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Quantitative analysis of the calorimetric parameters associated with the temperature induced aggregation of aqueous solutions of polyoxypropylene

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Abstract

High sensitivity differential scanning calorimetry (HSDSC)—coupled with the application of a previously outlined thermodynamic model [Patterson et al., Langmuir 13 (1997) 2219]—has been used to the obtain thermodynamic parameters that characterise thermal aggregation in aqueous solutions of polyoxypropylene (POP) of molecular mass 1000 g mol^{-1} over a range of concentrations (2.5–51.5 g dm^{-3}). An important aspect of the derived thermodynamic values, which complements previously reported HSDSC data [Armstrong et al., J. Phys. Chem. 99 (1995) 4590], is the elaboration of heat capacity changes which accompany the aggregation transition. The concentration dependence of the POP thermodynamic data, obtained in this investigation, has been established. These observations provide the means for establishing functional relationships between enthalpy and temperature as well as heat capacity and temperature. The parameters describing the quadratic relationship between enthalpy change associated with aggregation and temperature are in close agreement with those describing the linear relationship between heat capacity change and temperature.

Keywords: Calorimetry; Thermodynamic model fitting; Concentration effects; Scan rate effects; Polyoxypropylene; Poly(propylene glycol)

1. Introduction

Aqueous solutions of polyoxypropylene (POP also known as poly(propylene glycol) and poly(propylene oxide)) undergo phase separation on warming. The process is endothermic and is quantifiably detectable by high sensitivity differential scanning calorimetry (HSDSC) [1,2]. Almgren et al. [3] have reviewed the explanations put forward to describe the molecular

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processes involved in phase separation in aqueous polymer solutions. One hypothesis states that the temperature dependence of the aqueous solubility of POP is due to the ability of the polymer to be incorporated within an ice-like structure [4]. Interestingly polyoxyethylene (POE) has been shown to be easily incorporated into such an ice-like structure [4]. In the case of POE, the formation of this molecular assembly produces a favourable (exothermic) enthalpy change but results in an entropy penalty associated with the enhanced structuring of water. At low temperatures, this enthalpy contribution together with the combinatorial entropy contribution of the polymer chains, to the free energy of mixing, outweighs the entropy penalty. However, an increase in temperature reverses this balance, giving rise to phase separation. The pendant methyl group in POP produces a strain in the ice-like structure of water in the hydration sphere, which results in phase separation at lower temperatures than those observed in aqueous solutions of POE [4]. Such an explanation though is not without controversy. Finney and Soper [5] using neutron scattering have not found any evidence for water structuring around non-polar methyl groups. Other workers have proposed that the origin of the increasing hydrophobicity of POE as a function of increasing temperature is the result of changing conformations of OE segments [6]. For the backbone segments –O–C–C–O–, the preferred orientation about the bonds is *trans–gauche–trans* [6,7]. In such polar conformational states interaction with water is favoured; there being, on average, two water molecules per OE unit [7]. As there are only two polar conformations, this state is of low energy but also of low probability [6]. At higher temperatures less polar orientations are favoured; these are of higher energy but of higher probability—there being some 23 non-polar conformations. Self-evidently the less polar conformations interact less favourably with water. The resulting loss of water at higher temperatures permits OE chains to come together. This model has been used with some success to explain phase separation of OE in aqueous solutions [6] and non-aqueous solvents [8]. The conformational changes in C–C bonds from *gauche* to *trans*, thereby altering the polarity, has been confirmed by ^{13}C NMR [8,9]. POP phase separates for apparently similar reasons [3].

Crowther and Eagland [10] have investigated the rheology and density of aqueous solutions of POP (of molecular mass 400 g mol^{-1}) and have concluded that the solution behaviour of POP is dictated by hydrophobic interactions. Privalov [11] has argued that the denaturation of proteins, in aqueous solution, is accompanied by an exposure of hydrophobic amino acid residues to the solvent—which in turn causes an increase in water structure. This effect demonstrates itself, in HSDSC, as an increase in the heat capacity between the initial native state and the final unfolded state of the protein. It may therefore be concluded that in a system where the hydrophobic interactions become reduced there should be, a negative change in heat capacity. The purpose of this report is to use a previously published model [12] to obtain details of these heat capacity changes for phase separation transitions in aqueous solutions of POP.

2. Experimental

2.1. Materials

POP (HO–(CH(CH$_3$)–CH$_2$–O)$_x$–H) of molecular mass 1000 g mol^{-1}, where $x = 17$, was obtained from Aldrich Ltd., Dorset, UK. The sample gave a single elution peak by gel permeation chromatography analysis and was thus used without further purification. Polymer solutions (concentration range 2.5–51.5 g dm^{-3}) were prepared using doubly distilled water and were chilled at 277 K for 1 h in order to aid dissolution prior to examination by HSDSC.

2.2. Instrumentation

Scanning calorimetric data were obtained using a Microcal MC-2 high sensitivity differential scanning calorimeter (Microcal Inc., Amherst, MA, USA). The instrument was interfaced to an IBM Model 30 Personal Computer. Instrumental control and data acquisition was provided by the DA-2 software supplied by the manufacturers. All calorimetric scans were, unless otherwise stated, obtained at a scan rate of 1 K min^{-1}.

The following uncertainties—based upon multiple scans—have been estimated for the measured and calculated thermodynamic parameters: The temperature at the mid-point of the phase transition $T_{1/2}$ (±0.2%), calorimetric enthalpy ΔH_{cal} (±3%), van't Hoff enthalpy ΔH_{vH} (±3%), the number of molecular reaction units *n* (±6%) and the difference in heat capacity between the initial and final states of the system ΔC_p (±6%).

3. Results and discussion

Fig. 1a provides some indication of the quality of the data obtained in this investigation. The insert is the scan rate normalised data obtained for a 5 g dm^{-3} solution of POP scanned at 57.9 K h^{-1}. The instrumental raw data has the units of power (mcal s^{-1}). By normalising the data with respect to scan rate the data is converted to mcal K^{-1}. Division with respect to the molar quantity of POP in the sample cell converts the data to molar heat capacity. The application of equilibrium thermodynamics to the analysis of the data is only justified if it can be demonstrated that the data

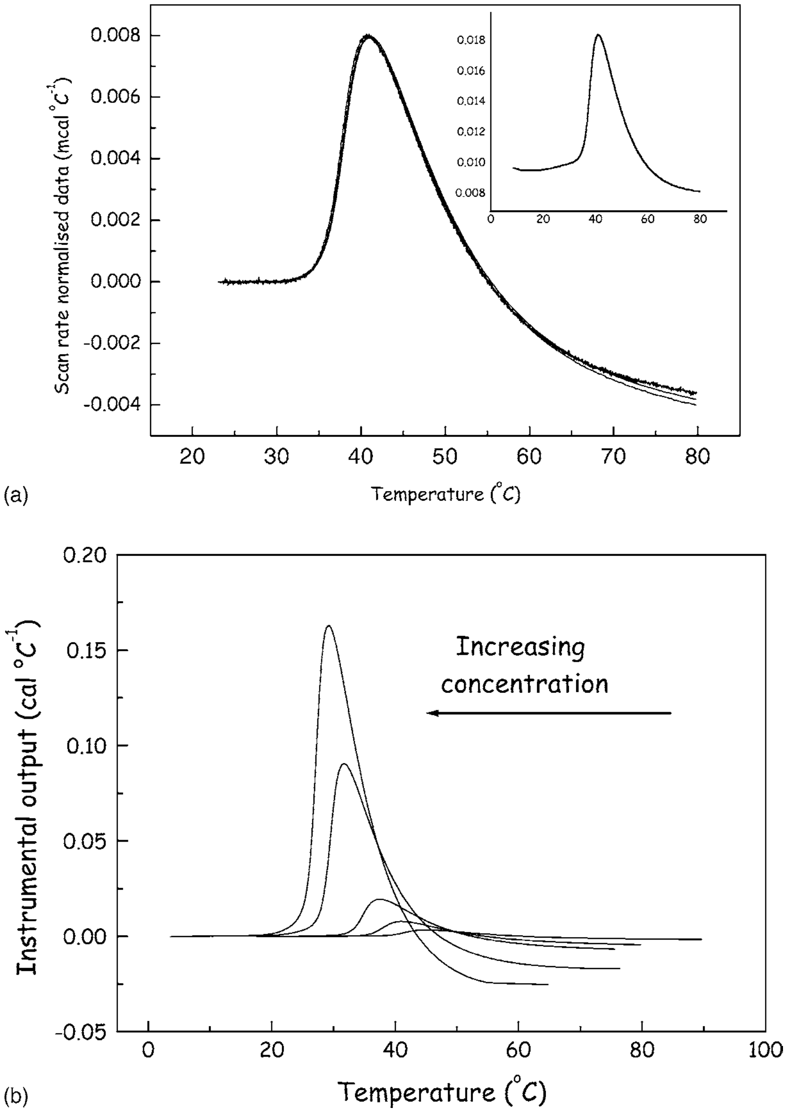

Fig. 1. (a) HSDSC signal captured for a POP solution of 5 g dm^{-3} concentration. The main diagram shows the scan rate independence of the transition and the insert shows the transition captured at a scan rate of 57.9 K h^{-1}. (b) HSDSC signals obtained for POP solutions concentrations of 2.5, 5.0 10, 30.6 and 51.5 g dm^{-3}.

show no scan rate dependence [13]. The main graph in Fig. 1 shows that the calorimetric data captured for the $5\,\mathrm{g\,dm^{-3}}$ solution of POP at scan rates varying between 12 and $90\,\mathrm{K\,h^{-1}}$ are largely superimposable. There is some mismatch at the high temperature end, which may be a reflection of a real phenomenon or it may simply reflect an artefact associated with the way in which the calorimetric signal was treated in order to create the diagram. A linear base line was fitted by eye—using the software tools in the Origin DSC data analysis package (Microcal Software Inc., Northampton, MA, USA)—to the pre-transition section of the data and then subtracted from the entire signal. A second important point is that the shape of the transition is strongly indicative of an aggregation phenomena whose thermodynamic properties may be described by a mass action model of association [14]. Fig. 1b shows the concentration dependence of the HSDSC signals for POP. In particular it demonstrates that as the POP concentration in the system increases the temperature range, over which aggregation occurs, decreases.

In several previous publications [12,14,15], we have outlined procedures that may be used for quantitative analysis of the calorimetric data obtained for these types of aggregating systems. Importantly we have argued that the application of a model which has as it basis a mass action description of aggregation is appropriate for analysing POP data despite the fact that the system undergoes phase separation. It is our contention that, mechanistically, phase separation in aqueous solutions of POP proceeds via nucleation and growth; and that it is the nucleation phase which is observable by HSDSC.

Briefly, model fitting the data involves the following. The techniques used to analyse the calorimetric data have been outlined previously [12,15]. In HSDSC, the observed change in enthalpy with respect to temperature for a process under strict thermodynamic control is given by

$$\frac{\mathrm{d}q_p}{\mathrm{d}T} = \phi C_{p,\mathrm{xs}} = \frac{\mathrm{d}}{\mathrm{d}T}(\alpha(\Delta H_{\mathrm{cal}}(T_{1/2}) + \Delta C_p(T - T_{1/2}))) \quad (1)$$

where q_p is the heat change at constant pressure; T the temperature; $\phi C_{p,\mathrm{xs}}$ the apparent excess heat capacity (i.e. the difference in heat capacity between the reference and sample cells); α the extent of change in the system; $\Delta H_{\mathrm{cal}}(T_{1/2})$ the experimentally determined enthalpy change (i.e. the integrated area of the HSDSC curve) at $T_{1/2}$ the temperature at which α equals 0.5; and ΔC_p the difference in heat capacity between the initial and final states of the system. Given the temperature independence of $T_{1/2}$ and $\Delta H_{\mathrm{cal}}(T_{1/2})$ and assuming ΔC_p is independent of temperature for the system of interest, Eq. (1) may be rewritten as

$$\phi C_{p,\mathrm{xs}} = \frac{\mathrm{d}\alpha}{\mathrm{d}T}(\Delta H_{\mathrm{cal}}(T_{1/2}) + \Delta C_p(T - T_{1/2})) + \alpha \Delta C_p \quad (2)$$

The extent of conversion to aggregates, α, for the aqueous polymer systems examined in this work is obtained from the temperature dependence of the equilibrium constant describing the incorporation of *polymer* unimers into *aggregates*

$$\left(\frac{\partial \ln K}{\partial T}\right)_p = \frac{\Delta H_{\mathrm{vH}} + \Delta C_p(\Delta H_{\mathrm{vH}}/\Delta H_{\mathrm{cal}})(T - T_{1/2})}{RT^2} \quad (3)$$

where ΔH_{vH} is the van’t Hoff enthalpy. The ratio of the van’t Hoff enthalpy and the calorimetric enthalpy provides a measure of the size of the co-operative unit involved in the *aggregation* process (11). The heat capacity change in Eq. (3) is therefore scaled to reflect this co-operativity in the system since the equilibrium constant reflects those processes involving this co-operative unit. $K(T)$ can be obtained by integrating Eq. (3) and this value can be used in the following form of Eq. (1) to evaluate α—the fraction of *polymer* in *aggregated* form:

$$K = \frac{[x_n]}{[x]^n} = \frac{\alpha C/n}{((1-\alpha)C)^n} \quad (4)$$

where C is the total concentration of polymer. The evaluation of α at various temperatures permits an evaluation of the temperature dependence of $\phi C_{p,\mathrm{xs}}$ in Eq. (2). These series of equations provide a mechanism for model fitting the HSDSC signals and for obtaining numerical values for the various thermodynamic parameters appearing in the above expressions. Fig. 2 provides some indication of the ability of the outlined model to adequately encapsulate the major features of the thermally induced transition.

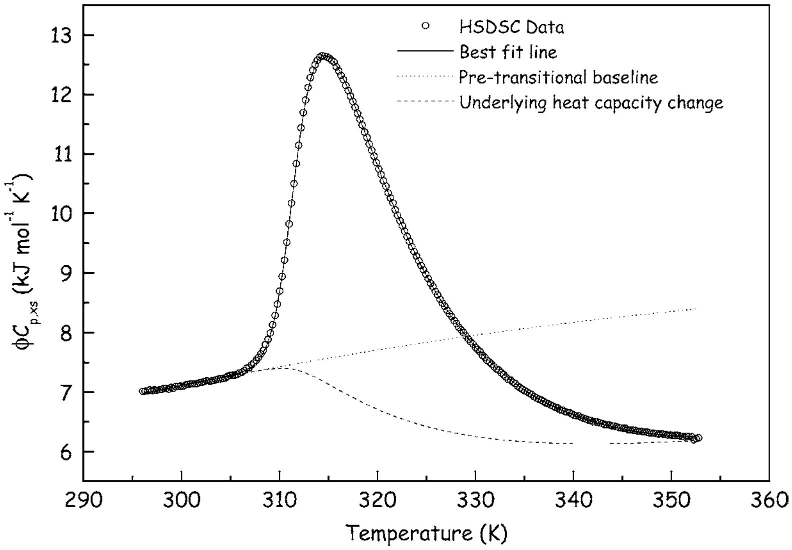

Fig. 2. The result of fitting the HSDSC data obtained for a 5 g dm^{-3} solution of POP to the thermodynamic model outlined in the text.

One major concern of this investigation was to delineate the temperature dependence of the calorimetric parameters. This is readily achieved by examining solutions of varying POP concentration. The HSDSC data clearly establishes that the nucleation event is endothermic. From the mass action description of the nucleation event, as depicted in Eq. (4), it is clear that if the aqueous solution concentration of the polymer is increased then the extent of aggregation itself will increase. Since aggregation is endothermic this implies that the temperature of the system will decrease. Thus under equilibrium conditions, it becomes obligatory for the temperature range over which aggregation occurs to decrease as polymer concentration increases.

It is important to appreciate the assumptions and thus the possible limitations of the model fitting procedure. Importantly, it is assumed that n is a constant value, whereas it is self evident that for a system in which phase separation occurs—through a mechanism of nucleation and growth—n must increase rapidly. Previously we have argued that n represents the number of molecular reaction units that initially join together to form the nucleation centre and growth proceeds through the exchange of molecules between one nucleation centre and another [16].

The concentration dependence data obtained from the fitting the calorimetric signals to the equations given above are displayed in Table 1. In the main there appear to be real trends in the data with changing concentration. The exception to this observation is the parametric data obtained for the aggregation numbers, n. The relative standard deviation (RSD) in n is 6%. The variation between the largest and smallest n values is of the order of ±6% and so it is reasonable to assert

Table 1
HSDSC parameters obtained for aqueous solutions of POP of molecular mass 1000 g mol^{-1}, as a function of concentration

Concentration (g dm^{-3})	ΔH_{cal} (kJ mol^{-1})	ΔH_{vH} (kJ mol^{-1})	n	$T_{1/2}$ (K)	ΔC_p (kJ mol^{-1} K^{-1})
2.5	103	461	12.2	331.2	−13.3
5	111	556	12.0	324.6	−15.5
10	121	709	11.6	318.5	−15.4
30.6	138	953	11.9	310.5	−20.4
51.5	143	987	13.1	308.3	−25.9

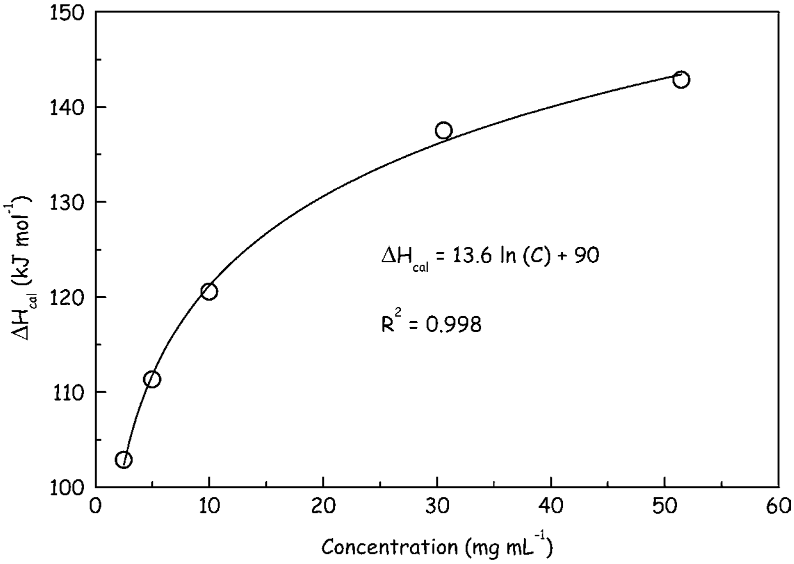

Fig. 3. Graph showing the concentration dependence of the optimised calorimetric enthalpy values for POP, obtained using the model fitting procedure.

that *n* is independent of polymer concentration. On the other hand, the variation in the other optimised parametric values with concentration is markedly greater than the RSD and must therefore denote genuine functional relationships with concentration. The graphical relationships between the enthalpy values, $T_{1/2}$ and concentration are shown in Figs. 3 and 4. The data clearly demonstrate a good log–linear relationship

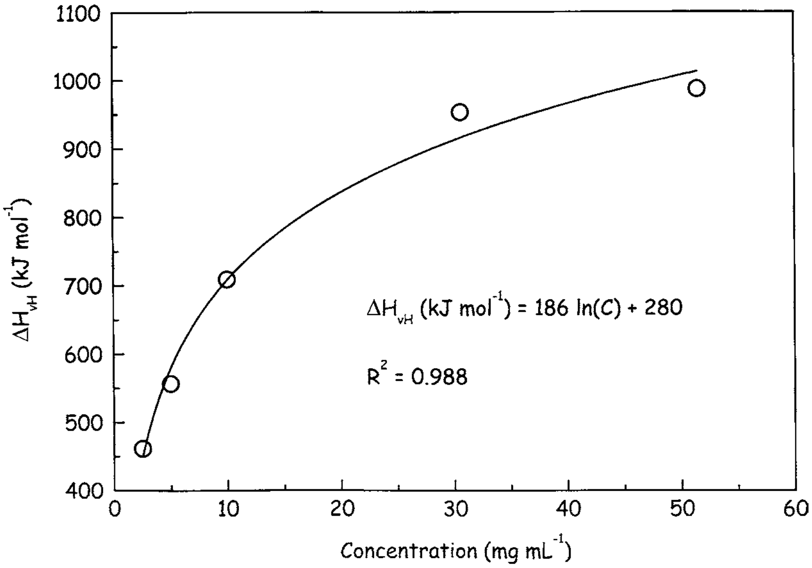

Fig. 4. Graph showing the concentration dependence of the optimised van’t Hoff enthalpy values for POP, obtained using the model fitting procedure.

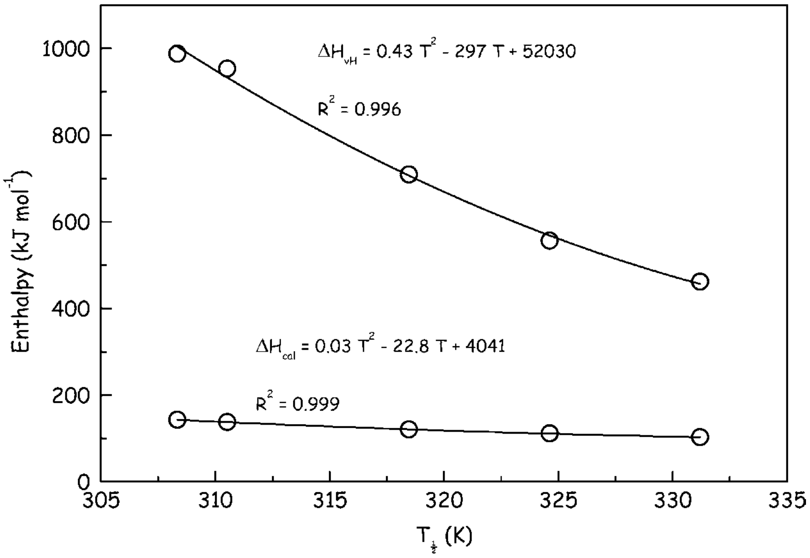

Fig. 5. Graph showing the relationship between the optimised values of $T_{1/2}$ and the van't Hoff and calorimetric enthalpy values for POP, obtained using the model fitting procedure.

between $T_{1/2}$ and concentration ($R^2 = 0.989$). Excellent log–linear relationships are also observed between the van't Hoff enthalpy and concentration ($R^2 = 0.988$) and the calorimetric enthalpy and concentration ($R^2 = 0.998$).

It seems reasonable to suggest that the reason for these functional thermodynamic dependencies lies in the relationship between the polymer concentration and temperature range over which aggregation occurs. This in turn leads to temperature dependence in the

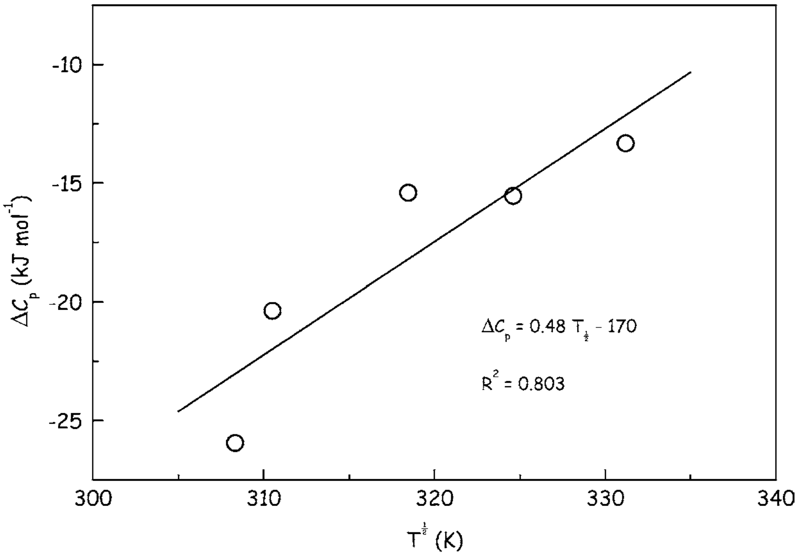

Fig. 6. Graph showing the relationship between the optimised values of $T_{1/2}$ and the heat capacity change values obtained for POP, using the model fitting procedure.

enthalpic parameters because of the existence of an observable heat capacity change between the initial and final states in the system.

To test this hypothesis, Figs. 5 and 6 show the functional relationships for $\Delta H_{\mathrm{cal}}(T_{1/2})$, $\Delta H_{\mathrm{vH}}(T_{1/2})$ and $\Delta C_p(T_{1/2})$ with $T_{1/2}$. Both sets of enthalpic data (Fig. 5) demonstrate an excellent curvilinear relationship with temperature. The following regression equations are obtained from the plots:

$$\Delta H_{\mathrm{cal}} = 0.03T^2 - 22.8T + 4041, \quad R^2 = 0.999$$

$$\Delta H_{\mathrm{vH}} = 0.43T^2 - 297T + 52030, \quad R^2 = 0.996$$

The heat capacity values shown in Fig. 6 are more variable, presumably reflecting the greater level of uncertainty in the determination of this parameter. However the data can be fit to a linear relationship:

$$\Delta C_p = 0.48T - 170, \quad R^2 = 0.803$$

The first derivative of enthalpy with respect to temperature is, of course, heat capacity. The following relationship for heat capacity is obtained if the van't Hoff enthalpy regression expression is differentiated:

$$\frac{\partial H_{\mathrm{vH}}}{\partial T} = \Delta C_{\mathrm{p}} = 0.86T - 297$$

The fact that the parametric values obtained for the slope and intercept are of the same order of magnitude and are fairly close in value to the regression parameters points to some consistency between the values obtained for the heat capacities and van't Hoff enthalpies. Though such a correlation could merely reflect cross correlation in the model fitting procedure.

Acknowledgements

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