QUARTERLY TECHNICAL REPORT

June 1, 1992 to August 31, 1992

RECEIVED

MAR 02 1993

OSTI

1. Project Title

Thermodynamic and Rheological Properties of Solid-Liquid Systems in Coal Processing
U.S. DOE Grant No: DE-FG22-91PC91300

2. Investigators:

Vinayak N. Kabadi, and Shamsuddin Ilias, Department of Chemical engineering, North Carolina A&T State University, Greensboro, NC 27411

3. Project Objectives and Scope:

The objective of this project is to develop a model for solid-liquid equilibria and a model for viscosities of the products of coal liquefaction processes. The same characterization procedure and representation by continuous distributions as used in our previous work on vapor-liquid equilibria and excess enthalpies of coal liquids will be used. Models when fully developed will give the solid-liquid phase equilibrium properties and viscosities as factors of temperature and pressure for known molecular weight distribution and structural characterization of the coal liquid. To accomplish this well, the project requires three tasks:

- (1) Solid-liquid phase equilibrium model development: This will require data compilations for vapor pressures of solids and available single and multi-component solid-liquid phase equilibrium data. Model development will include models for thermodynamics of solids such as in coal products, thermodynamics of defined solid-liquid systems and finally application to complex coal derived products.
- (2) Experimental Viscosity Measurements: A viscometer will be purchased to measure viscosities of coal liquids and slurries at different temperatures and pressures. The data will be used in conjunction with literature data for viscosity model development.
- (3) Viscosity Model Development: Viscosity model development will require collection of physical property data for model compounds to estimate the model parameters. Both group contribution and corresponding states methods will be used to account for the effect of pressure and temperature on the liquid viscosity. The model will then be extended to coal liquid fractions. The experimentally measured viscosity data will be used to evaluate the model and recommend modifications.

MASTER

ok

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

4. Technical Highlights and Milestones:

A review of viscosity models available in the literature has been completed and is reported below. Model development work for viscosities is scheduled to begin in the next quarter.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Review of Models For Viscosity

Kinetic gas theory assumes that the radius of the molecule is negligible. In liquids, instead of transporting momentum by their own motion from one layer to another, the atoms transfer it to their neighbors by the action of interatomic forces. So far, there is no general agreement on whether viscosity is essentially due to attractive or repulsive forces.

Although more popular theories use quantum mechanical concepts such as tunnelling through potential barriers and virtual intermediate states, it has not been proved that the introduction of quantum mechanics is really necessary to explain viscosity. Theories of viscosities must be able to deduce correct formulas for viscosity without employing assumptions not already verified by experiments on equilibrium properties [9].

Andrade's equation[4] predicts absolute values of viscosity at particular temperatures without employing any molecular constants already known. To generalize it without adjustable parameters is difficult. Fluid dynamics treats fluids as continuous bodies described by certain differential equations although on a microscopic level, fluids are made of atoms and molecules.

However for engineering calculations, it is sometimes necessary to know not only the viscosity of a fluid at various temperatures but also how the fluid behaves under large deformations. Various theories have been proposed on theory of liquids. An interesting theory is the "vortex atom" model by Lord Kelvin and others. Here it was proposed that atoms and thus all matter could be reduced to local disturbances in a continuous medium filling all space. The mathematical treatment of this "vortex" theory turned out to be very difficult.

As we review the various attempts at explaining the theory of liquids, it appears that popular concepts like "energy of viscosity" is used often and it probably stems from the statistical view of molecular processes championed by Maxwell and Boltzman.

For engineering calculations, it may be pragmatic to use various empirical formulae giving a functional relationship between viscosity and some other physical property. It appears that many of the empirical correlations are formulae which best fits experimental data. These formulae, though useful for prediction of viscosity have the main drawback that no one formula is applicable to all fluids. This is even more true for undefined mixtures like coal liquids.

Viscosity is a non equilibrium property on a macro scale. It is observed that the viscosities of liquids decrease exponentially (almost) with increasing temperature. de Guzman had suggested the following relation

$$\log \eta = A - B/T$$

based on Kirchoff's law for vapor pressure. ($\log p = A - B/T - C \log T$)

In 1930 ,Andrade[4] put forward the simple exponential formula

$$\eta v^{1/3} = C e^{(a/vT)}$$

which is actually the form of the de Guzman equation. Although Andrade reports errors of less than 3%, it may not actually be the case, for, the viscosity data determined using capillary type viscometer is not reliable.

Gambill (9) says that the best formula to use when no experimental data is available is the following

$$\log \eta = 0.1167 \rho_1^{1/2} 10^\alpha \quad (3)$$

where $\alpha = B(T_c - T)/T$

B is made up of contributions from the various atoms and groups in the molecule (eg-carbon=-0.462, hydrogen = 0.249, double bond = .478 etc). The above is a special case of the popular empirical formula proposed by Andrade [4] and de Guzman.

Various experimenters have proposed various formulae for

viscosity, some of which are given below:

$$\log \eta = A/T + B \log T - CT - D$$

$$\eta = (A + B/T)^3$$

$$\eta = A T e^{B/T} + C T$$

$$\log \eta = B + A T^{-n}$$

$$\log \eta = -A e^{D/T} [-Ei(D/T)] - B + C e^{D/T}$$

(where $Ei(x)$ is the exponential integral.)

$$\log \eta = A T^{-2} + B T^{-1} + C$$

$$\log \eta = A + B T^{-3}$$

In the above formulae, the constants are functions of T_c , P_c , contributions of the various groups etc. These formulae have been tested by various experimenters and their deviation from actual observed data have been determined.

Various empirical correlations with the respective constants have been presented for pure components by Duhne [10]. The difficulty with the above is that no single formula is applicable to all fluids.

Various correlations for determination of viscosity have been found to be applicable to various liquids with varying ranges of temperatures and pressures. Andrade's exponential formula [4] although not applicable to all liquids, did explain the variation

of viscosity with temperature for a number of liquids.

The predictive methods for viscosity have been classified in this report into four categories. (a) Corresponding states methods (b) Group contribution methods (c) Methods used for hydrocarbons (d) Other models. Some of these methods are presented below:

Corresponding States Methods

Many researchers [7,18] have proposed correlations for viscosity based on the law of corresponding states which states that two fluids which have the same values of reduced temperature and reduced pressure, are said to be in corresponding states. [40,41,42,43,13,33,35]

Pedersen et. al. [35] suggested a corresponding states method for evaluation of viscosity using T_c , P_c , M.W. A parameter $\alpha = f(P_c, \text{M.W.})$ is used as a correction factor. The model works well for hydrocarbon fluids. Mixing rules have been used for T_c , P_c and M.W.

R.J. Greet and J.H. Magill [13] give a corresponding states relation for viscosity by plotting graphs $\log(\text{viscosity})$ vs T_m/T for various classes of liquids. Only pure fluids are considered in this treatment and doesn't include mixtures. (Here T_m is the melting point of the pure fluid)

A.S. Teja and P. Rice [42] proposed a generalized corresponding states method

$$\ln(\eta\xi) = \ln(\eta\xi)^{(r1)} + [\omega - \omega^{(r1)}] / [\omega^{(r2)} - \omega^{(r1)}] [\ln(\eta\xi)^{(r2)} - \ln(\eta\xi)^{(r1)}]$$

where $r1$ and $r2$ are two non spherical reference fluids.

$$\xi = V_c^{2/3} T_c^{-1/2} M^{-1/2}$$

The above equation is extended to mixtures using van der waal's one fluid model to replace T_c , V_c , W and $M.W$ by the respective equivalent properties of a hypothetical fluid.

The above method is difficult to be extended to undefined mixtures since the specific components are unknown and, moreover, we need the properties of two reference fluids in this case.

The above model was tested for Benzene - n - Hexane mixtures[43]. The overall average absolute error was 10%.

Abbot and Kaufmann (2) describe a corresponding states method using molecular weight, normal boiling point and critical temperature and pressure and acentric factor to predict viscosities of liquid n-alkanes.

The method has been tested only for certain classes of organic compounds. It can not be extended to coal liquids at this stage, since it is not applicable to undefined mixtures.

Teja and Willman [52,53] have proposed the use of characteristic viscosity ($\eta_r @ T_r = 0.6$) as a third parameter in a corresponding states treatment for undefined mixtures like coal liquids. The parameters T_c , P_c , W and M have been related to specific gravity and normal boiling point. Further, the critical viscosity η_c must be known for the coal liquid. That renders the method non viable to be extended to coal liquids. However this method of characterizing coal liquids and correlating viscosity have been proposed by Hwang et al [19] and is explained on page 7.

A.S. Teja et al [41] describe a method for calculation of viscosity of coal liquids using T_c , P_c and W , Watson characterization factor, molecular weight and normal boiling point. Mixing rules have been used to find the critical properties and acentric factor. The agreement with experimental data had an average absolute deviation of 20%. This means that this method or similar approaches cannot be directly applied to coal liquids. It is possible that some other correction factor incorporating the

effects of structural groups may predict the values of viscosity better.

Monnery et. al.[33] have incorporated shape factors in an extended corresponding states treatment which uses propane as a reference fluid. This method clearly cannot be applied to coal liquids since coal liquids are undefined mixtures containing a high percent of aromatics.

There are other corresponding states methods [18] which don't apply to coal liquids since coal liquids are undefined and different from petroleum.

Group Contribution Methods

Available correlations using group contribution methods are fewer than corresponding states methods. This is probably due to the extensive experimental confirmation required for the contribution of each group and/or bond.

Van Velzen et al [49] have suggested an empirical relation similar to Andrade equation. Here the constants are to be determined using a new property called equivalent chain length defined as the chain length (in Carbon Atoms) of a hypothetical n-alkane having a viscosity equal to 1 cp at the same temperatures as the compound being considered. This relation cannot be extended to coal liquids since the chain lengths for compounds like quinoline, thiophene etc... have not been given.

D.T. Wu [55] proposes a group contribution method for prediction of mixture viscosity based on Eyring viscosity model, combined with a departure term for non ideality as a function of free energy of mixing to be determined using UNIFAC model. This model is difficult to be extended to coal liquids since group interaction parameters for sulfur and nitrogen compounds have not been given.

A.S. Teja and J.M. Allan[3] propose a method using effective carbon length for prediction of liquid viscosity. Although the method was tested by the author for crude oil fractions giving absolute average errors of 10.3%, it cannot be extended to coal liquids due to the different composition of coal liquids.

Methods used for Hydrocarbons / Crude Oils

The method of Abbott and kaufmann [1] which is given below has been known to work well for pure hydrocarbons, petroleum fractions and waxy lubes

$$\log v = A[K_w , API] + B[K_w , API] / [API + C(K_w)]$$

where K_w is the Watson characterization factor given by

$$K_w = (T_b (^{\circ}R))^{1/3} / S.G$$

S.G.= Specific gravity

Mehrotra [27] proposes a relation

$$\log (h+0.8) = 100 (0.01T)^b$$

where b is a function of molecular weight and boiling point. The average absolute error is reported to be 2-3% for branched paraffins and 10% for fused ring aromatics.

Mehrotra [28] has extended the above relation for light and medium hydrocarbons by making the parameter b to be a function of acentric factor, molecular weight, T_c and boiling point.

Baltau M.E. [5] has proposed a corresponding states correlation for viscosity in terms of the viscosity of a reference fluid valuated at the corresponding density and temperature. Critical properties are related to normal boiling point and specific gravity. This method appears to have possibilities for

extension to coal liquids.

Other Models for prediction of Viscosity

Various other methods of evaluating viscosity of liquids have been developed [8,11,14,15,16,21,23,24,29,30,31,32,34,36,39,40,45,46,47,48,49,51,52]. Most of these models predict viscosity as a function of temperature, critical properties etc. These cannot be used directly to coal liquids due to the specific nature of coal liquids (High aromaticity, undefined mixtures etc.). However a few models based on the fluidity equation are mentioned below, even though their applicability to coal liquids is doubtful.

Przezdziecki and Sridhar[37] used the Hildebrand fluidity equation

$$1/\eta_L = B [(V-V_0)/V_0]$$

where B is a function of V_c , M.W., P_c , T_f , T_c , w. The average absolute error for 27 hydrocarbon liquids was 8.7%. Here $(V-V_0)/V_0$ is the fractional excess of its molal volume V_0 , at which the molecules are so close that viscous flow stops. This is obviously not a good model for coal liquids since it is difficult to obtain values for $(V-V_0)/V_0$.

J.H. Hildebrand[17] proposes a correlation for viscosity as a function of fluidity

$$1/\eta = B [(V-V_0)/V_0]$$

Here, $B=V_0/C$ is constant for a range of liquids from C^1 to C_{12} alkanes, carbon disulfide, chloroform etc.

Luckas and Lucas [25] incorporated activation energy and free volume in their correlation

$$\eta = X_{tv} \eta_t + (1 - X_{tv}) \eta_v$$

$$\eta_v = [(V_{ref} - V_0) / (V - V_0)]^{1.15}$$

$$\log \eta_c = B[1/T - 1/T_0]$$

$$X_{tv} = f_2(T_c)$$

Although the correlation works well for over 300 substances that were tested, it cannot be extended to coal liquids for the reasons mentioned earlier.

PROPOSED APPROACH

Hwang et al [19,20] have determined density, viscosity, surface tension of coal liquids up to 850 F and 1200psi. Using these data they have verified the applicability of correlations to coal liquids. A petroleum correlation [1] and a pure component correlation [2] were tested. The average absolute deviation was 16% using the pure component correlation and 42% for the petroleum correlation.

It is proposed to test the above model using the data on coal liquids reported by Gray et al [12]. The outline of the method is as described below:

(a) Petroleum correlation:

For temperatures of 100 F and 210 F the following correlation proposed by Abbott et al [1] is to be used:

$$\log v = f_1(K_w, API) + f_2(K_w, API)$$

For other temperatures the Walther equation is to be used:

$$\log[\log(v+c)] = a + b \log T \quad (\text{Upto } 450F)$$

$$\log [\log(v+c)] = a + b T \quad (\text{Beyond } 450F)$$

where c is a function of viscosity

(b) Pure component correlation:

Here the following correlation proposed by Abbott et al [2] is to be used:

$$\ln v_r = \ln (v/v_c) = A(\rho_R - 1) + B(\rho_R - 1)^{7/2} + C_1 [\exp(\rho_R - 1) - 1]$$

$$C_2 [\exp(\rho_R - 1)^{3/2} - 1] + C_3 [\exp(\rho_R - 1)^2 - 1] + C_4 [\exp(\rho_R - 1)^{5/2} - 1]$$

$$+ C_5 [\exp(\rho_R - 1)^3 - 1]$$

where

$$A = 3.71104 \omega^2$$

$$B = 0.25121 - 0.65882 \omega$$

$$C_1 = 0$$

$$C_2 = 0$$

$$C_3 = 1.27195 \times 10^{-2}$$

$$C_4 = -2.411 \times 10^{-4} \omega$$

$$C_5 = 2.33529 \times 10^{-7} \omega^2$$

The Uyehara and Watson [48] correlation is to be used to calculate the critical kinematic viscosity:

$$\nu_c = 61.154 \times 10^{-4} (T_c^{5/6} / M^{1/2}) (R Z_c / P_c)^{1/3}$$

The reduced density is to be calculated using the modified Riedel equation:

$$\rho_R - \rho / \rho_c = 1 + 0.85 (1 - T_R) + (1.6916 + 0.9846 \omega) (1 - T_R)^{1/3}$$

Here the liquid density at saturation pressure is calculated using the relationship

$$\rho = \rho_R (\rho_{ref} / \rho_{R,ref})$$

At higher pressures, the Lydersen's tabular correlation for critical properties is to be used.

Further, two other petroleum models viz. Baltau et al[5] and Mehrotra[27] may be tested for applicability to coal liquids using the model compound data.

REFERENCES

- 1 Abbot, M.M., Kaufmann, T.G. and Domash, L., "A correlation for predicting liquid viscosities of petroleum fractions", Can J. Chem. Eng., vol 49, p.379, June, 1971
- 2 Abbott, M.M. and Kaufmann, T.G., "Correlation of orthobaric kinematic viscosities of liquid n-alkanes", Can. J. Chem. Eng., vol. 48, p. 90, February, 1970
- 3 Allan, J.M. and Teja, A.S., "Correlation and prediction of the viscosity of defined and undefined hydrocarbon liquids", Can. J. Chem. Eng., Vol. 69, p.986, August, 1991
- 4 Andrade, E.N. da C., "The viscosity of liquids", Endeavour, Vol. 13, p.117, 1954
- 5 Baltau, M.E., "Prediction of the liquid viscosity for petroleum fractions", Ind. Eng. Chem. Process Des. Dev., Vol. 21, p.192, 1982
- 6 Betrand, G.L., "Application of the Hildebrand fluidity equation to liquid mixtures", Ind. Eng. Chem. Fundam., Vol. 16, No. 4, p.492, 1977
- 7 Brule, M.R., Lin, C.T., Lee, L.L. and Starling, K.E., "Multiparameter corresponding-states correlation of coal-fluid thermodynamic properties", AIChE Journal, Vol.28, No.4, p.618, July, 1982
- 8 Brule, M.R. and Starling, K.E., "Thermophysical properties of complex systems: Applications of multiproperty analysis", Ind. Eng. Chem. Process Des. Dev. Vol.23, p.833, 1984

- 9 Brush, S.G., "Theories of liquid viscosity", Chemical Reviews, Vol.62, p.513, 1962
- 10 Duhne, C.R., "Viscosity-temperature correlations for liquids", Chem. Eng., July 17, 1979
- 11 Girifalco, L.A., "Temperature dependence of viscosity and its relation to vapor pressure for associated liquids", J. Chem. Phys., Vol.23, p.2446, 1956
- 12 Gray, J.A., Brady, J.C., Cunningham, J.R., Freeman, J.R. and Wilson, G.M., "Thermophysical properties of coal liquids. 1. Selected physical, chemical and thermodynamic properties of narrow boiling range coal liquids", Ind. Eng. Chem. Process Des. Dev., 1983, Vol.22, p.410, 1983
- 13 Greet, R.J., and Magill, J.H., "An empirical corresponding states relationship for liquid viscosity", J. Phys. Chem., Vol.71, No.6, May, 1976
- 14 Greist, E.M., Webb, W., and Scheissler, R.W., "Effect of pressure on viscosity of higher hydrocarbons and their mixtures", J. Chem. Phys., Vol.29, No.4, Oct. 1958
- 15 Grunberg, L. and Nissan, A.H., "Mixture law for viscosity", Nature, Vol.164, No. 4175, Nov. 5, 1949
- 16 Harada, Makoto, Tanigaki, M., and Eguchi, W., "Viscosity of liquid mixtures", J. Chem. Eng. Japan, Vol.8, No.1, p.1, 1975
- 17 Hildebrand, J.H., "Motions of molecules in liquids: Viscosity diffusivity", Science, Vol.174, p.490, 1971

- 18 Hwang, M.J., and Whiting, W.B., "A corresponding states treatment for the viscosity of polar fluids", Ind. Eng. Chem. Res., Vol.26, p.1758, 1987
- 19 Hwang, S.C., Tsonopoulos, C., Cunningham, J.R., Wilson, G.M., "Density, Viscosity and surface tension of coal liquids at high temperatures and pressures", Ind. Eng. Chem. Process Des. Dev., Vol.21, p.127, 1982
- 20 Hwang, S.C., and Tsonopoulos., "A correlation for predicting liquid viscosities of petroleum fractions", Can. J. Chem. Eng., Vol.62, p.570, 1984
- 21 Innes, K.K., "Temperature dependence of viscosity of liquids", J. Phys. Chem., Vol.60, p.817, 1956
- 22 Islam, N. and Ibrahim, M., "Status of models for flow behaviour of organic liquids", Ind. J. Chem., Vol.20A, p.963 Oct.1981
- 23 Jossi, J.A., Stiel, L.I., and Thodos, G., "The viscosity of pure substances in the dense gaseous and liquid phases", AIChE, Vol.8, No.1, p.59, 1962
- 24 Lowitz, D.A., Spencer, J.W., Webb, W. and Schiessler, R.W., "Temperature-pressure-structure effects on the viscosity of several higher hydrocarbons", J. Chem. Phys., Vol.30, No.1 Jan. 1959
- 25 Luckas, M. and Lucas, K., "Viscosity of liquids:An equation with parameters correlating with structural groups", AIChE Journal, Vol.32, No.1, P.139, January, 1986
- 26 Mehrotra, A.K., "A generalized viscosity equation for pure heavy hydrocarbons", Ind. Eng. Chem. Res., Vol.30, p.420, 1991

- 27 Mehrotra, A.K., "Generalized one-parameter viscosity equation for pure heavy hydrocarbons", Ind. Eng. Chem. Res. Vol.30, p.420, 1991
- 28 Mehrotra, A.K., "Generalized one-parameter viscosity equation for light and medium liquid hydrocarbons", Ind. Eng. Chem. Res., Vol.30, p.1367, 1991
- 29 Miller, A.A., "Free volume and the viscosity of water", J. Chem. Phys., Vol.38, No.7, 1 April, 1963
- 30 Miller, A.A., "Free volumes and viscosities of benzene and carbon tetrachloride", J. Phys. Chem., Vol.67, p.2809, 1963
- 31 Miller, A.A., "Free volume and viscosity of liquids:Effect of temperature", J. Phys. Chem., Vol.67, p.1031, May 1963
- 32 Miller, J.W., Schorr, G. R., and Yaws, C.L., Shah, P.N. and Patel, P.M., "Correlation constants for chemical compounds", Chem. Eng., November 22, 1976
- 33 Monnery, W.D., Mehrotra, A.K., and Svrcek, W.Y., "Modified shape factors for improved viscosity predictions using corresponding states", Can. J. Chem. Eng., Vol.69, p.1213, October, 1991
- 34 Noda, Katsuji, and Ishida, Kiyoharu., "Correlation and prediction of the viscosity of liquid mixtures", J. Chem. Eng. Japan., Vol.10, No.6, p.478, 1977.
- 35 Pedersen, K.S.P., Fredenslund, A., Christensen, P.L., and Thomassen, P., "Viscosity of crude oils", Chem. Eng. Sci., Vol.39, No.6, p.1011, 1984

- 36 Plazek, D.J., and Magill, J.H., "Physical properties of aromatic hydrocarbons IV. An analysis of the temperature dependence of the viscosity and the compliance of 1,3,5-tri-alpha-naphthylbenzene", J. Chem. Phys., Vol.49, No.8, 1967
- 37 Przewdziecki, J.W., and Sridhar, T., "Prediction of liquid viscosities", AIChE Journal, Vol.31, No.2, p.333, February, 1985
- 38 Reid, R.C., Prausnitz, J.M., and Poling, B.E., "The properties of gases and liquids", 4Th.ed., McGraw-Hill, N.Y., 1987
- 39 Riazi, M.R., and Daubert, T.E., "Prediction of molecular type analysis of petroleum fractions and coal liquids", Ind. Eng. Chem. Proc. Des. Dev., Vol.25, p.1009, 1986
- 40 Stairs, R.A., "Viscosity of binary solutions of polar liquids", Can. J. Chem., Vol.58, p.296, 1980
- 41 Teja, A.S. and Rice, Peter., "A multifluid corresponding states principle for the thermodynamic properties of fluid mixtures", Chem. Eng. Sci., Vol.36, pp.1-6, 1981
- 42 Teja, A.S. and Rice, P., "Generalized corresponding states method for the viscosities of liquid mixtures", Ind. Eng. Chem. Fundam, Vol.20, p.77, 1981
- 43 Teja, A.S. and Rice, P., "The measurement and prediction of the viscosities of some binary liquid mixtures containing n-Hexane", Chem. Eng. Sci., Vol.36, p.7, 1981.
- 44 Teja, A.S., Thurner, Paul.A., and Pasumarti, Bapi, "Calculation transport properties of mixtures for synfuels process design", Ind. Eng. Chem. Process Des. Dev., Vol.24,

p. 344, 1985

- 45 Telang, M.S., "On the application and derivation of the new viscosity-temperature relationship of liquids."
- 46 Telang, M.S., "Correlation of viscosities of liquids with temperatures", J. Phys. Chem., Vol.49, p.579, 1945
- 47 Thomas, L.H., Smith, H., and Davies, G.H., "The viscosity of liquids at temperatures approaching the freezing point and molecular association of polyphenyls and related compounds", Chem. Eng. J., Vol.16, p.223, 1978
- 48 Uyehara, O.A., and Watson, K.M., "A universal viscosity correlation", National petroleum News., October 4, 1944
- 49 Van Velzen, D., Cardozo, R.L., and Langenkamp., "A Liquid viscosity-temperature chemical constitution relation for organic compounds", Ind. Eng. Chem. Fundam., Vol.11, No.1, p.20, 1972
- 50 Vogel, H., and Weiss, A., "Transport properties of liquids I. Self-diffusion, viscosity and density of nearly spherical and disk-like molecules in the pure liquid phase", Ber. Bunsenges. Phys. Chem., 85, p.539, 1981
- 51 Vogel, H., and Weiss, A., "Transport properties of liquids, III. Viscosity of a thermal liquid mixtures", Ber Bunsenges Phys. Chem., Vol.86, p.193, 1982
- 52 Wei, I.C., Rowley, R.L., "A local composition model for multicomponent liquid mixture shear viscosity", Chem. Eng. Sci., Vol.40, No.3, p.401, 1985
- 53 Willman, and Teja, A.S., "Characteristic viscosity as a third parameter in corresponding states calculations of

transport properties. PartI. Defined mixtures", Chem. Eng. J., Vol.37, p.65, 1988

- 54 Willman, B. and Teja, A.S., "Characteristic viscosity as a third parameter in corresponding states calculations of transport properties PartII. Undefined mixtures", Chem. Eng. J., Vol.37, p.71, 1988
 - 55 Wu, D.T., "Prediction of viscosities of liquid mixtures by a group contribution method", Fluid phase equilibria, Vol.30, p.149, 1986
-

END

**DATE
FILMED**

3 / 29 / 93