

An Extension of the Group Contribution Method for Estimating Thermodynamic and Transport Properties Part II. Polyatomic Gases (F₂, Cl₂, CS₂, H₂S, NO and N₂O)

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Abstract—Earlier work on the group contribution method applied to the Kihara potential is extended to polyatomic gases for the calculation of second virial coefficients, viscosities and diffusivities of dilute gases with a single set of gas group parameters. Functional group parameters are evaluated from the simultaneous regression of second virial coefficient and viscosity data of pure gases. Parameters for gas groups (F₂, Cl₂, CS₂, H₂S, NO, and N₂O) are found to provide good predictions of second virial cross coefficients, mixture viscosities and binary diffusion coefficients of gas-gas mixtures. Application of the model shows that second virial coefficient data can be represented with good results comparable to the values by means of the corresponding states model. The reliability of the present model in viscosity predictions is proved by comparison with the Lucas method. Predictions of binary diffusion coefficients are in excellent agreement with experimental data and compare well with values obtained by means of the Fuller method.

Key words: Theory, Group Contribution, Kihara Potential, Second Virial Coefficient, Viscosity, Diffusivity

INTRODUCTION

A number of methods have been proposed for the prediction of second virial coefficients and dilute gas transport properties. Although most studies have focused on individual properties, a number of workers [Dymond and Alder, 1969; O'Connell and Prausnitz, 1965; Tee et al., 1966] have used statistical mechanics and the kinetic theory of gases to represent both thermodynamic and transport properties with a single set of parameters, namely, those appearing in an intermolecular potential function. In one particularly interesting study of [Tee et al., 1966], the Lennard-Jones potential parameters were related to the critical properties and acentric factor. The result was a corresponding states correlation for simultaneous prediction of second virial coefficients and dilute gas viscosities for molecules ranging in shape from spherical to chains as long as n-heptane.

However, two difficulties are faced in corresponding states calculations. First, critical properties and acentric factors may not be available for all of the compounds in question. Second, and perhaps more important, extension of corresponding states methods to mixtures requires additional information, generally in the form of a binary interaction coefficient.

The group contribution concept has formed an alternative to the corresponding states framework for the prediction of thermodynamic properties and dilute gas transport properties. Here, a single set of parameters, appearing in an intermolecular potential function, is assigned to interactions between intermolecular functional groups. An advantage of this method is that it does not require values for the critical properties and acentric factors, which may not be available for all of the compounds in question, and that it is ap-

plicable with only information of both functional groups and van der Waals volume in molecules. Since the number of functional groups is much smaller than the number of possible chemical species, a relatively small number of group parameters can describe a large number of different mixtures. This concept forms the basis for the UNIFAC [Fredenslund et al., 1975] and ASOG [Derr and Deal, 1969] activity coefficient models and for the GPSCT [Jin et al., 1986] and GSPHCT [Georgeton and Teja, 1988] equations of state models.

A group contribution concept was applied to the Kihara potential functions for calculating second virial coefficients of pure gases and mixtures [Campbell, 1989]. Functional group parameters for CH₂ and CH₃ groups in normal alkanes were determined from second virial coefficient data for pure C₂-n-C₈ alkanes, and parameters for CH₄ groups were determined from second virial coefficient for pure methane. Then these parameters were used to predict, without additional parameters, second virial cross coefficients of alkane mixtures. The model was found to perform well, even for such asymmetric systems as methane-eicosane. Since the group contribution method is based on an intermolecular potential function, it showed the possibility of predicting dilute gas transport properties (viscosities and diffusion coefficients) as well using Chapman and Enskog theory [Chapman and Cowing, 1939].

Previous works [Oh, 1989; Oh and Campbell, 1997] proved the feasibility of applying group contribution method to simultaneous representation of second virial coefficient, viscosity and diffusion coefficient of dilute gases. Parameter values for functional groups were estimated by regressing second virial coefficient and viscosity data for pure gases together. It was noted that diffusivity data were not supplied to data regression steps for parameter estimation. By introducing the concept of a group binary interaction coefficient, the model was extended to chemically dissimilar mixtures of nitro-

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gen- and carbon dioxide-hydrocarbons, with success.

In the previous work [Oh and Sim, 2002], a set of functional group parameters for pure alkanes were re-evaluated with revised recommendations of second virial coefficient data of pure alkanes presented by Tsonopoulos et al. [1989] and Tsonopoulos and Dymond [1997] in order to improve the reliability of predictions. The group contribution method using Kihara potential was repeated for calculating second virial coefficients, dilute gas viscosities and binary diffusion coefficients of normal and branched alkanes, alkenes, nitrogen and carbon dioxide. And applications were extended to industrially important pure linear gases (carbon monoxide, oxygen and hydrogen), as well as to mixtures of these gases with reliable calculations and predictions of second virial cross coefficients and mixture viscosities.

In this paper, extension of the group contribution method is made to polyatomic gases (fluorine, chlorine, carbon disulfide, hydrogen sulfide, nitric oxide and nitrous oxide). Applicability of the method based on the spherical core potential of Kihara [1978] is tested by assuming that all compounds studied here were to consist of a single functional group. It is considered for simple fluids examined here that use of the group contribution concept is not reasonable. Simultaneous regression of second virial coefficient and viscosity data for pure gases was done for the determination of functional group parameters. The scope of this work is to examine the possibility of applying this characteristic feature of the group contribution method to the simultaneous representation of second virial coefficients, dilute gas viscosities and diffusion coefficients with a single set of group parameters. Values of the collision integrals for viscosity and diffusion (Ω_V and Ω_D) for Kihara potentials, required for the Chapman and Enskog theory, were tabulated in Oh [1989].

GROUP CONTRIBUTION MODEL

The expression for group contribution rules for functional group parameters appearing in Kihara potential function was given in the previous paper [Oh and Campbell, 1997]. For better understanding, however, it is necessary to describe it briefly.

Group contribution rules for the spherical core Kihara potential parameters are written for the general case of non-identical molecules 1 and 2. Calculations for pure gases are made by setting molecule 2 identical to molecule 1. The rules for ϵ_{12} and σ_{12} are

$$\epsilon_{12}\sigma_{12}^3 = \sum \sum N_{i1}N_{j2}\epsilon_{ij}\sigma_{ij}^3 \quad (1)$$

and

$$\sigma_{12} = \frac{(\sum N_{i1}\sigma_{i1}^3)^{1/3} + (\sum N_{j2}\sigma_{j2}^3)^{1/3}}{2} \quad (2)$$

where N_{i1} is the number of functional groups of type i in molecule 1, N_{j2} is the number of functional groups of type j in molecule 2, ϵ_{12} and σ_{12} are the well depth and collision diameter for interactions between molecules 1 and 2, and ϵ_{ij} and σ_{ij} are the well depth and the collision diameter for interactions between intermolecular groups i and j , respectively. This rule for the Kihara potential is also required for the core radius a_{12} , where the group additivity of the reduced core radii is assumed:

$$a_{11}^* = \sum N_{i1}a_{i1}^* \quad (3)$$

and

$$a_{22}^* = \sum N_{j2}a_{j2}^* \quad (4)$$

followed by

$$a_{12} = \frac{a_{11} + a_{22}}{2} \quad (5)$$

where

$$a_{11} = \frac{\sigma_{11}a_{11}^*}{2(1+a_{11}^*)} \quad (6)$$

with an analogous expression for a_{22} .

The rules given above express ϵ_{12} , σ_{12} and a_{12} in terms of group interaction parameters ϵ_{ij} and σ_{ij} and group core parameters a_{ij} . For interactions between two identical groups i , we assume

$$\epsilon_{ii} = \alpha_{ii} + \frac{\beta_{ii}}{T} \quad (7)$$

$$\sigma_{ii} = \xi V_{vdw,ii}^{1/3} \quad (8)$$

where α_{ii} and β_{ii} are group parameters, ξ is an undetermined universal van der Waals volume constant, and $V_{vdw,ii}$ is the van der Waals volume for functional group i as tabulated by Bondi [1964]. The Kihara potential function is spherically symmetric, and is applied here to polyatomic gases. The reciprocal temperature term in Eq. (7) is used as a rough way of accounting for nonsphericity of the molecule, as suggested by Campbell [1989].

For mixtures of chemically dissimilar substances such as hydrocarbon-gas, the Lorentz-Berthelot combining rules for intermolecular interactions between unlike groups i and j were assumed.

$$\epsilon_{ij} = (1 - k_{ij,gc}) \sqrt{\epsilon_{ii}\epsilon_{jj}} \quad (9)$$

$$\sigma_{ij} = (\sigma_{ii} + \sigma_{jj})/2 \quad (10)$$

, where $k_{ij,gc}$ is a group binary interaction coefficient defined in analogy with the binary interaction coefficient k_{12} of the corresponding state calculations.

In addition to the value of universal van der Waals volume constant ξ , application of the model requires parameter values (α_{ii} , β_{ii} , and a_{ii}^*) for each functional group i within molecules 1 and 2. In order to extend the model to gas-gas and hydrocarbon-gas mixtures examined here, values of group binary interaction coefficient $k_{ij,gc}$ for each interactions between intermolecular groups i and j might be required for better predictions.

Although the group contribution model contains a number of parameters, it is practically applicable to pure gases, and as well as to a variety of mixtures. Hence, group parameter values may often be determined from data for pure substances. Data used for the group parameter evaluations and for predictions of thermodynamic properties and dilute gas transport properties of pure gases and mixtures are discussed in the following section.

RESULTS AND DISCUSSION

1. Pure Gases

As a part of the systematic program of our researches, the group contribution method was extended to polyatomic gases (F_2 , Cl_2 , CS_2 , H_2S , NO , and N_2O). Functional group parameters α_{ii} , β_{ii} and a_{ii}^* were

Table 1. Properties of the functional groups examined in this study (universal van der Waals volume constant=1.3692^a)

Group	$V_{vdw,ii}^b$	a_{ii}^*	α_{ii}	β_{ii}
F ₂	14.2	0.2199	147.48	-
Cl ₂	24.1	0.4716	555.85	-
CS ₂	31.2	0.3194	713.21	-
H ₂ S	18.0	0.9478	657.13	-
NO	13.9	0.1534	160.49	2089.2
N ₂ O	18.9	0.0529	178.18	2794.5

^ataken from Oh and Campbell [1997].

^btaken from Bondi [1964].

evaluated by regressing second virial coefficient and viscosity data of pure gases together, in which all gases studied here were assumed to consist of a single functional group. As shown in Eq. (8), values of van der Waals volume for gases required were taken from Bondi [1964]. The universal van der Waals volume constant ξ evaluated in the previous paper [Oh and Sim, 2002] was used in the data regressions for the determination of function group parameters for pure gases, and in all subsequent calculations and evaluations.

Second virial coefficient data for pure gases were taken from several references: Dymond and Smith [1980] for F₂, Cl₂, CS₂, and H₂S; Boushehri et al. [1987] for NO and N₂O. And pure viscosity data required for the parameter estimation were obtained from several references: Stephan and Lucas [1979] for F₂; Trautz and Ruf [1939] for Cl₂; Titani [1933] for CS₂; Schuil [1939] for H₂S; Boushehri et al. [1987] for NO and N₂O.

Gas group parameter values (a_{ii}^* , α_{ii} and β_{ii}) for pure gases (F₂, Cl₂, CS₂, H₂S, NO and N₂O) examined are shown in Table 1 and the sources of data used to obtain them are indicated in Table 2. The potential well depth for gas groups (F₂, Cl₂, CS₂, and H₂S) were regarded to be independent of temperature. Regression results proved it, as expected for essentially symmetric molecules. However, the temperature dependence of the potential well depth for other gases (NO and N₂O) turned out to be considered to account for non-sphericity of the molecule, as proved by regression results. Values of the reduced core radius for all compound examined here are between 0 and 1, proving that by using Kihara spherical core potential [Kihara, 1978] the application of the present model to these polyatomic gases was made well.

As shown in Table 2, resulting deviations between experimental and calculated data from data regression are presented by the RMSD (root mean square deviation) values in cm³ mol⁻¹ for second virial coefficients and by the %RMSDr (percent relative root mean square deviation, relative) values for viscosities. Also included in Table 2 are the references for second virial coefficients and viscosity data for pure gases. A comparison was made with the corresponding correlation [Tsonopoulos, 1974] on the calculation of second virial coefficients, and with the Lucas method [Lucas, 1980] on the calculation of viscosities.

Overall average RMSD values of second virial coefficients for six pure gases examined are 2.1 cm³ mol⁻¹ and 8.8 cm³ mol⁻¹ for the proposed method and the Tsonopoulos correlation, respectively, indicating that the proposed model is in excellent agreement with the experimental data and compares very well with the Tsonopoulos correlation. As for the second virial coefficient calculations for

Table 2. Deviations between experimental second virial coefficients and viscosities, and those calculated using group parameters examined in this study

Compound	Number of points*	Average RMSD in B (cm ³ mol ⁻¹)		Data source	Number of points*	Average RMSDr in η (%)		Data source
		Present study	Tsonopoulos			Present study	Lucas	
<i>Regression results:</i>								
Flourine	45	0.7	3.0	[a]	28	0.6	7.8	[c]
Chlorine	13	2.9	6.0	[a]	6	1.7	8.1	[d]
Carbon disulfide	9	2.4	46.9	[a]	6	2.9	3.6	[e]
Hydrogen sulfide	6	1.5	15.1	[a]	3	4.2	15.3	[f]
Nitric oxide	27	3.1	9.0	[b]	27	2.2	5.5	[b]
Nitrous oxide	24	3.1	5.0	[b]	24	0.6	4.2	[b]
Overall	124	2.1	8.8	94	1.4	6.2		
<i>Prediction results:</i>								
Carbon disulfide	-	-	4	3.9	3.4	[f]		
Hydrogen sulfide	8	2.8	6.7	[g]	-	-		
Nitric oxide	32	16.2	18.7	[a, h]	47	5.8	6.2	[f, i, j, k]
Nitrous oxide	10	9.8	4.0	[h]	77	3.1	3.6	[i, j, l, m-t]

*Number of data points for second virial coefficient.

^aDymond and Smith [1980].

^bBoushehri et al. [1987].

^cStephan and Lucas [1979].

^dTrautz and Ruf [1934].

^eTitani [1933].

^fSchuil [1939].

^gKhoury and Robinson [1971].

^hLide [1995].

ⁱClifford et al. [1981].

^jJohnston and McClosky [1940].

^kEllis and Raw [1959].

^lFisher [1909].

^mTrautz and Kurz [1931].

ⁿRaw and Ellis [1958].

**Number of data points for viscosity.

^oChakraborti and Gray [1965].

^pHarris et al. [1979].

^qKestin and Wakeham [1979].

^rTakahashi et al. [1996].

^sKestin and Ro [1982].

^tVogel [1914].

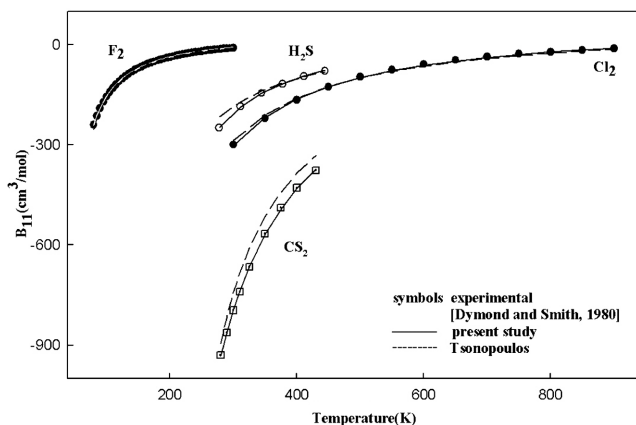


Fig. 1. Comparison of experimental and predicted second virial coefficients for pure gases (F_2 , Cl_2 , CS_2 and H_2S).

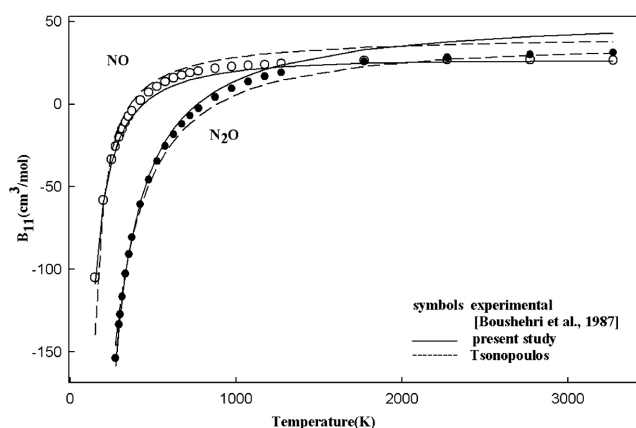


Fig. 2. Comparison of experimental and predicted second virial coefficients for pure gases (NO and N_2O).

pure CS_2 and H_2S gas, deviation values obtained by the Tsonopoulos correlation ($46.9 \text{ cm}^3 \text{ mol}^{-1}$ and $15.1 \text{ cm}^3 \text{ mol}^{-1}$, respectively), are extremely higher than those of the present model ($2.4 \text{ cm}^3 \text{ mol}^{-1}$ and $1.5 \text{ cm}^3 \text{ mol}^{-1}$, respectively). Dymond and Smith [1980] mention that experimental uncertainties of the CS_2 gas are between ± 15 and $30 \text{ cm}^3 \text{ mol}^{-1}$ and the reliability of the experimental data for H_2S gas is quite low. A comparison of the measured and predicted second virial coefficients for pure gases (F_2 , Cl_2 , CS_2 , and H_2S) and gases (NO and N_2O) are presented in Fig. 1 and Fig. 2, respectively.

Resulting deviations from parameter estimation for pure gases between measured and calculated viscosity data are shown in Table 2; the overall 1.4% RMSDr value obtained by the method compares well with 6.2% RMSDr by means of the Lucas method. The present study is more reliable than the Lucas method, on the whole, and provides better viscosity predictions within the experimental uncertainties (3 to 5%) for all gases than those from the Lucas method, whose lowest deviation is between 3.6% (carbon disulfide) to 15.3% (hydrogen sulfide). Comparisons of the experimental and predicted viscosities for pure gases (F_2 , Cl_2 , CS_2 , and H_2S) and gases (NO and N_2O) are made in Fig. 3 and Fig. 4, respectively.

Second virial coefficient and viscosity data, not supplied to the parameter estimation procedure, were then calculated with group parameter values determined in advance. As for the second virial

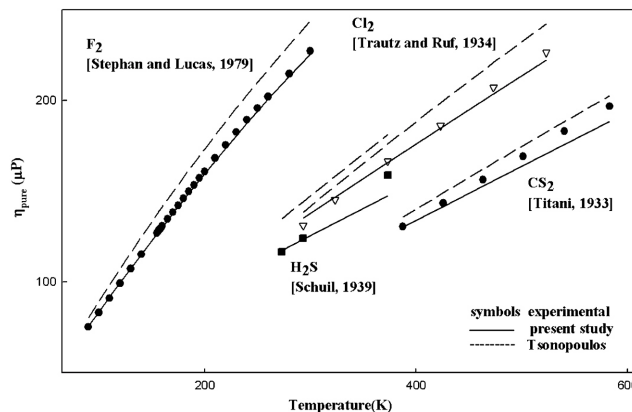


Fig. 3. Comparison of experimental and predicted viscosities for pure gases (F_2 , Cl_2 , CS_2 and H_2S).

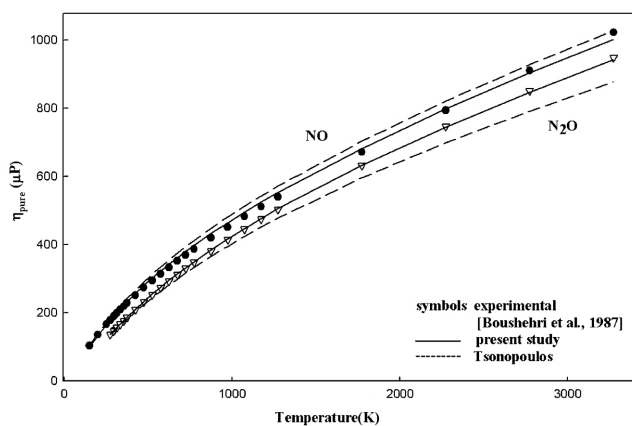


Fig. 4. Comparison of experimental and predicted viscosities for pure gases (NO and N_2O).

coefficient (H_2S , NO and N_2O) and viscosity (CS_2 , NO and N_2O) calculations, both methods are shown to be favorably comparable to each other. It is noted that resulting deviations from regressions are quite smaller than those of calculations for NO and N_2O gases. The reason is that the data used for calculations were obtained from different types of experimental measurements by several researchers, which experimental uncertainties are relatively larger.

2. Gas-gas Mixtures

An advantage of the group contribution method is that mixture properties can be predicted by using parameter values obtained from properties of pure compounds without additional parameters. Group parameter values, evaluated by means of the simultaneous regression of second virial coefficient and viscosity data for pure gases, were then used to predict second virial cross coefficients and mixture viscosities for gas-gas mixtures. Binary diffusion coefficients for gas-gas mixtures, which data were not supplied to data regression for the estimations of group parameters, can be estimated by using gas group parameters, since the group contribution method is based on the intermolecular potential function.

By the nature of the model, group binary interaction coefficients $k_{ij,gc}$ were added for better calculations to mixtures consisting of chemically dissimilar compounds, as mentioned in the previous work [Oh and Campbell, 1997]. A single group binary interaction coefficient

Table 3. Deviations between experimental and calculated second virial cross coefficients

Mixtures	Number of points	Average RMSD in B (cm ³ mol ⁻¹)		Data source
		Present study ($K_{ij,gc}=0$)	Tsonopoulos ($K_{12}=0$)	
Gas-gas mixtures				
Carbon disulfide				
- carbon dioxide	1	3.4	5.8	[a]
- hydrogen	1	22.7	48.6	[a]
- nitrogen	1	28.6	38.5	[a]

^aDymond and Smith [1980].

Table 4. Deviations between experimental and calculated mixture viscosities

Mixtures	Number of points	Average RMSDr in η (%)		Data source
		Present study ($K_{ij,gc}=0$)	Lucas	
Gas-gas mixtures				
Nitrous oxide				
- nitrogen	10	0.5	2.4	[a]
- hydrogen	16	3.3	8.5	[b]
- carbon dioxide	25	1.8	6.3	[a, b]
<i>Overall</i>	42	2.0	6.2	

^aKestin and Ro [1982]. ^bTrautz and Kurz [1931].

cient, required for every possible interaction between gas and gas groups, was determined by reducing second virial cross coefficient data for mixtures of gas i and gas j, along with universal van der Waals volume constant value (1.3627) evaluated by Oh and Sim [2002]. However, in this work, $k_{ij,gc}$ values for all interactions between all compounds (diatomic or simple polyatomic gases) studied here were assumed to be zero. One second virial cross coefficient data point is available in the literature [Dymond and Smith, 1980] for each three carbon disulfide mixtures, such that group binary interaction coefficient $k_{ij,gc}$ for CS₂ mixture was not considered here. No second virial cross coefficient data other than ones shown in Table 3 are available for gas-gas mixtures. It is noted that the use of $k_{ij,gc}$ for polyatomic gas-hydrocarbon mixtures is out of scope of this work.

Resulting deviations between observed and calculated second virial cross coefficient data for gas-gas mixtures are presented in Table 3. Also included for comparison in Table 3 are results from the corresponding states correlation. The Tsonopoulos correlation may require a value for the binary interaction coefficient k_{12} when extended to second virial cross coefficients for gas-gas mixtures of different type; however, k_{12} is assumed to be zero for equivalent comparisons. With zero value of $k_{ij,gc}$ or K_{12} , the proposed method yields deviation values (3.4, 22.7 and 22.7 cm³ mol⁻¹), while Tsonopoulos correlation obtains 5.8, 48.6 and 38.5 cm³ mol⁻¹, respectively, in order shown in Table 3. It is mentioned here that more data points are needed to compare the reliability of both models reasonably.

For mixture viscosity calculations, no data other than nitrous oxide mixtures were available. As shown in Table 4, the present study with the assumption of $k_{ij,gc}=0$ provides a less resulting RMSDr value (2.0%) than the Lucas method (6.2%), showing that the present method is more reliable for the calculations of mixture viscosities for nitrous oxide mixtures with nitrogen, hydrogen and carbon

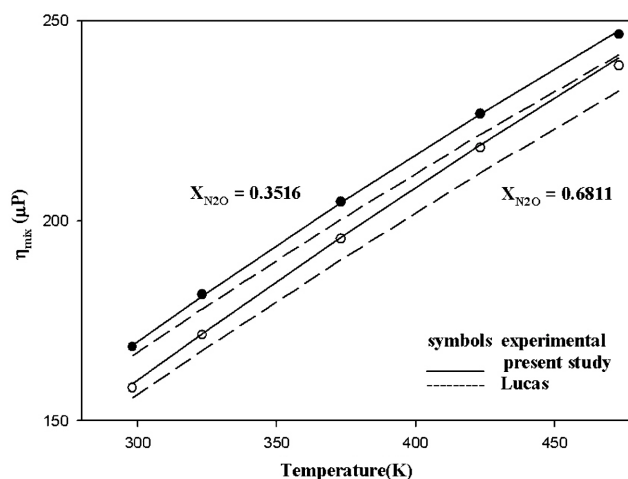


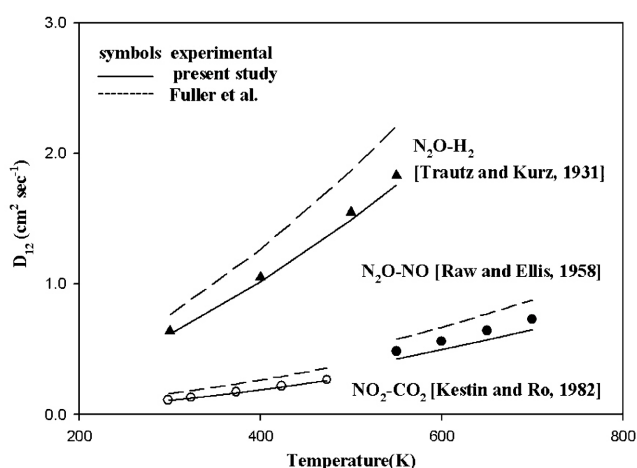
Fig. 5. Comparison of experimental and predicted mixture viscosities for N₂O and N₂ mixtures.

dioxide. The comparison of experimental and calculated viscosities for nitrous oxide-nitrogen mixture at two different mole fractions of N₂O is shown in Fig. 5.

Deviations between measured and predicted properties are given for binary diffusion coefficients in Table 5. Also included for comparison are resulting deviations obtained from the corresponding states method by Fuller et al. [1966]. Higher deviations from the proposed model than those of the Fuller method were found for NO-gas mixtures, while the model shows better agreements between measured and predicted binary diffusion coefficients for CS₂-gas and N₂O-gas mixtures: on the whole, it can be said that for binary diffusion coefficient predictions the comparison of the present method is made well with the Fuller method, showing that overall %

Table 5. Deviations between experimental and calculated binary diffusion coefficients

Mixtures	Number of points	Average RMSDr in D (%)		Data source
		Present study ($K_{ij,gc}=0$)	Fuller et al.	
Gas-gas mixtures				
Carbon disulfide				
- carbon dioxide	1	8.1	85.4	[a]
Nitric oxide				
- nitrogen	3	7.6	7.0	[b, c]
- hydrogen	1	6.0	5.4	[d]
Nitrous oxide				
- nitric oxide	4	1.1	19.7	[e, f, g]
- hydrogen	6	0.5	20.8	[c, d, h]
- carbon dioxide	22	6.1	35.8	[a, i-o]
- nitrogen	5	1.0	21.5	[n]
Overall	42	4.4	28.8	

^aReid et al. [1987].^bTrautz and Muller [1935].^cTrautz and Sorg [1931].^dKlemec [1923].^eRaw and Ellis [1958].^fEllis and Raw [1959].^gHawksworth et al. [1962].^hChapman and Cowling [1939].ⁱAmdur et al. [1952].^jBoardman and Wild [1937].^kWall and Kidder [1946].^lHoward [1930].^mTrautz and Kurz [1931].ⁿKestin and Ro [1982].^oLide [1995].**Fig. 6. Comparison of experimental and predicted binary diffusion coefficients for mixture of N_2O with gases (H_2 , NO and CO_2).**

RMSDr values resulted from the present model and the Fuller method are 3.4% and 28.8%, respectively. Comparison of experimental and predicted binary diffusion coefficients for mixtures of nitrous oxide with hydrogen, nitric oxide and carbon dioxide is shown in Fig. 6 with data sources.

CONCLUSIONS

The group contribution method in the previous work [Oh and Sim, 2002] for the calculation of second virial coefficients, viscosities and diffusion coefficients has been extended to polyatomic gases. All compounds examined here were assumed to consist of a single gas group, not functional groups in molecules. Gas group parameters were obtained from the simultaneous regression of second virial

coefficient and viscosity data for pure gas. New group parameter values for pure gases (F_2 , Cl_2 , CS_2 , H_2S , NO , and N_2O) were reported.

Group binary interaction coefficients for chemically dissimilar mixtures of compounds could not be estimated since no second virial cross coefficient data other than H_2S -ethane mixture [Dymond and Smith, 1980] are available in the literature, such that group binary interaction coefficients for each interaction between gas-gas examined here were assumed to be zero.

Application of the model shows that second virial coefficient data can be represented with results comparable to those obtained by the corresponding states method [Tsonopoulos, 1974]. The accuracy of the model in viscosity predictions is comparable to the Lucas method [1980]. The characteristic feature of the group contribution method makes possible diffusivity predictions as well, which data were not used in parameter estimations. The reliability of the model in diffusion coefficient predictions is evaluated nicely by comparison with the Fuller method [1966].

A strong advantage of the method is that it is capable of representing several different properties with one set of group parameter values. Thus, it may use data for one property to predict a different property. On top of that, since this method does not require the critical properties and acentric factor, it may be used to predict properties of substances in question for which these data are not available.

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NOMENCLATURE

- a : core radius [angstrom]
 a^* : reduced core radius, $2a/(\sigma-2a)$

B : second virial coefficient [$\text{cm}^3 \text{mol}^{-1}$]
 D : diffusion coefficient [$\text{cm}^2 \text{sec}^{-1}$]
 k_{12} : binary interaction coefficient for Tsonopoulos correlation
 $k_{ij,gc}$: groupbinaryinteractioncoefficientforinteractionsbetween
 intermolecular functional groups i and j
 N_{i1} : number of groups i in molecule 1
 N_{j2} : number of groups j in molecule 2
 P : pressure [atm]
 RMSD: root mean square deviation [$\text{cm}^3 \text{mol}^{-1}$]
 %RMSDr : percent relative root mean square deviation, relative
 [%]
 T : temperature [K]
 T^* : reduced temperature [kT/ϵ]
 V : volume [cm^3]
 $V_{vdw,ii}$: van der Waals volume of group i [$\text{cm}^3 \text{mol}^{-1}$]
 x : mole fraction

Greek Letters

α : functional group parameter for potential well depth [J]
 β : functional group parameter for potential well depth [J K]
 ϵ : potential well depth [J]
 η : viscosity [μP]
 ξ : universal van der Waals volume constant (1.3627) in Eq.
 (8)
 σ : collision diameter [angstrom]
 Ω_v : collision integral for viscosity
 Ω_D : collision integral for diffusivity

Subscripts

1, 11 : property of molecule 1
 2, 22 : property of molecule 2
 12 : interaction property for molecules 1 and 2
 ij : interaction property for intermolecular groups i and j
 C : critical property
 GAS : property of gas group
 gc : property of group binary interaction coefficient
 F2 : property of F_2 gas group
 Cl2 : property of Cl_2 gas group
 CS2 : property of CS_2 gas group
 H2S : property of H_2S gas group
 NO : property of NO gas group
 N2O : property of N_2O gas group

REFERENCES

- Amdur, I., Irvine, J. W. Jr., Mason, E. A. and Ross, J., "Diffusion Coefficients of the Systems $\text{CO}_2\text{-CO}_2$ and $\text{CO}_2\text{-N}_2\text{O}$," *J. Chem. Phys.*, **20**(3), 436 (1952).
 Boardman, L. E. and Wild, N. E., *Proc. Roy. Soc. (London)*, **A162**, 511 (1937).
 Bondi, A., "van der Waals Volumes and Radii," *J. Phys. Chem.*, **68**(3), 441 (1964).
 Boushehri, A., Bzowski, J., Kestin, J. and Mason, E. A., "Equilibrium and Transport Properties of Eleven Polyatomic Gases at Low Density," *J. Phys. Chem. Ref. Data*, **16**, 445 (1987).
 Campbell, S. W., "Application of the Group Contribution Concept to the Kihara Potential for the Calculation of Second Virial Coefficients," *Fluid Phase Equilibria*, **47**, 47 (1989).
 Chakraborti, P. K. and Gray, P., "Viscosities of Gaseous Mixtures Containing Polar Gases: Mixtures with One Polar Constituent," *Trans. Faraday Soc.*, **61**, 2422 (1965).
 Chapman, S. and Cowling, T. G., *The Mathematical Theory of Nonuniform Gases*, Cambridge University Press, New York (1939).
 Chueh, P. L. and Prausnitz, J. M., "Vapor-liquid Equilibria at High Pressures: Calculation of Partial Molar Volumes in Nonpolar Liquid Mixtures," *AIChE J.*, **13**(5), 1099 (1967).
 Clifford, A. A., Gray, P. and Scott, A. C., "Viscosities of Gaseous Nitric Oxide, Nitrous Oxide and Sulfur Dioxide at High Temperatures," *J. Chem. Soc., Trans. 1*, **177**, 997 (1981).
 Derr, E. L. and Deal, C. H., *Inst. Chem. Eng. Symp. Ser.*, **32**, 40 (1969).
 Dymond, J. H. and Alder, B. J., "Pair Potential for Argon," *J. Chem. Phys.*, **51**(1), 309 (1969).
 Dymond, J. H., Cholinski, J. A., Szafranski, A. and Wyrzykowska-Stankiewicz, D., "Second Virial Coefficients for n-Alkanes; Recommendations and Predictions," *Fluid Phase Equilibria*, **27**, 1 (1986).
 Dymond, J. H. and Smith, E. B., *The Virial Coefficients of Pure Gases and Mixtures - A Critical Compilation*, Clarendon Press, Oxford (1980).
 Ellis, C. P. and Raw, C. J. G., "High-Temperature Gas Viscosities. II. Nitrogen, Nitric Oxide, Boron Trifluoride, Silicon Tetrafluoride, and Sulfur Hexafluoride," *J. Chem. Phys.*, **30**, 574 (1959).
 Eubank, P. T. and Kerns, W. J., "Adsorption and Molecular Association in the Burnett Apparatus," *AIChE J.*, **19**(4), 711 (1973).
 Fisher, W. J., "The Coefficients of Gas Viscosity," *Phys. Rev. (Series I)*, **28**, 73 (1909).
 Fredenslund, A., Jones, R. L. and Prausnitz, J. M., "Group-contribution Estimation of Activity Coefficients in Nonideal Liquid Mixtures," *AIChE J.*, **21**(6), 1086 (1975).
 Fuller, E. N., Schettler, P. D. and Giddings, J. C., "New Method for Prediction of Binary Gas-Phase Diffusion Coefficients," *Ind. Eng. Chem.*, **58**(5), 18 (1966).
 Georgeton, G. K. and Teja, A. S., "A Group Contribution Equation of State Based on the Simplified Perturbed Hard Chain Theory," *Ind. Eng. Chem. Res.*, **27**, 657 (1988).
 Harris, E. J., Hope, G. C., Gough, G. W. and Smith, E. B., "Viscosity of Gaseous Carbon Dioxide, Sulfur Hexafluoride and Nitrous Oxide at Low Temperature," *J. Chem. Soc., Faraday Trans. 1*, **75**, 892 (1979).
 Hawksworth, A., Nourse, H. H. E. and Raw, C. J. G., "High-Temperature Gas Viscosities. III. NON2O Mixtures," *J. Chem. Phys.*, **37**(4), 918 (1962).
 Howard, A. J., "Studies in Diffusion 1 - Estimation of Diffusivities in Gaseous Systems," *Industrial and Engineering Chemistry*, **22**, 1091 (1930).
 Hudson, G. H., McCoubrey, J. C. and Ubbelohde, A. R., *Trans. Faraday Soc.*, **56**, 1144 (1960).
 Ivakin, B. A. and Suetin, P. E., *Soviet Phys.-Tech. Phys. (English Trans. I.)*, **8**, 748 (1964).
 Jin, G., Walsh, J. M. and Donahue, M. D., "A Group-contribution Correlation for Predicting Thermodynamic Properties with the Perturbed-Soft-Chain Theory," *Fluid Phase Equilibria*, **31**, 123 (1986).
 Johnston, H. L. and McClosky, K. E., "Viscosities of Several Common Gases between 90 K and Room Temperature," *J. Phys. Chem.*, **44**, 1038 (1940).
 Kestin, J. and Ro, S. T., "The Viscosity and Diffusion Coefficient of Bi-

- nary Mixtures with Ar, N₂, CO₂," *Ber. Bunsen-Ges. Physik. Chem.*, **86**, 948 (1982).
- Kestin, J. and Wakeham, W. A., "The Viscosity of Three Polar Gases;" *Ber. Bunsen-Ges. Physik. Chem.*, **83**, 573 (1979).
- Khoury, F. and Robinson, D. B., "Second Virial Coefficients and Intermolecular Force Constants of the Ethane-Hydrogen Sulfide System;" *J. Chem. Phys.*, **55**(2), 834 (1971).
- Kihara, T., *Intermolecular Forces*, Wiley, New York (1978).
- Klemec, A. and Remi, W., *Monatsh. Chem.*, **44**, 307 (1923).
- Lide, D. R., *Handbook of Chemistry and Physics*, 76th Ed., CRC Press (1995).
- Lucas, K., *Phase Equilibria and Fluid Properties in the Chemical Industry*, Dechema, Frankfurt (1980).
- O'Connell, J. P. and Prausnitz, J. M., *Advances in Thermophysical Properties at Extreme Temperatures and Pressures*, 3rd Symposium of Thermophysical Properties, ASME, New York (1965).
- Oh, S.-K., *A Group Interaction Model for Second Virial Coefficients of Pure Gases and Mixtures*, M.S. Thesis, University of S. Florida, Tampa (1989).
- Oh, S.-K. and Campbell, S. W., "A Group Contribution Model for Thermodynamic and Transport Properties of Dilute Gases;" *Fluid Phase Equilibria*, **129**, 69 (1997).
- Oh, S.-K. and Sim, C.-H., "An Extension of the Group Contribution Model for Thermodynamic and Transport Properties of Dilute Gases;" *Korean J. Chem. Eng.*, **19**(5), 843 (2002).
- Raw, C. J. G. and Ellis, C. P., "High-Temperature Gas Viscosities I. Nitrous Oxide and Oxygen;" *J. Chem. Phys.*, **28**, 1198 (1958).
- Reid, R. C., Prausnitz, J. M. and Sherwood, T. K., *The Properties of Gases and Liquids*, 4th Ed., McGraw-Hill, New York (1987).
- Schuil, A. E., "A Note on the Viscosity of Gases and Molecular Mean Free Path;" *Phil. Mag.*, **28**, 679 (1939).
- Scott, D. S. and Cox, K. E., *Can. J. Chem. Eng.*, **38**, 201 (1960).
- Stephan, K. and Lucas, K., *Viscosity of Dense Fluids*, Plenum Press, New York (1979).
- Takahashi, M., Shibasaki-Kitakawa, N., Yokoyama, C. and Takahashi, S., "Viscosity of Gaseous Nitrous Oxide from 298.15 K to 398.15 K at Pressures up to 25 Mpa;" *J. Chem. Eng. Data*, **41**, 1495 (1996).
- Tee, L. S., Gotoh, S. and Stewart, W. E., "Molecular Parameters for Normal Fluids. Kihara Potential with Spherical Core;" *Ind., Eng. Chem. Fund.*, **5**, 363 (1966).
- Titani, T., "The Viscosity of Vapours of Organic Compounds. Part III;" *Bull. Chem. Soc. Japan*, **8**, 255 (1933).
- Trautz, M. and Kurz, F., "Viscosity, Thermal Conductivity and Diffusion of Gas Mixture XV. Viscosity of H₂, N₂O, CO₂ and C₃H₈ and Their Binary Mixtures (in German);" *Ann. Phys.*, **9**, 981 (1931).
- Trantz, M. and Muller, W., *Ann. Phys.*, **414**, 333 (1935).
- Trautz, M. and Ruf, F., "Die Reibung, Wärmeleitung und Diffusion in Gasmischungen XXVII. Die innere Reibung von Chlor und von Jodwasserstoffe Eine Nachprüfung der eta-Messungsmethode für Aggressive Gase;" *Ann. Phys.*, **20**(5), 127 (1934).
- Trautz, M. and Sorg, K., *Ann. Phys.*, **10**, 81 (1931).
- Tsonopoulos, C., "An Empirical Correlation of Second Virial Coefficients;" *AIChE J.*, **20**(2), 263 (1974).
- Tsonopoulos, C. and Dymond, J. H., "Second Virial Coefficients of Normal Alkanes, Linear 1-Alkanols (and Water), Alkyl Ethers, and Their Mixtures;" *Fluid Phase Equilibria*, **133**, 11 (1997).
- Wall, F. T. and Kidder, G. A., "Mutual Diffusion of Pairs of Gases;" *J. Phys. Chem.*, **50**(3), 235 (1946).
- Tsonopoulos, C., Dymond, J. M. and Szafranski, A. M., "Second Virial Coefficients of Normal Alkanes, Linear 1-Alkanols and Their Binaries;" *Pure & Appl. Chem.*, **61**(6), 1387 (1989).
- Vogel, H., "On the Viscosity of Several Gases and Its Temperature Dependence at Low Temperature;" *Ann. Phys.*, **43**, 1235 (1914).
- Wormald, C. J. and Wurzberger, B., "Ammonia-benzene Association. Second Virial Cross Coefficients for Ammonia-benzene and Ammonia-cyclo Hexane Derived from Gas Phase Excess Enthalpy Measurements;" *J. Chem. Thermodyn.*, **34**, 1279 (2002a).