Liquid Viscosity of Octane and Pentane + Octane Mixtures from 298.15 K to 373.15 K up to 25 MPa

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This paper reports liquid viscosities for octane and pentane + octane over the entire composition range collected with a rolling-ball viscometer at temperatures from 298.15 K to 373.15 K and pressures up to 25 MPa. The experimental values agree with literature values within 5%. The current viscosities compare to existing correlations within 9%.

Introduction

Equipment design and fluid transport usually require liquid viscosities of pure hydrocarbons and their mixtures under pressure. Viscosities can be measured experimentally or calculated from accurate correlating techniques. Unfortunately, few experimental values exist in the literature for hydrocarbon mixtures at high pressure. Therefore, the accuracy of existing predictive correlations is limited to the temperature and pressure ranges of the experimental data used in their development. Assael et al. (1992a; 1992b) have reviewed experimental viscosity data for pure *n*-alkane and multicomponent mixtures of *n*-alkanes.

Dymond and Young (1980) have measured liquid viscosities of octane using a suspended level viscometer from 283 to 378 K at atmospheric pressure. Knapstad et al. (1989) have measured the viscosity of octane at 313 K. Recently, Tanaka et al. (1991) have measured the viscosity of several hydrocarbons, including octane, at pressures as high as 150 MPa. Kiran and Sen (1992) report viscosity data for butane, pentane, hexane, and octane from 310 to 450 K at pressures up to 70 MPa. Only Aucejo et al. (1995) have reported data for the binary mixture pentane + octane. Their data cover the entire range of composition at 298.15 K and atmospheric pressure.

From our laboratories, Barrufet et al. (1996) report the viscosity of hydrocarbon mixtures with carbon dioxide; Estrada-Baltazar et al. (1998a) and Estrada-Baltazar et al. (1998b) provide the viscosity of decane and octane + decane and of pentane and pentane + decane at temperatures from 298.15 to 373.15 K at pressures up to 25 MPa, respectively. Here, we present new viscosity measurements for octane and pentane + decane at temperatures from 298.15 K to 373.15 K and at pressures up to 25 MPa collected using a rolling-ball viscometer.

Experimental Apparatus

Estrada-Baltazar et al. (1998a) provide a full description of the apparatus, so here we mention only the most important features of the apparatus. The measuring system is a stainless steel, high-pressure housing fitted with an internal cylindrical barrel. The total capacity of the barrel is 20 cm^3. In the upper part of the barrel, a plug containing the barrel seal and a solenoid closes the housing in which a stainless steel sphere rolls on a polished surface. The inner diameter of the housing where the sphere rolls is 0.64 cm. The solenoid holds the sphere until the control unit interrupts the current. A watch is activated and deactivated electronically when the current is interrupted, and when the sphere reaches the end of the housing, it measures the travel time automatically. The repeatability of the roll time measurements is ±0.1%.

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

Calibration

In the rolling-ball viscometer, a stainless steel sphere rolls through a fluid of unknown viscosity at given conditions of temperature and pressure for a precise distance. The viscosity is a function of the rolling time 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 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. We have used a Cannon certified viscosity standard, pentane, and octane as calibrating fluids. For pentane, experimental densities

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10.1021/je990043z CCC: $18.00

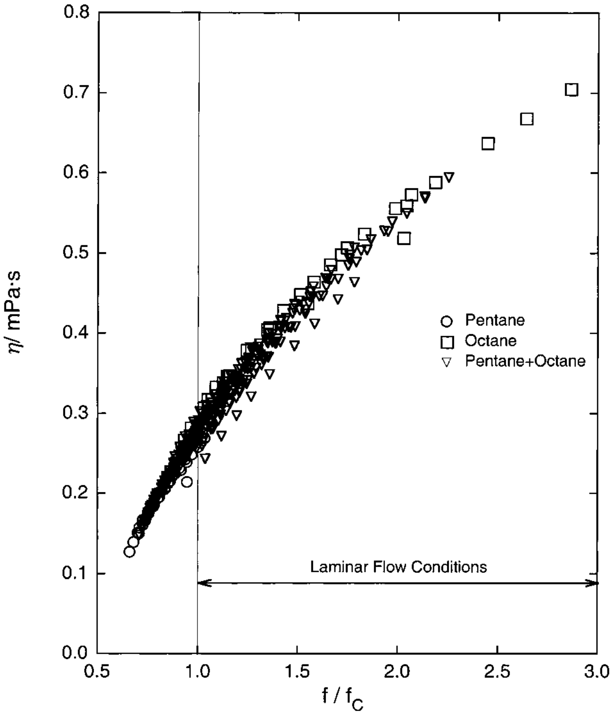

Figure 1. Variation of the viscosity with the resistance factor ratio.

and viscosities are taken from Lee and Ellington (1965) and Kiran and Sen (1992). For octane, experimental measurements are from Kashiwagi and Makita (1982) and Kiran and Sen (1992). Estrada-Baltazar et al. (1998a) provide details of the calibration procedure. K is

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

with

$$\kappa(t) = -0.06929 + 0.01153(t/\mathrm{s}) - 1.3 \times 10^{-4}(t/\mathrm{s})^2 \tag{3}$$

and

$$\begin{aligned} X(T,P,t) = {} & 0.75218 + 9.207 \times 10^{-5}(T/\mathrm{K})(P/\mathrm{MPa}) - \\ & 9.352 \times 10^{-6}(T/\mathrm{K})^{1.5} + 722.511(t/\mathrm{s})^{-3.5} - \\ & 7793.08(t/\mathrm{s})^{-4.5} + 0.81681(T/\mathrm{K})^{-0.5} + \\ & 0.83608(T/\mathrm{K})^{-1.5}(P/\mathrm{MPa}) + \\ & 0.02604[(t/\mathrm{s})(P/\mathrm{MPa})]^{-4.5} \end{aligned} \tag{4}$$

The sphere has a diameter of 0.6 cm, and the inclination angle is 23° for all time measurements. Hubbard and Brown (1943) have established that the viscosity correlates well with the time if the measurement is performed in a laminar flow regime. Under these conditions, the ratio of the friction factor at experimental conditions and that at the critical velocity is greater than unity. Hubbard and Brown (1943) give details of the procedure to calculate the resistance factor using the diameter ratio between the sphere and the tube, the velocity of the sphere, and the resistance force. Figure 1 demonstrates that our flow regime is laminar.

The Tait equation proposed by Assael et al. (1994) provides fluid densities. They report an average deviation of ±0.5% for their correlation with respect to experimental values of n-alkanes. For hydrocarbon mixtures, they report a procedure that gives an average deviation of 0.6% with respect to experimental values.

Samples

Lancaster Synthesis Inc. supplied the pentane and octane samples with a minimum stated purity of 99+%. We prepared the binary mixture 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

Tables 1 and 2 present experimental values for octane and pentane + octane mixtures. Experimental viscosities for pure pentane were measured by Estrada-Baltazar et al. (1998b). At atmospheric pressure and high temperatures, measurements are not reported because the mixture is in a gas or fluid phase. Each measurement was repeated 10 times at thermal and mechanical equilibrium, and the final value is an average of these measurements. The mean standard deviation of the roll times is ±0.015 s.

We have compared our results to the correlation of Assael et al. (1992a). They express the viscosity as

$$\eta = (0.1657 \times 10^{-8})\frac{\eta^*_{\mathrm{exp}}}{V^{2/3}}\left[\frac{1}{MRT}\right]^{-1/2} \tag{5}$$

where V is the molar volume, M is the molecular weight, T is the absolute temperature, and η^*_{exp} is the reduced experimental viscosity calculated from

$$\log\left(\frac{\eta^*_{\mathrm{exp}}}{R_\eta}\right) = \sum_{i=0}^{7} a_i\left(\frac{V_0}{V}\right)^i \tag{6}$$

with $a_0 = 1.0945$, $a_1 = -9.26324$, $a_2 = 71.0385$, $a_3 = -301.9012$, $a_4 = 797.69$, $a_5 = -1221.9770$, $a_6 = 987.5574$, and $a_7 = -319.4636$. In eq 6, R_η includes the effects caused by the nonsphericity of the molecules given by

$$R_\eta = 0.995 - 0.0008944C + 0.005427C^2 \tag{7}$$

where C is the number of carbon atoms in the molecule. The reducing volume V_0 is given by the following function of temperature and the number of carbon atoms:

$$\begin{aligned} 10^6 V_0 = {} & 117.874 + 0.15(-1)^c - 0.25275T + \\ & 0.000548T^2 - (4.246 \times 10^{-7})T^3 + (C - 6)(1.27 - \\ & 0.0009T)(13.27 + 0.025C) \end{aligned} \tag{8}$$

This equation is valid only for C_5H_{12} to $C_{16}H_{34}$.

Assael et al. (1992b) propose simple mixing rules for V_0 and R_η, given by

$$V_{0,m} = \sum_i x_i V_{0,i} \tag{9}$$

and

$$R_{\eta,m} = \sum_i x_i R_{\eta,i} \tag{10}$$

Figure 2 illustrates that for octane our results agree with the values predicted by the Assael et al. correlation within 6%. Our results agree reasonably well with values given

Table 1. Experimental Viscosities for Octane

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	0.5195	328.05	0.101	0.3744	358.25	0.101	0.2769
297.95	4.995	0.5602	328.05	4.995	0.4066	358.25	4.995	0.3091
297.95	9.913	0.5894	328.05	9.913	0.4072	358.25	9.913	0.3185
297.95	14.815	0.6378	328.05	14.815	0.4492	358.25	14.815	0.3387
297.95	21.696	0.6688	328.05	21.696	0.4863	358.25	21.696	0.3468
297.95	24.626	0.7056	328.05	24.626	0.5075	358.25	24.626	0.3793
313.05	0.101	0.4377	343.15	0.101	0.3171	373.35	0.101	0.2486
313.05	4.995	0.4645	343.15	4.995	0.3474	373.35	4.995	0.2670
313.05	9.913	0.4986	343.15	9.913	0.3471	373.35	9.913	0.2824
313.05	14.815	0.5249	343.15	14.815	0.3813	373.35	14.815	0.3074
313.05	21.696	0.5569	343.15	21.696	0.4048	373.35	21.696	0.3178
313.05	24.626	0.5739	343.15	24.626	0.4289	373.35	24.626	0.3337

Table 2. Experimental Viscosities for Pentane (1) + Octane (2) at Mole Fraction x_1

T/K	P/MPa	η/mPa·s	T/K	P/MPa	η/mPa s	T/K	P/MPa	η/mPa·s
				$x_1 = 0.8946$				
297.95	0.101	0.2443	328.05	0.101		358.25	0.101	
297.95	4.995	0.2567	328.05	4.995	0.2028	358.25	4.995	0.1637
297.95	9.913	0.2692	328.05	9.913	0.2132	358.25	9.913	0.1728
297.95	14.815	0.2810	328.05	14.815	0.2227	358.25	14.815	0.1817
297.95	21.696	0.2920	328.05	21.696	0.2363	358.25	21.696	0.1916
297.95	24.626	0.3038	328.05	24.626	0.2464	358.25	24.626	0.2012
313.05	0.101		343.15	0.101		373.35	0.101	
313.05	4.995	0.2276	343.15	4.995	0.1801	373.35	4.995	0.1487
313.05	9.913	0.2420	343.15	9.913	0.1910	373.35	9.913	0.1580
313.05	14.815	0.2494	343.15	14.815	0.2018	373.35	14.815	0.1661
313.05	21.696	0.2602	343.15	21.696	0.2091	373.35	21.696	0.1766
313.05	24.626	0.2754	343.15	24.626	0.2205	373.35	24.626	0.1844
				$x_1 = 0.8097$				
297.95	0.101	0.2723	328.05	0.101		358.25	0.101	
297.95	4.995	0.2844	328.05	4.995	0.2236	358.25	4.995	0.1778
297.95	9.913	0.2987	328.05	9.913	0.2335	358.25	9.913	0.1886
297.95	14.815	0.3129	328.05	14.815	0.2462	358.25	14.815	0.1974
297.95	21.696	0.3266	328.05	21.696	0.2577	358.25	21.696	0.2103
297.95	24.626	0.3378	328.05	24.626	0.2669	358.25	24.626	0.2188
313.05	0.101		343.15	0.101		373.35	0.101	
313.05	4.995	0.2506	343.15	4.995	0.1983	373.35	4.995	0.1610
313.05	9.913	0.2617	343.15	9.913	0.2101	373.35	9.913	0.1732
313.05	14.815	0.2725	343.15	14.815	0.2208	373.35	14.815	0.1821
313.05	21.696	0.2885	343.15	21.696	0.2296	373.35	21.696	0.1927
313.05	24.626	0.3024	343.15	24.626	0.2399	373.35	24.626	0.2005
				$x_1 = 0.7095$				
297.95	0.101	0.2978	328.05	0.101		358.25	0.101	
297.95	4.995	0.3148	328.05	4.995	0.2482	358.25	4.995	0.1926
297.95	9.913	0.3306	328.05	9.913	0.2631	358.25	9.913	0.2080
297.95	14.815	0.3422	328.05	14.815	0.2728	358.25	14.815	0.2194
297.95	21.696	0.3611	328.05	21.696	0.2846	358.25	21.696	0.2352
297.95	24.626	0.3711	328.05	24.626	0.2974	358.25	24.626	0.2480
313.05	0.101	0.2604	343.15	0.101		373.35	0.101	
313.05	4.995	0.2846	343.15	4.995	0.2176	373.35	4.995	0.1760
313.05	9.913	0.2981	343.15	9.913	0.2287	373.35	9.913	0.1861
313.05	14.815	0.3121	343.15	14.815	0.2445	373.35	14.815	0.1963
313.05	21.696	0.3294	343.15	21.696	0.2548	373.35	21.696	0.2118
313.05	24.626	0.3418	343.15	24.626	0.2678	373.35	24.626	0.2218
				$x_1 = 0.5998$				
297.95	0.101	0.3216	328.05	0.101		358.25	0.101	
297.95	4.995	0.3381	328.05	4.995	0.2630	358.25	4.995	0.2137
297.95	9.913	0.3574	328.05	9.913	0.2745	358.25	9.913	0.2246
297.95	14.815	0.3722	328.05	14.815	0.2917	358.25	14.815	0.2385
297.95	21.696	0.3900	328.05	21.696	0.3049	358.25	21.696	0.2484
297.95	24.626	0.4094	328.05	24.626	0.3180	358.25	24.626	0.2617
313.05	0.101	0.2816	343.15	0.101		373.35	0.101	
313.05	4.995	0.2989	343.15	4.995	0.2333	373.35	4.995	0.1917
313.05	9.913	0.3128	343.15	9.913	0.2456	373.35	9.913	0.2076
313.05	14.815	0.3254	343.15	14.815	0.2593	373.35	14.815	0.2167
313.05	21.696	0.3379	343.15	21.696	0.2711	373.35	21.696	0.2289
313.05	24.626	0.3563	343.15	24.626	0.2827	373.35	24.626	0.2389
				$x_1 = 0.5066$				
297.95	0.101	0.3498	328.05	0.101		358.25	0.101	
297.95	4.995	0.3702	328.05	4.995	0.2947	358.25	4.995	0.2381
297.95	9.913	0.3882	328.05	9.913	0.3106	358.25	9.913	0.2495
297.95	14.815	0.4082	328.05	14.815	0.3264	358.25	14.815	0.2649
297.95	21.696	0.4253	328.05	21.696	0.3441	358.25	21.696	0.2792
297.95	24.626	0.4474	328.05	24.626	0.3590	358.25	24.626	0.2922
313.05	0.101	0.3205	343.15	0.101		373.35	0.101	
313.05	4.995	0.3385	343.15	4.995	0.2614	373.35	4.995	0.2117
313.05	9.913	0.3560	343.15	9.913	0.2804	373.35	9.913	0.2257
313.05	14.815	0.3742	343.15	14.815	0.2918	373.35	14.815	0.2392
313.05	21.696	0.3897	343.15	21.696	0.3059	373.35	21.696	0.2491
313.05	24.626	0.4073	343.15	24.626	0.3217	373.35	24.626	0.2606

Table 2 (Continued)

T/K	P/MPa	η/mPa·s	T/K	P/MPa	η/mPa s	T/K	P/MPa	η/mPa·s
				$x_1 = 0.4015$				
297.95	0.101	0.3847	328.05	0.101	0.3047	358.25	0.101	
297.95	4.995	0.4086	328.05	4.995	0.3249	358.25	4.995	0.2514
297.95	9.913	0.4300	328.05	9.913	0.3413	358.25	9.913	0.2679
297.95	14.815	0.4471	328.05	14.815	0.3570	358.25	14.815	0.2820
297.95	21.696	0.4687	328.05	21.696	0.3741	358.25	21.696	0.2951
297.95	24.626	0.4899	328.05	24.626	0.3919	358.25	24.626	0.3095
313.05	0.101	0.3504	343.15	0.101		373.35	0.101	
313.05	4.995	0.3659	343.15	4.995	0.2828	373.35	4.995	0.2323
313.05	9.913	0.3885	343.15	9.913	0.3000	373.35	9.913	0.2408
313.05	14.815	0.4065	343.15	14.815	0.3154	373.35	14.815	0.2585
313.05	21.696	0.4295	343.15	21.696	0.3271	373.35	21.696	0.2692
313.05	24.626	0.4465	343.15	24.626	0.3409	373.35	24.626	0.2849
				$x_1 = 03044$				
297.95	0.101	0.4126	328.05	0.101	0.3255	358.25	0.101	
297.95	4.995	0.4379	328.05	4.995	0.3462	358.25	4.995	0.2757
297.95	9.913	0.4596	328.05	9.913	0.3662	358.25	9.913	0.2910
297.95	14.815	0.4854	328.05	14.815	0.3806	358.25	14.815	0.3028
297.95	21.696	0.5051	328.05	21.696	0.3995	358.25	21.696	0.3200
297.95	24.626	0.5281	328.05	24.626	0.4194	358.25	24.626	0.3333
313.05	0.101	0.3676	343.15	0.101	0.2908	373.35	0.101	
313.05	4.995	0.3903	343.15	4.995	0.3104	373.35	4.995	0.2440
313.05	9.913	0.4091	343.15	9.913	0.3226	373.35	9.913	0.2584
313.05	14.815	0.4256	343.15	14.815	0.3442	373.35	14.815	0.2728
313.05	21.696	0.4461	343.15	21.696	0.3559	373.35	21.696	0.2868
313.05	24.626	0.4693	343.15	24.626	0.3703	373.35	24.626	0.3000
				$x_1 = 0.1992$				
297.95	0.101	0.4431	328.05	0.101	0.3415	358.25	0.101	0.2692
297.95	4.995	0.4684	328.05	4.995	0.3645	358.25	4.995	0.2853
297.95	9.913	0.5042	328.05	9.913	0.3838	358.25	9.913	0.3040
297.95	14.815	0.5289	328.05	14.815	0.3997	358.25	14.815	0.3190
297.95	21.696	0.5510	328.05	21.696	0.4154	358.25	21.696	0.3332
297.95	24.626	0.5696	328.05	24.626	0.4353	358.25	24.626	0.3494
313.05	0.101	0.3894	343.15	0.101	0.3004	373.35	0.101	
313.05	4.995	0.4102	343.15	4.995	0.3191	373.35	4.995	0.2529
313.05	9.913	0.4315	343.15	9.913	0.3364	373.35	9.913	0.2678
313.05	14.815	0.4531	343.15	14.815	0.3556	373.35	14.815	0.2856
313.05	21.696	0.4695	343.15	21.696	0.3700	373.35	21.696	0.3009
313.05	24.626	0.4987	343.15	24.626	0.3877	373.35	24.626	0.3106
				$x_1 = 0.1048$				
297.95	0.101	0.4645	328.05	0.101	0.3436	358.25	0.101	0.2603
297.95	4.995	0.4935	328.05	4.995	0.3626	358.25	4.995	0.2742
297.95	9.913	0.5178	328.05	9.913	0.3784	358.25	9.913	0.2919
297.95	14.815	0.5406	328.05	14.815	0.4013	358.25	14.815	0.3088
297.95	21.696	0.5720	328.05	21.696	0.4172	358.25	21.696	0.3243
297.95	24.626	0.5956	328.05	24.626	0.4372	358.25	24.626	0.3396
313.05	0.101	0.3939	343.15	0.101	0.2963	373.35	0.101	
313.05	4.995	0.4169	343.15	4.995	0.3140	373.35	4.995	0.2472
313.05	9.913	0.4416	343.15	9.913	0.3323	373.35	9.913	0.2589
313.05	14.815	0.4592	343.15	14.815	0.3472	373.35	14.815	0.2721
313.05	21.696	0.4794	343.15	21.696	0.3632	373.35	21.696	0.2898
313.05	24.626	0.5074	343.15	24.626	0.3816	373.35	24.626	0.3030

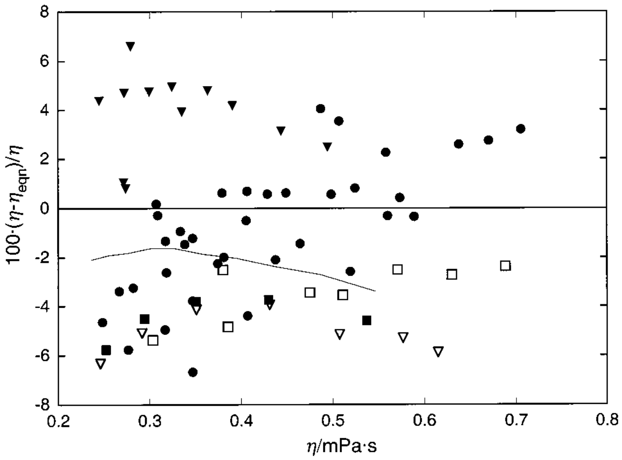

Figure 2. Relative deviation of measured octane viscosities and published viscosities from the equation of Assael et al. (1992a): (▽) Dymond and Young (1980); (—) Rossini et al. (1985); (■) Knastad et al. (1989); (□) Tanaka et al. (1991); (▼) Kiran and Sen (1992); (●) this work.

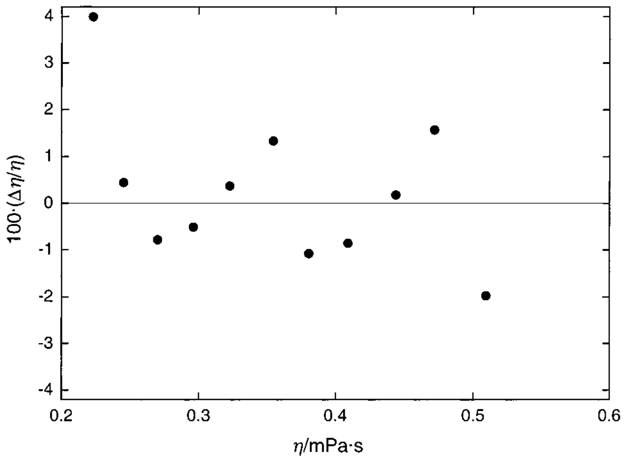

Figure 3. Relative deviation of measured pentane + octane viscosities at 0.1 MPa from the viscosities measured by Aucejo et al. (1995).

by Knapstad et al. (1989), Dymond and Young (1980), and Tanaka et al. (1991), but for viscosities greater than 0.5 mPa·s the discrepancies between the new viscosity values

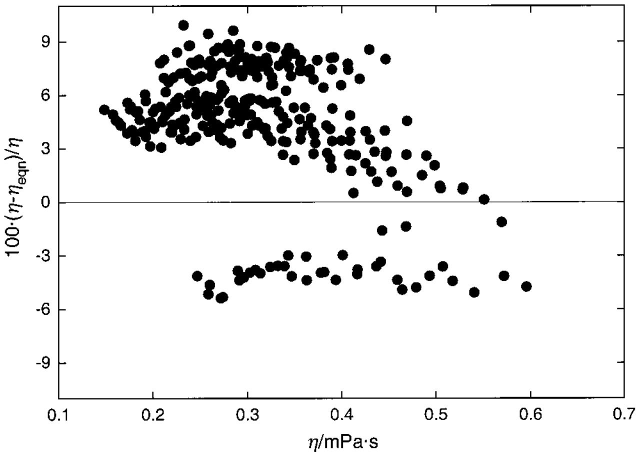

Figure 4. Relative deviation of measured pentane + octane viscosities from the equation of Assael et al. (1992b).

and those of Dymond and Young (1980) are as high as 6%. The results of Kiran and Sen (1992) for octane agree with our measurements within an average value of 4%. The smoothed values given in API-44 by Rossini et al. (1983) compare to the new experimental measurements within 2%. For the binary mixture, we compare our viscosity measurements of pentane + octane to values at 298.15 K and 0.1 MPa given by Aucejo et al. (1995). The latter is the only set of measurements existing in the literature for this mixture. Figure 3 shows that agreement between both sets of data is within an average value of ±1.2%. Figure 4 shows that the predictive capability of the Assael et al. correlation is within 9%, although its is based upon measurements at atmospheric pressure. The correlation underestimates most of the experimental data with the exception of one set of data that corresponds to a pentane mole fraction of 0.1059. We have found no obvious experimental errors for these data that could explain this discrepancy.

Conclusions

We have measured the viscosity of octane and pentane + octane mixtures using a rolling-ball apparatus. The experimental values for octane agree with published measurements within a maximum deviation of 5%. The new measurements for the binary mixture agree with the only existing values at atmospheric pressure within an average deviation of 1.2%. These new viscosity data should be useful for developing predictive models for liquids at high pressures.

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Received for review February 9, 1999. Accepted August 4, 1999. Texas A&M University and the Instituto Tecnológico de Celaya have provided financial support for this work.

JE990043Z