programme, changes in density due to changes in sample composition are therefore probably within the combined measurement uncertainties.

3.2 Viscosity at ambient pressure

Unless otherwise noted, all references to viscosity are to dynamic viscosity. In the cases where kinematic viscosities were measured by capillary viscometers, the values were recalculated to their dynamic analogues by using Eq. 3 and the appropriate parameters in Table 2. All viscosity data, that had been measured for a specified blend at atmospheric pressure between 0 °C and 50 °C (the common temperature range) with four different devices at three different institutes, were fitted to a fourth-order polynomial in temperature

$$\eta_{\text{fit}}(t) = \eta_0 \left\{ 1 + [b_1 + b_2(t - t_0) + b_3(t - t_0)^2 + b_4(t - t_0)^3](t - t_0) \right\} \quad (4)$$

where η_0 is the reference viscosity at $t_0 = 15$ °C. η_0 and the coefficients b_1 to b_4 , which describe its temperature dependence, are summarized in Table 3. Figures 7 to 11 show the relative deviations of the measured viscosities for the respective fitted means for B0, B5-RME, B5-SME, B100-RME and B100-SME. The results obtained at LNE with capillary viscometers and at PTB with a rotational viscometer or Ubbelohde-type capillary viscometer are generally in agreement within their uncertainties. The deviations increase at temperatures below 20 °C and are most pronounced for the curves obtained at NEL. The overall trend of the viscosity vs. temperature curves supports the assumption that volatile components of lower viscosity evaporated from the samples during transportation and/or handling. This will have a much larger effect on viscosity than on density. Performing a similar comparison to that described above for the density of the B100-RME and B100-SME samples shows that the viscosities changed by about 1 % from the values provided by the suppliers (Table 1).

Whilst it is clearly possible to measure the viscosity of a biofuel with an uncertainty of better than 1 % ($k = 2$), the time-dependent nature of such fluids means that the effective uncertainty is much higher (unless that sample has just been measured). Thus, for example, for the application of viscosity data to flow metering, one has to take into account changes of the order of 5 % due to transportation, storage and handling.

The dependence of the reference viscosities on the composition can be considered linear within the relative expanded uncertainties (5 %, $k = 2$) and the composition range under study (cf. Table 3).

3.3 Density at elevated pressure

With the exception of the B0, B5-RME and B100-RME samples, all the samples showed evidence of partial freezing at elevated pressures. Figures 12 and 13 show the variation of density with pressure for iso-octane and the B100-SME sample respectively, as determined from the (calibrated) Micro-pVT. For iso-octane at all three isotherms, the variation of density with temperature is smooth across the full pressure range, as expected for a single-phase fluid. However, for the B100-SME sample, there is clear evidence of a change in slope of the 20 and 30 °C isotherms. At 20 °C this occurs at about 130 MPa and at 30 °C it has moved up to about 175 MPa. This is consistent with partial freezing of the sample, as one component of the mixture freezes. These observations are confirmed by the high pressure viscosity data for this sample (see Section 3.4).

For each fluid the full data set was initially fitted to an equation of the form

$$\rho_{t,p} = 1000 \sum_{i=1}^{19} a(i) \theta^{m(i)} \pi^{n(i)} \quad (5)$$

where θ is the reduced temperature, $\theta = t / 100$ when t is expressed in ITS90 Celsius degrees,

π is the reduced pressure, $\pi = p / 300$ when p is in MPa,

$a(i)$ are coefficients and

$m(i)$ and $n(i)$ are exponents,

and the residuals examined. These provide a very clear indication of a change in the density versus pressure relationship at any temperature, such as would be caused by one component of the mixture changing phase. Figure 14 shows the residuals for the B100-SME sample, clearly illustrating the occurrence of effects at about 130 MPa at 20 °C and about 175 MPa at 29 °C. Refitting the data, omitting the values above the phase change regions at each isotherm then results in much lower residuals for the ranges over which the fit is valid.

3.4 Viscosity at elevated pressure

With the exception of the B0 sample, all the samples showed evidence of partial freezing at elevated pressures. Figure 15 shows the variation of viscosity with pressure for the B100-SME sample. At 20 °C no fall times were obtained at pressures above 125 MPa whilst at 30 °C no fall times were obtained above 195 MPa. These findings are consistent with the data obtained from the elevated pressure density measurements and with speed of sound

data obtained by INRiM, where at approximately the same pressure the signal-to-noise ratio of the ultrasonic burst decreased so much to prevent the measurement [7].

3.5 Heat capacity at elevated pressure

Since density appears as a first derivative in the calculation of heat capacity from speed of sound, Eq. 2, this particular procedure is especially sensitive to the density. The maximum permissible uncertainty for density is therefore about 0.1 %. Equation 2's sensitivity to speed-of-sound is much lower since it only occurs as its value and not in the form of a derivative. Density measurement effects can be seen, for example, in the case of the B100-RME sample. New density data, reported in this work, show differences from those previously used in [6], because preliminary values have been now corrected for minor temperature dependent effects. After reprocessing density data for B100-RME, significant discrepancies can be seen between the different data sets. Figure 16 shows an increment of about $50 \text{ J kg}^{-1} \text{ K}^{-1}$ and a slightly different points distribution compared to the previous results [6]. Taking account of such effects, the typical uncertainty of the heat capacity data has been increased to 2 % ($k = 2$).

From a practical point of view, in order to determine c_p , it is necessary to select properly the set of experimental density and speed-of-sound input data. For all the analyzed biofuels, with the implemented method it is only possible to obtain smooth c_p values in a subset of the speed-of-sound and density common p - T range. In particular, density measurements have been limited to between 20 °C and 60 °C and speed-of-sound measurements to 150 MPa (due to the maximum available pressure for B100-SME). The pressure range has been further reduced to 100 MPa in order to avoid regions with possible phase change of biofuel components.

4 Figures

5 Tables

6 Conclusions

The density, viscosity and specific heat capacity of diesel blends with rapeseed and soybean oil methyl ester have been measured at ambient and high pressure conditions. The chemical nature of RME and SME is such that they are prone to change during handling, transport and storage. Measurements of density, viscosity and, as a consequence, heat capacity are sensitive methods to detect such changes.

With the exception of the pure mineral diesel (B0), partial freezing was detected for all the samples at elevated pressures. At temperatures above 50 °C this effect was small but it is worth noting that at cold-start conditions, fuel may be entering the injection system in a Diesel engine at temperatures significantly below 20 °C, resulting in partial freezing and potential blocking of the micro-fine injectors. This will lead to loss of power and increased hydrocarbon emissions, due to poor atomisation of the fuel and hence incomplete combustion.

Partial freezing of samples at elevated pressures was detected by three different measurement techniques, (density by a piston-in-a-bottle method, viscosity by a falling sinker method and specific heat capacity by speed of sound measurements), with good agreement between the methods for any sample at a particular isotherm.

Heat capacities from speed of sound measurements can be determined with slightly lower uncertainties than with DSC measurements provided that the density measurements used in the calculations have uncertainties within 0.1 %.

The time-dependant nature of the thermophysical properties of biofuels and biofuel blends presents significant challenges in dealing with these materials. Pure mineral-derived hydrocarbon fuels are essentially time invariant. As a consequence, it has been possible to develop correlations and equations of state to describe their key

parameters as functions of temperature and pressure. However, the results from this study, in particular the variation of density and viscosity over time, suggests that it may not be possible to develop simple correlations such as those currently used to correct density (and hence volume of fuel dispensed) to a reference value. This suggests that further work is required to develop robust, accurate, on-line methods for determining key thermophysical properties for fuel applications.

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Figure Captions

Figure 1: Relative deviation of the densities of summer diesel B0 from a fitted mean in the temperature range 0 °C to 50 °C. (●) data from PTB; (▲) data from CNAM-LNE.

Figure 2: Relative deviation of the densities of B5-RME from a fitted mean in the temperature range 0 °C to 50 °C. (●) data from PTB; (■) data from NEL; (▲) data from CNAM-LNE.

Figure 3: Relative deviation of the densities of B5-SME from a fitted mean in the temperature range 0 °C to 50 °C. (●) data from PTB; (■) data from NEL; (▲) data from CNAM-LNE.

Figure 4: Relative deviation of the densities of B100-RME from a fitted mean in the temperature range 0 °C to 50 °C. (●) data from PTB; (■) data from NEL; (▲) data from CNAM-LNE.

Figure 5: Relative deviation of the densities of B100-SME from a fitted mean in the temperature range 0 °C to 50 °C. (●) data from PTB; (■) data from NEL; (▲) data from CNAM-LNE.

Figure 6: Relative deviation of the densities of B100RME from a fitted mean. The fit extends from 0 °C to 50 °C. The increase in density below 0 °C indicates the initiation of solidification at ambient pressure. (●) data from PTB.

Figure 7: Relative deviation of the viscosities of B0 summer diesel from a fitted mean in the temperature range 0 °C to 50 °C. (●) data from PTB; (■) data from NEL; (▲) data from CNAM-LNE.

Figure 8: Relative deviation of the viscosities of B5-RME from a fitted mean in the temperature range 0 °C to 50 °C. (●) data from PTB; (■) data from NEL; (▲) data from CNAM-LNE.

Figure 9: Relative deviation of the viscosities of B5-SME from a fitted mean in the temperature range 0 °C to 50 °C. (●) data from PTB; (■) data from NEL; (▲) data from CNAM-LNE.

Figure 10: Relative deviation of the viscosities of B100-RME from a fitted mean in the temperature range 0 °C to 50 °C. (●) data from DMA 5000 at PTB; (○) data from capillary viscometry at PTB; (■) data from NEL; (▲) data from CNAM-LNE.

Figure 11: Relative deviation of the viscosities of B100-SME from a fitted mean in the temperature range 0 °C to 50 °C. (●) data from PTB; (■) data from NEL; (▲) data from CNAM-LNE.

Figure 12: Variation in density with pressure for iso-octane. (--) 21.5 °C; (-.-) 48.5 °C; (—) 58.5 °C

Figure 13: Variation in density with pressure for B100-SME sample. (.....) 20 °C; (-.-) 30 °C; (-.-) 40 °C; (-.-) 50 °C; (—) 60 °C

Figure 14: Residuals for curve fit of density with pressure for B100-SME sample. (.....) 20 °C; (-.-) 30 °C; (-.-) 40 °C; (-.-) 50 °C; (—) 60 °C

Figure 15: Variation in viscosity with pressure for B100-SME sample. (■) 20°C; (○) 30 °C; (▲) 40 °C; (●) 60 °C; (*) 80 °C

Figure 16: Isobaric specific heat capacity in rapeseed oil methyl ester. Symbols show values of each isotherm: (■) $T = 20$ °C; (○) $T = 30$ °C; (▲) $T = 40$ °C; (▽) $T = 50$ °C; (*) $T = 60$ °C.