J. Chem. Eng. Data **1998,** *43,* 601−604

Liquid Viscosities of Pentane and Pentane + Decane from 298.15 K to 373.15 K and up to 25 MPa

Alejandro Estrada-Baltazar and Gustavo A. Iglesias-Silva*

Departamento de Ingeniería Química, Instituto Tecnológico de Celaya, Celaya, Guanajuato, CP 38010, México

María A. Barrufet

Petroleum Engineering Department, Texas A&M University, College Station, Texas 77843

The liquid viscosity of pentane and pentane + decane was measured using a rolling ball viscometer at temperatures from 298.15 K to 373.15 K and at pressures up to 25 MPa over the entire composition range. The experimental values are compared with the literature values, and they agree within 3%. Deviation of viscosities results with existing correlations is within 6.6%.

Introduction

Experimental liquid viscosities of pure hydrocarbons and their mixtures under pressure are important to simulate the behavior of the fluid at oil field conditions. Also, experimental measurements over a wide range of temperature and pressure are needed to test the effectiveness of semitheoretical and empirical viscosity models. Unfortunately, few experimental values for hydrocarbon mixtures at high-pressure exist in the literature. A summary of pure *n*-alkane and binary *n*-alkane viscosity data is given by Assael et al. (1992a) and Assael et al. (1992b), respectively.

Experimental measurements of pentane have been published by Lee and Ellington (1965), Kiran and Sen (1992), Reamer et al. (1959), and TRC SOURCE (1996). They used a capillary tube, a falling sinker, and a rotating cylinder viscometer. For the binary mixture pentane + decane, the measurements of Aucejo et al. (1995) are the only published values. They measured the viscosity of this mixture using a Ubbelohde viscometer at 298.15 K and at atmospheric pressure over the entire range of composition.

This work is part of our program on viscosity measurements of hydrocarbons. Recently, we have reported the viscosity of hydrocarbon mixtures with carbon dioxide (Barrufet et al., 1996). In the second part, we have measured the viscosity of decane and octane + decane using a rolling ball viscometer at pressures up to 25 MPa (Estrada-Baltazar et al., 1998). In this work, using the same apparatus, we present new viscosity measurements for pentane + decane at temperatures from 298.15 K to 373.15 K and at pressures up to 25 MPa over the entire composition range. Additionally, viscosity measurements on pentane are presented over the same range of pressure and temperature to check the calibration of the apparatus.

Experimental Apparatus

We have used a high-pressure rolling ball viscometer previously described by Estrada-Baltazar et al. (1998). Here, we will mention only the most important aspects of the apparatus.

The measuring system consists of a stainless steel high-pressure housing fixed with an internal cylindrical barrel in which a stainless steel sphere rolls on a perfectly polished surface. A plug containing the barrel seal and a solenoid closes the lower end.

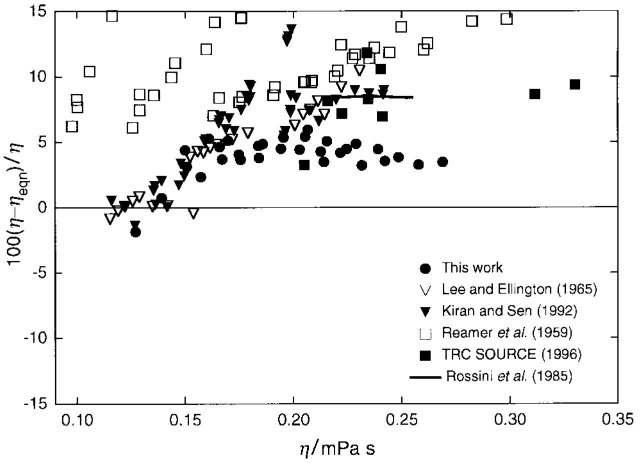

Figure 1. Relative deviation of measured pentane viscosities and published viscosities from the equation of Assael et al. (1992a).

The solenoid holds the steel sphere in the upper part of the barrel, and the sphere will not fall until the solenoid current is interrupted in the control unit. The traveling time is measured with a watch that is activated electronically when the current is interrupted and is stopped when the sphere reaches the end of its travel. Repeatability of the roll time measurements is ±0.1%.

The temperature of the viscometer can be controlled within ±0.2 K. The measuring fluid is injected into the system using a Ruska high-pressure pump with a maximum capacity of 68 MPa. The pressure can be read with an accuracy of ±0.001 MPa.

Calibration

A rolling-ball principle is used to determine the fluid viscosities. The method consists of rolling a stainless steel sphere through a fluid of unknown viscosity at given conditions of temperature and pressure for a precise

S0021-9568(97)00269-0 CCC: $15.00

Table 1. Experimental Viscosities for Pentane

T/K	P/MPa	η/mPa s	T/K	P/MPa	η/mPa s	T/K	P/MPa	η/mPa s
297.95	0.101	0.2141	328.05	0.101		358.25	0.101	
297.95	4.995	0.2289	328.05	4.995	0.1838	358.25	4.995	0.1499
297.95	9.913	0.2391	328.05	9.913	0.1954	358.25	9.913	0.1610
297.95	14.815	0.2486	328.05	14.815	0.2066	358.25	14.815	0.1698
297.95	21.696	0.2579	328.05	21.696	0.2126	358.25	21.696	0.1757
297.95	24.626	0.2690	328.05	24.626	0.2217	358.25	24.626	0.1841
313.05	0.101		343.15	0.101		373.35	0.101	
313.05	4.995	0.2055	343.15	4.995	0.1660	373.35	4.995	0.1271
313.05	9.913	0.2155	343.15	9.913	0.1749	373.35	9.913	0.1391
313.05	14.815	0.2245	343.15	14.815	0.1858	373.35	14.815	0.1508
313.05	21.696	0.2316	343.15	21.696	0.1942	373.35	21.696	0.1573
313.05	24.626	0.2423	343.15	24.626	0.2029	373.35	24.626	0.1671

Table 2. Experimental Viscosities for Pentane (1) + Decane (2)

T/K	P/MPa	η/mPa s	T/K	P/MPa	η/mPa s	T/K	P/MPa	η/mPa s
				$x_1 = 0.1031$				
297.95	0.101	0.7711	328.05	0.101	0.5511	358.25	0.101	0.4113
297.95	4.995	0.8437	328.05	4.995	0.5971	358.25	4.995	0.4342
297.95	9.913	0.8814	328.05	9.913	0.6163	358.25	9.913	0.4534
297.95	14.815	0.9276	328.05	14.815	0.6585	358.25	14.815	0.4825
297.95	21.696	0.9722	328.05	21.696	0.6934	358.25	21.696	0.4977
297.95	24.626	1.0160	328.05	24.626	0.7129	358.25	24.626	0.5242
313.05	0.101	0.6585	343.15	0.101	0.4671	373.35	0.101	0.3692
313.05	4.995	0.7102	343.15	4.995	0.4949	373.35	4.995	0.3815
313.05	9.913	0.7454	343.15	9.913	0.5235	373.35	9.913	0.4024
313.05	14.815	0.7904	343.15	14.815	0.5527	373.35	14.815	0.4263
313.05	21.696	0.8220	343.15	21.696	0.5805	373.35	21.696	0.4509
313.05	24.626	0.8582	343.15	24.626	0.6090	373.35	24.626	0.4757
				$x_1 = 0.2082$				
297.95	0.101	0.6992	328.05	0.101	0.5014	358.25	0.101	0.3646
297.95	4.995	0.7464	328.05	4.995	0.5434	358.25	4.995	0.3887
297.95	9.913	0.7885	328.05	9.913	0.5714	358.25	9.913	0.4106
297.95	14.815	0.8275	328.05	14.815	0.6006	358.25	14.815	0.4349
297.95	21.696	0.8574	328.05	21.696	0.6295	358.25	21.696	0.4536
297.95	24.626	0.9122	328.05	24.626	0.6599	358.25	24.626	0.4770
313.05	0.101	0.5949	343.15	0.101	0.4279	373.35	0.101	0.3364
313.05	4.995	0.6464	343.15	4.995	0.4524	373.35	4.995	0.3508
313.05	9.913	0.6821	343.15	9.913	0.4803	373.35	9.913	0.3726
313.05	14.815	0.7187	343.15	14.815	0.5091	373.35	14.815	0.3957
313.05	21.696	0.7457	343.15	21.696	0.5276	373.35	21.696	0.4174
313.05	24.626	0.7865	343.15	24.626	0.5576	373.35	24.626	0.4394
				$x_1 = 0.3062$				
297.95	0.101	0.6136	328.05	0.101	0.4446	358.25	0.101	0.3525
297.95	4.995	0.6549	328.05	4.995	0.4789	358.25	4.995	0.3760
297.95	9.913	0.6847	328.05	9.913	0.5021	358.25	9.913	0.3988
297.95	14.815	0.7174	328.05	14.815	0.5323	358.25	14.815	0.4203
297.95	21.696	0.7580	328.05	21.696	0.5600	358.25	21.696	0.4391
297.95	24.626	0.7973	328.05	24.626	0.5804	358.25	24.626	0.4581
313.05	0.101	0.5183	343.15	0.101	0.3993	373.35	0.101	0.3043
313.05	4.995	0.5560	343.15	4.995	0.4297	373.35	4.995	0.3252
313.05	9.913	0.5881	343.15	9.913	0.4541	373.35	9.913	0.3438
313.05	14.815	0.6198	343.15	14.815	0.4780	373.35	14.815	0.3640
313.05	21.696	0.6538	343.15	21.696	0.4959	373.35	21.696	0.3802
313.05	24.626	0.6760	343.15	24.626	0.5230	373.35	24.626	0.4008
				$x_1 = 0.4080$				
297.95	0.101	0.5536	328.05	0.101	0.4143	358.25	0.101	0.3094
297.95	4.995	0.5879	328.05	4.995	0.4368	358.25	4.995	0.3369
297.95	9.913	0.6181	328.05	9.913	0.4664	358.25	9.913	0.3552
297.95	14.815	0.6545	328.05	14.815	0.4844	358.25	14.815	0.3763
297.95	21.696	0.6861	328.05	21.696	0.5088	358.25	21.696	0.3939
297.95	24.626	0.7071	328.05	24.626	0.5359	358.25	24.626	0.4133
313.05	0.101	0.4627	343.15	0.101	0.3574	373.35	0.101	0.2674
313.05	4.995	0.5220	343.15	4.995	0.3779	373.35	4.995	0.2839
313.05	9.913	0.5511	343.15	9.913	0.4050	373.35	9.913	0.3069
313.05	14.815	0.5787	343.15	14.815	0.4261	373.35	14.815	0.3189
313.05	21.696	0.5991	343.15	21.696	0.4444	373.35	21.696	0.3363
313.05	24.626	0.6283	343.15	24.626	0.4659	373.35	24.626	0.3461
				$x_1 = 0.5061$				
297.95	0.101	0.4708	328.05	0.101	0.3625	358.25	0.101	0.2821
297.95	4.995	0.5020	328.05	4.995	0.3855	358.25	4.995	0.2994
297.95	9.913	0.5295	328.05	9.913	0.4079	358.25	9.913	0.3138
297.95	14.815	0.5544	328.05	14.815	0.4285	358.25	14.815	0.3342
297.95	21.696	0.5804	328.05	21.696	0.4457	358.25	21.696	0.3487
297.95	24.626	0.6087	328.05	24.626	0.4723	358.25	24.626	0.3677
313.05	0.101	0.4237	343.15	0.101	0.3121	373.35	0.101	
313.05	4.995	0.4482	343.15	4.995	0.3413	373.35	4.995	0.2574
313.05	9.913	0.4701	343.15	9.913	0.3564	373.35	9.913	0.2731
313.05	14.815	0.4926	343.15	14.815	0.3740	373.35	14.815	0.2905
313.05	21.696	0.5217	343.15	21.696	0.3914	373.35	21.696	0.3044
313.05	24.626	0.5453	343.15	24.626	0.4111	373.35	24.626	0.3209

Table 2. Continued

				x = 0.6029				
297.95	0.101	0.4339	328.05	0.101	0.3268	358.25	0.101	
297.95	4.995	0.4590	328.05	4.995	0.3360	358.25	4.995	0.2691
297.95	9.913	0.4862	328.05	9.913	0.3531	358.25	9.913	0.2859
297.95	14.815	0.5088	328.05	14.815	0.3707	358.25	14.815	0.3029
297.95	21.696	0.5332	328.05	21.696	0.3894	358.25	21.696	0.3181
297.95	24.626	0.5626	328.05	24.626	0.4094	358.25	24.626	0.3311
313.05	0.101	0.3644	343.15	0.101	0.2753	373.35	0.101	
313.05	4.995	0.3933	343.15	4.995	0.2938	373.35	4.995	0.2370
313.05	9.913	0.4092	343.15	9.913	0.3103	373.35	9.913	0.2528
313.05	14.815	0.4296	343.15	14.815	0.3260	373.35	14.815	0.2674
313.05	21.696	0.4506	343.15	21.696	0.3445	373.35	21.696	0.2805
313.05	24.626	0.4734	343.15	24.626	0.3610	373.35	24.626	0.2955
				x_1= 0.7058				
297.95	0.101	0.3667	328.05	0.101	0.2850	358.25	0.101	
297.95	4.995	0.3865	328.05	4.995	0.3020	358.25	4.995	0.2419
297.95	9.913	0.4055	328.05	9.913	0.3172	358.25	9.913	0.2558
297.95	14.815	0.4246	328.05	14.815	0.3315	358.25	14.815	0.2695
297.95	21.696	0.4449	328.05	21.696	0.3519	358.25	21.696	0.2822
297.95	24.626	0.4684	328.05	24.626	0.3647	358.25	24.626	0.2979
313.05	0.101	0.3189	343.15	0.101	0.2477	373.35	0.101	
313.05	4.995	0.3388	343.15	4.995	0.2629	373.35	4.995	0.2070
313.05	9.913	0.3587	343.15	9.913	0.2781	373.35	9.913	0.2208
313.05	14.815	0.3789	343.15	14.815	0.2907	373.35	14.815	0.2348
313.05	21.696	0.3928	343.15	21.696	0.3102	373.35	21.696	0.2452
313.05	24.626	0.4112	343.15	24.626	0.3250	373.35	24.626	0.2555
				x_1 = 0.8040				
297.95	0.101	0.3200	328.05	0.101	0.2432	358.25	0.101	
297.95	4.995	0.3398	328.05	4.995	0.2612	358.25	4.995	0.2123
297.95	9.913	0.3572	328.05	9.913	0.2736	358.25	9.913	0.2245
297.95	14.815	0.3713	328.05	14.815	0.2918	358.25	14.815	0.2387
297.95	21.696	0.3853	328.05	21.696	0.3034	358.25	21.696	0.2491
297.95	24.626	0.4023	328.05	24.626	0.3168	358.25	24.626	0.2609
313.05	0.101	0.2801	343.15	0.101		373.35	0.101	
313.05	4.995	0.2974	343.15	4.995	0.2345	373.35	4.995	0.1881
313.05	9.913	0.3119	343.15	9.913	0.2449	373.35	9.913	0.1993
313.05	14.815	0.3280	343.15	14.815	0.2565	373.35	14.815	0.2119
313.05	21.696	0.3393	343.15	21.696	0.2733	373.35	21.696	0.2242
313.05	24.626	0.3591	343.15	24.626	0.2874	373.35	24.626	0.2329
				x_1 = 0.9008				
297.95	0.101	0.2645	328.05	0.101		358.25	0.101	
297.95	4.995	0.2787	328.05	4.995	0.2206	358.25	4.995	0.1764
297.95	9.913	0.2912	328.05	9.913	0.2337	358.25	9.913	0.1879
297.95	14.815	0.3054	328.05	14.815	0.2451	358.25	14.815	0.1970
297.95	21.696	0.3200	328.05	21.696	0.2587	358.25	21.696	0.2090
297.95	24.626	0.3353	328.05	24.626	0.2702	358.25	24.626	0.2200
313.05	0.101	0.2396	343.15	0.101		373.35	0.101	
313.05	4.995	0.2546	343.15	4.995	0.2008	373.35	4.995	0.1553
313.05	9.913	0.2645	343.15	9.913	0.2140	373.35	9.913	0.1630
313.05	14.815	0.2764	343.15	14.815	0.2251	373.35	14.815	0.1730
313.05	21.696	0.2947	343.15	21.696	0.2364	373.35	21.696	0.1806
313.05	24.626	0.3051	343.15	24.626	0.2473	373.35	24.626	0.1907

distance. The viscosity is a function of the rolling time used to travel the distance and the density difference between the sphere and fluid

$$\eta = K(t, P, T)(\rho_s - \rho_f) \tag{1}$$

where η is the absolute viscosity, t is the sphere roll time, ρ_s is the density of the sphere, ρ_f is the density of the fluid, and K is a function obtained by calibrating the viscometer with a substance of known viscosity and density.

The calibration procedure is similar to the one used by Kiran and Sen (1992). Details of the calibration procedure are given by Estrada-Baltazar et al. (1998). They found that the function K can be expressed as

$$K(t, P, T) = \frac{\kappa(t)}{X(T, P, t)} \tag{2}$$

$$\kappa(t) = -0.069\,29 + 0.011\,53(t/\mathrm{s}) - 1.3 \times 10^{-4}(t/\mathrm{s})^2 \tag{3}$$

$$X(T, P, t) = 0.752\,18 + 9.207 \times 10^{-5}(T/\mathrm{K})(P/\mathrm{MPa}) - 9.352 \times 10^{-6}(T/\mathrm{K})^{1.5} + 722.511(t/\mathrm{s})^{-3.5} - 7793.08(t/\mathrm{s})^{-4.5} + 0.816\,81(T/\mathrm{K})^{-0.5} + 0.836\,08(T/\mathrm{K})^{-1.5}(P/\mathrm{MPa}) + 0.026\,04[(t/\mathrm{s})(P/\mathrm{MPa})]^{-4.5} \tag{4}$$

A sphere of 0.6 cm diameter and an angle of 23° are used for all measurements. With these conditions a laminar regime is obtained during the measurements at different pressures and temperatures. This ensures a good correlation of the viscosity with the time as suggested by Hubbard and Brown (1943). Fluid densities are calculated using the correlation of Assael et al. (1994). They reported an average deviation of their correlation with respect to the experimental values of decane and pentane of 0.1%.

Samples

The pentane and decane samples were purchased from Lancaster Synthesis Inc. and had a minimum stated purity of 99+% samples. The hydrocarbon binary mixture was prepared gravimetrically using a Mettler PM4600 balance with an accuracy of ±0.01 g. The estimated accuracy in the preparation of the mixture was better than ±0.01% on a mass basis.

Results and Discussion

Experimental values of pentane and pentane + decane are shown in Tables 1 and 2, respectively. Each measurement is the result of an average value of 10 measurements of the roll time taken when thermal and mechanical

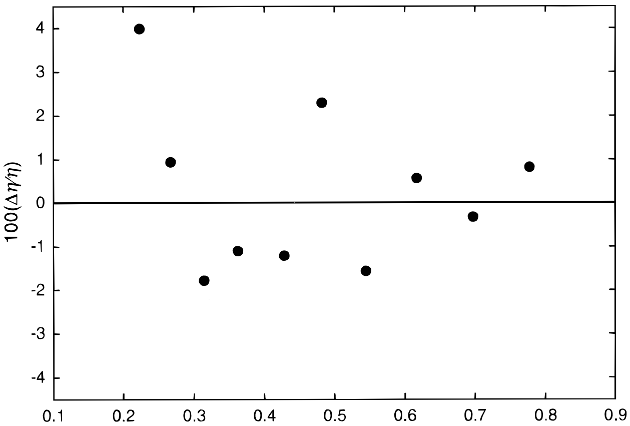

Figure 2. Relative deviation of measured pentane + decane viscosities at 0.1 MPa from the viscosities measured by Aucejo et al. (1995).

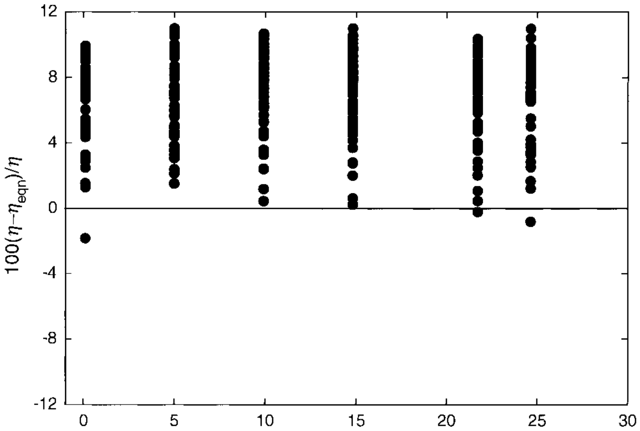

Figure 3. Relative deviation of measured pentane + decane viscosities from the equation of Assael et al. (1992b).

equilibrium are reached in the viscometer. The mean standard deviation of the roll time sets is ±0.02 s, and the maximum and minimum average value of the roll time is 25.47 and 7.54 s, respectively.

Our experimental results of pentane are compared with the correlation of Assael et al. (1992a). They agree over the whole range within 5% of the values predicted by this correlation as indicated in Figure 1. The agreement between new viscosity values and the results of Lee and Ellington (1965) is within 2% but reaches a maximum of 7% at the highest viscosities, which correspond to pressures of the order of 21 MPa. Kiran and Sen (1992) also measured the viscosity of pentane, and their results agree with our measurements within an average value of 6.5%. Experimental measurements from Reamer et al. (1959) agree with our measurements within an average value of 10%, but the disagreement between some of their values and Assael's correlation is more than 15%.

We compare our viscosity measurements of pentane + decane with values given by Aucejo et al. (1995). Unfortunately, we can compare our results only at 0.1 MPa and at 298.15 K. Figure 2 shows the agreement between both sets of data. They agree within an average value of 1.6%. The correlation published by Assael et al. (1992b) underestimates the viscosity up to 11% at higher pressures, as shown in Figure 3. However, the predictive capability of the correlation is good considering that the correlation was based on measurements at atmospheric pressure.

Conclusions

We have measured the viscosity of pentane and the binary mixture of pentane + decane. The experimental values of pentane agree with published values within an average percentage error of 3%. The new measurements for the binary mixture could be used to correct the correlation developed for Assael et al. (1992b) at high pressures or to develop new predictive models.

Literature Cited

Assael, M. J.; Dymond, J. H.; Papadaki, M.; Patterson, P. M. Correlation and Prediction of Dense Fluid Transport Coefficients. I. *n*-Alkanes. *Int. J. Thermophys.* **1992a**, *13*, 269−281.

Assael, M. J.; Dymond, J. H.; Papadaki, M.; Patterson, P. M. Correlation and Prediction of Dense Fluid Transport Coefficients. III. *n*-Alkanes Mixtures. *Int. J. Thermophys.* **1992b**, *13*, 659−669.

Assael, M. J.; Dymond, J. H.; Exadaktilou, D. An Improved Representation for *n*-Alkane Liquid Densities. *Int. J. Thermophys.* **1994**, *15*, 155−164.

Aucejo, A.; Berguet, M. C.; Muñoz, R.; Márquez, J. L. Densities, Viscosities, and Refractive Indices of Some *n*-Alkane Binary Liquid Systems at 298.15 K. *J. Chem. Eng. Data* **1995**, *40*, 141−147.

Barrufet, M. A.; Salem, S. K.; Tantawy, M.; Iglesias-Silva, G. A. Liquid Viscosities of Carbon Dioxide + Hydrocarbons fomm 310 K to 403 K. *J. Chem. Eng. Data* **1996**, *41*, 436−439.

Estrada-Baltazar, A.; Alvarado, J. F. J.; Iglesias-Silva, G. A.; Barrufet, M. A. Experimental Liquid Viscosities of *n*-Decane and *n*-Octane + *n*-Decane from 298.15 to 373.15 K and up to 25 MPa. *J. Chem. Eng. Data* **1998**, *43*, 441−446.

Hubbard, R. M.; Brown, G. G. The Rolling Ball Viscometer. *Ind. Eng. Chem. Anal.* **1943**, *15*, 212−218.

Kiran, E.; Sen, Y. L. High-Pressure Viscosity and Density of *n*-Alkanes. *Int. J. Thermophys.* **1992**, *13*, 411−442.

Lee, A. L.; Ellington, R. T. Viscosity of *n*-Pentane. *J. Chem. Eng. Data* **1965**, *10*, 101−104.

Reamer, H. H.; Cokelet, G.; Sage, B. H. Viscosity of Fluids at High Pressures. Rotating Cylinder Viscometer and the Viscosity of *n*-Pentane. *Anal. Chem.* **1959**, *31*, 1423−1428.

Rossini, F. D.; Pitzer, K. S.; Arnett, R. L.; Braun, R. M.; Pimental, G. C. *Selected Values of Physical and Thermodynamic Properties of Hydrocarbons and Related Compounds*; American Petroleum Institute Research Project #44; Carniege Press: Pittsburgh, PA, 1983.

TRC Databases for Chemistry and Engineering−SOURCE Database, Version 1996−2. Thermodynamics Research Center, Texas A&M University System: College Station, TX, 1996.

Received for review November 12, 1997. Accepted April 6, 1998. Texas A&M University and the Instituto Tecnológico de Celaya have provided financial support for this work.

JE9702697